Multi-scale analysis of the effects of forestry operations on the stream morphology and sedimentology of the Cascapédia River, Eastern Québec

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ABSTRACT

Forest harvesting is blamed for a perceived increase in the flashiness and turbidity of the Cascapédia River's water. This has raised questions over the source of the sediment (harvest parcels, roads, or stream banks) and its potential impact on the sedimentology of the river. The objectives of this research are twofold. The first is to ascertain if harvesting operations are associated to a widening of low-order tributaries, creating a source of sediment. The second is to determine if variations in the sedimentology along four segments of the Cascapédia can be associated to harvesting operation intensity. Firstly, analysis of stream width in low-order tributaries shows that, once the variations associated with basin area and D50 are removed and within the range of harvesting in our dataset, there appears to be a 25% increase in width associated with the harvesting activities of the last five years, as well as with road density, both in a 60 m stream buffer for a number of the sampled streams. Secondly, the models relating harvesting intensity and changes in sedimentology are sensitive to a few sites or contrary to theory. Future studies should determine the underlying hydrological processes responsible for stream enlargement and the process of sediment deposition.

Résumé

Les gestionnaires de la ressource salmonicole de la Cascapédia s'inquiètent à propos de l'intensité de l'activité forestière et d'un accroissement possible des charges en suspension causé par un apport sédimentaire accru, qui pourrait entraîner une baisse de la qualité de l'habitat salmonicole. Notre premier objectif vise à tester l'hypothèse d'un accroissement de la production de sédiments fins due à l'élargissement des petits cours d'eau de tête situés près des parterres de coupe. Le deuxième objectif vise à tester l'hypothèse que l'intensité de l'activité forestière a un effet sur la qualité de l'habitat salmonicole. L'analyse statistique démontre que l'intensité des coupes des cinq dernières années et la densité de routes, tous deux dans un périmètre de 60 m autour des cours d'eau, sont positivement corrélées à la largeur de ces petits tributaires (une fois ces largeurs ajustées pour l'effet de la superficie du bassin et la composition granulométrique du lit). L'analyse révèle que les relations entre les activités forestières et la quantité de sédiments fins dans les seuils sont sensibles à quelques sites et certaines n'ont pas de base théorique. Des études complémentaires devront confirmer les mécanismes hydrologiques sous-jacents ainsi que le processus de déposition des fines injectées dans la rivière.

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I INTRODUCTION

I.1 Recent concerns over how harvesting affects the Cascapédia River

Over the years, controversies have arisen in various parts of the world over harvesting and its potential impacts on the surrounding landscape. In the Cascapédia River basin, in Eastern Quebec, the debate has centred on how harvesting has altered the flashiness and turbidity of the river, although no scientific data have yet been collected to support these claims. Two questions are identified: 1) can the source of the sediment be established and 2) does sediment deposition occur in potential salmonid habitat and alter its sedimentology? The goal of this research is to answer these questions for the Cascapédia River, a salmon-run river. An increase in the river's flashiness and turbidity could affect the river's Atlantic salmon stock by altering salmonid reproduction, feeding behaviour and efficiency (Hicks *et al.,* 1991).

The general impacts of large-scale forestry activities in a watershed are well documented: increased peak flows (Harr and McCorison, 1979), higher soil moisture content due to reduced evapotranspiration, increased overland flow, and increased sediment yield (Plamondon, 1993; Slaymaker, 2000). Furthermore, the potential impacts of increasing the fine sediment content (i.e. sediment with a diameter $<$ 2 mm) in salmonid habitats are well understood: a decrease in the supply of dissolved oxygen to embryos (Silver *et al.,* 1963; Hicks *et al.,* 1991), a reduction of waste removal, and egg smothering (Parkinson *et al.,* 1999; Soulsby *et al.,* 2001). However, rivers flowing in different watersheds do not necessarily share sediment types, climate, topography, salmonid species, or harvesting technology. For example, results from Carnation Creek are specific to Pacific salmon, which has a different life cycle than Atlantic salmon (Tschaplinski, 1998, 2000). Consequently, results from forest-fish interaction studies cannot be considered universal due to the lack of transferability between watersheds (Ward, 1971; Alila and Beckers, 2001; Caissie *et al.*, 2002). Thus, the goal of this research is to determine whether forestry operations affect the stream morphology and sedimentology of the Cascapédia River in Eastern Quebec. While other factors can also affect these, this research focuses solely on the impacts of harvesting, so as to minimise the study variables.

I.2 Context

The timber and fish resources in the Cascapédia watershed are used by different groups. Each has its own view of how the resources should be managed. The Micmacs have subsistence fishing rights at the mouth of the river, while wealthy sport fishermen fish in mainstem pools at a cost of up to $1000 CAN/day. The Cascapédia Society manages the river, employing locals as guides and wardens. Timber is extracted by forestry companies, who have been exploiting the watershed since the early 1900's (Alcock, 1935). In the past, few objections were raised to the harvesting intensity in the watershed. However, a conflict now exists between foresters and fishermen, who wish to maintain quality fish habitat and oppose the increasing intensity of forest extraction. They claim harvesting operations have changed the river's response to rain events, arguing that the river's flashiness (i.e. the intensity of response to a rain event) and suspended sediment loads have increased, although no scientific data exist to test this hypothesis or determine the source of the extra sediment. Anglers are concerned that an increase in the river's fine sediment content could exceed its transport capacity and that the surplus sediment will deposit in the river bed. Sediment deposition in potential spawning habitat could decrease its quality, endangering the salmonid population's survival if it continues unchecked.

In the late 1990's, the Cascapédia Society challenged the forestry regulations of the Quebec Ministry of Natural Resources (MNR) regarding the impacts of harvesting on the river's ability to maintain quality fish habitat because of the economic importance of fishing in the region. Provincial regulations allow harvest of up to 50% of a watershed, a rate at which a stream's hydrological response is believed to remain unaltered (Langevin and Plamondon, 2003). CIRSA (Centre Interuniversitaire de Recherche sur le Saumon Atlantique) was then mandated to study the biological and geomorphic impacts of harvesting on salmonid habitat. While a "before-after" study would best confirm any changes in turbidity and flashiness, pre-harvesting data for these variables are not available for the Cascapédia. Secondly, this type of study requires an undisturbed control basin to determine the inter-annual natural variations in turbidity and flashiness. There is no such basin within the Cascapédia watershed or on the Gaspé Peninsula, since all watersheds are harvested to some level. Thus, as an alternative, this study investigates possible associations between stream morphology, sedimentology and harvesting by determining if stream banks are widened, creating a source of sediment and if the sediment deposits in potential spawning habitat. The focus is on key geomorphological aspects of salmonid habitat (stream slope, bed sediment composition, and channel width) because these are easily and quickly measured at multiple sites and the methodology is easily replicated. Moreover, because stream width is related to basin area, changes such as widening can be indicative of changes in runoff and sediment production (Rosgen, 1996), which could be associated to higher harvesting intensities (Slaymaker, 2000).

This thesis has two general objectives. The first is to determine if low-order tributaries have been widened in association with harvesting intensity in the Cascapédia watershed, making them a potential source of fine sediment (i.e. sediment with a diameter of up to 2 mm). The second objective is to determine if there is an association between variations in riffle sedimentology and the harvesting intensity along four mainstem segments of the Cascapédia River. These segments have potential spawning habitat and are located downstream of the sampled low-order streams. Specific objectives and hypotheses are presented in Chapter III.

I.3 Chapter organisation

This thesis is divided into nine chapters. Chapter I provides a general introduction to the topic and Chapter II reviews the relevant literature. Based on the literature, the specific study objectives are explained in Chapter III. The study site is described in Chapter IV. The first objective is explored in Chapters V and VI, which look at low-order tributaries and discuss the associations between variations in stream characteristics and large-scale landscape structure variables (Ch. V) and harvesting operations (Ch. VI). The second objective is examined in Chapters VII and VIII. Chapter VII determines the relation between the variations in pavement mean sediment diameter (D50) and riffle fine sediment content (%fines) of mainstem segments associated to large-scale landscape-structure and reach-scale variables. Chapter VIII tests the relations between harvesting perturbations and the remaining variations in D50 and %fines (i.e. the residuals). Finally, major findings and conclusions are explained in Chapter IX.

II LITERATURE REVIEW

II.1 Impacts of harvesting

Forestry operations change the surrounding landscape (Harr and McCorison, 1979). The impacts relevant to the research questions studied in this thesis are changes in runoff, sediment production, and stream morphology and characteristics. These are summarised below. While runoff and sediment production were not measured directly in this study, it is important to understand how harvesting can affect these to understand any changes in stream morphology.

II.1.1 Runoff

Harvesting modifies watershed cover characteristics and influences runoff patterns. This affects the timing and quantity of flow in the harvested basin's channels and may also affect sediment input to streams (Chamberlain *et al.,* 1991; Richards and Host, 1994; Megahan *et al.*, 2001). These impacts usually persist until the tree cover, soil and leaf litter, soil infiltration, and moisture retention capacity of the soil recover, with recovery rates varying based on a site's native tree species (Trenhaile, 1998). While some studies show increases in streamflow peaks, others find no conclusive evidence of this, even when 25% of the basin is harvested (Lewis *et al.*, 2001), especially if the soil is undisturbed by skid roads (Harr and McCorison, 1979). However, when the soil is disturbed and roads occupy at least 12% of the area harvested, significant increases in peak flow magnitudes occur (Harr and McCorison, 1979).

An increase in peak flows can influence local flood risk (Chamberlain *et al.,* 1991; Lewis *et al.,* 2001), especially in intensely harvested (> 70%) basins of < 2 km^2 (Brandt *et al.,* 1988). Stream discharge controls the degree of increase in peak flow. Therefore, the increase in spring flows is greater in basins > 10 km^2 because their streams have larger discharges (Plamondon, 1993). In a few rare cases, peak flows have been reduced and delayed because of a reduction in soil water movement and an increase in snow accumulation coupled with a delay in melt (Harr and McCorison, 1979). Changes in streamflow are usually not observed in basins of 25-55 km^2 when < 20% of the watershed is harvested (Plamondon, 1993; Caissie *et al.,* 2002). Observed changes in streamflow at this harvesting intensity are quite minimal because of the difficulties in detecting harvesting impacts using the hydrometric method (Swanson *et al.,* 1986). Studies of basins of 5 km^2, harvested at 31%, showed no changes in streamflow (Plamondon, 1993). Langevin and Plamondon (2003) assert that, in Quebec, harvesting $<$ 50% of a basin does not alter streamflow, and this has become the legal limit of harvesting within a watershed. Therefore, harvesting can change peak flows, although this depends on the intensity of the activity and on the size of the harvested basin. Three theories explain why runoff increases following harvesting: increased overland flow, reduced evapotranspiration, and increased snowmelt intensity. These are discussed in turn.

Overland flow is rare in undisturbed basins because the soil's infiltration capacity is greater than the rate of precipitation (Arnell, 1996). However, by removing vegetation and compacting the soil, harvesting reduces the soil's permeability and its infiltration rate, increasing runoff from overland flow (Campbell and Doeg, 1989; Jewett *et al.*, 1995). Soil permeability is also reduced on forest roads (Bowling and Lettenmaier, 2001), which increases the volume of water available for overland flow in two ways. First, more precipitation is intercepted on the road's compacted surface, where it becomes overland flow due to the road's low infiltration capacity. Second, shallow subsurface flow is intercepted at the road cutbanks and converted to surface runoff (Meehan *et al.,* 1969; Swanson *et al.,* 1986; Wemple *et al.,* 1996). Roads also alter the hydrology of harvested basins because their ditches extend the drainage network and alter the basin's flow routing efficiency (known as the timing effect) (Bowling and Lettenmaier, 2001). Up to 57% of a basin's roads and ditches can contribute to increasing the stream network's length (Wemple *et al.,* 1996), providing a fast and direct way for sediment and runoff to reach the river (Plamondon, 1993; Slaymaker, 2000; Bowling and Lettenmaier, 2001). Therefore, careful consideration must be given to road layout, construction, and maintenance to prevent road failures, minimise extension of the drainage network, and minimise increases in surface runoff (Slaymaker, 2000).

Evapotranspiration decreases in proportion to the intensity of harvesting because of lower rain and fog interception and a decrease in leaf area index (Campbell and Doeg, 1989;

Jewett *et al.,* 1995). Fewer trees intercept a smaller amount of precipitation, increasing throughfall and reducing the amount of precipitation available for evaporation. This increases streamflow, which is usually highest in the first year following harvest and declines as the vegetation recovers (Plamondon, 1993; Slaymaker, 2000). A reduction in interception and evaporation increases the soil moisture content and may raise the water table in harvested areas (Chamberlain *et al.,* 1991; Buttle *et al.,* 2000; Slaymaker, 2000; Caissie *et al.,* 2002). As a result, smaller precipitation events can produce larger runoff in harvested areas because the soil has a higher conductivity, supplying water to the stream at a faster rate (Hudson, 2001; Sidle *et al.*, 2001).

Runoff also increases in harvested areas due to a change in the dynamics of snow accumulation and melt. In the spring, large peak flow increases occur when warm rain falls on ripe snowpacks (Hudson, 2001). Harvested areas of moderate size accumulate more snow during the winter than forested areas (Plamondon, 1993). This snow melts earlier and faster because of increased solar radiation at ground level and from rain-on-snow events (Lyons and Beschta, 1983; Brandt *et al.,* 1988; Plamondon, 1993; Buttle *et al.,* 2000; Caissie *et al.*, 2002), increasing peak flows and summer baseflows, in addition to raising the water table (Brandt *et al.*, 1988; Hinton *et al.,* 1993; Plamondon, 1993; Jewett *et al.,* 1995; Wei and Davidson, 1998). The impact on baseflow is also related to stand age. Older stands have lower water uptakes than young stands. Therefore, their harvest creates fewer changes in baseflow. Conversely, younger stands use more water and when these are removed, baseflow increases are greater than in older stands (Plamondon, 1993). Increases in peak flows can be moderated by harvesting in a mosaic pattern, which desynchronises snow melt in the watershed and water contributions from tributaries (Plamondon, 1993, Langevin and Plamondon, 2003).

To accurately determine the effect of harvesting on runoff generation, studies concerned with changes in runoff following harvesting need to control for differences in precipitation and antecedent soil moisture content (ASM) before, during, and after the harvesting period (Hudson, 2001; Caissie *et al.,* 2002). Controlling for ASM is important because of its role in determining how peak flow increases (Hudson, 2001). Dry ASM conditions usually yield little or no runoff when compared to wet conditions (Lewis *et al.,* 2001). Changes in runoff may also be seasonal. In some cases, changes occur only in summer flows (Wei and Davidson, 1998). In addition, the changes may not be in the quantity of runoff, but in the timing of spring snowmelt (Plamondon, 1993). While harvesting impacts occur throughout the watershed (Brandt *et al.*, 1988), forest managers are often not concerned with low-order tributaries since these do not support fish populations (Hudson, 2001), even though the impacts at this scale are usually more severe because these streams are highly responsive to changes in their riparian vegetation and their surrounding watershed (Chamberlain *et al.*, 1991; Church, 1996).

II.1.2 Sediment production

In natural, undisturbed watersheds, sediment is injected into streams at times of high flow (i.e. at maximum sediment transport capacity). Harvesting can inject sediment into streams during low flow, when sediment deposition is more likely (Chamberlain *et al.*, 1991; Kondolf, 2000). Sediment can come from harvested parcels or logging roads and skid trails (Chamberlain *et al.*, 1991; Grant and Wolff, 1991; Plamondon, 1993), which destroy the soil's protective vegetation and increase erosion (Megahan *et al.*, 2001) or from the erosion of the stream bed and banks (Knighton, 1984; Rosgen, 1996). Harvesting in the riparian zone can decrease bank stability and lead to channel enlargement and straightening (Barrett *et al.*, 1998). Clearcutting without leaving a buffer around a stream increases the amount of sand (sediment with a diameter from 0.0625 mm to 2 mm) found at depths of 12 to 35 cm in the bed (Tschaplinski, 1998, 2000). In undisturbed systems, the spring freshet flushes excess fine sediments from the bed and cleans the gravel substrate. However, the sediment injected into the river from harvesting can deposit on the bed and the spring freshet may not be sufficient to flush this excess sediment out of the substrate, degrading the quality of potential habitat (Tschaplinski, 2000). Buffer zones are thus required to attenuate disturbances to the soil and vegetation (Meehan, 1991; Plamondon, 1993). The USDA Soil Conservation Service suggests these should be 100 m in width on either side of the channel (Purdum, 1997).

Sediment production peaks in the first year following road construction and then decreases exponentially (Luce and Black, 2001; Wemple *et al.*, 2001). In some cases, changes in sediment production associated to harvesting are only seen in watersheds of tens of km^2 or less; longer sediment transit times may allow larger basins to absorb the effects of forestry (Slaymaker, 2000). Sediment production is also closely related to precipitation, particularly rain events. Large rain events can initiate erosion either from large landslides or sediment movement within the watershed where there would otherwise be little or no erosion (Grant and Wolff, 1991).

Harvesting also increases sediment production by reducing the permeability of compacted soil and increasing surface erosion (Reid and Dunne, 1984; Campbell and Doeg, 1989). Roads are a large source of sediment, accounting for 30 to 90% of the erosion attributed to forestry operations (Barrett *et al.,* 1998; Campbell and Doeg, 1989; Slaymaker, 2000; Lewis *et al.,* 2001; Grace, 2002). Proper road design and maintenance reduces the amount of sediment that enters the stream, reducing potential impacts on fish habitat. It can also minimise future costs by preventing costly road failure repairs (Harr and Nichols, 1993). Sediment production from roads is of concern for two reasons. First, the sediment can be introduced directly to a stream. Second, the sediment produced from roads is finer than 2 mm, the portion that causes a decline in fish habitat quality if it constitutes over 15% of the substrate (Petersen and Metcalfe, 1981; Reid and Dunne, 1984). Road traffic plays a role in the amount of sediment produced. Heavily used roads (over four loaded trucks per day) generate up to 70% of the total sediment produced from all roads (Reid and Dunne, 1984). Larger harvested areas and longer road sections increase runoff, sediment yield, and have a higher probability of delivering sediment to the stream through gullies and landslides (Wemple *et al.,* 1996; Lopes *et al.,* 2001; Luce and Black, 2001). Basin shape, length, and relief also affect how sediment is eroded from the land and injected into the stream (Trenhaile, 1998). The severity of road sedimentation problems also depends on road age, slope gradient, aspect and length, material, and cutslope height (Luce and Black, 2001; Megahan *et al.,* 2001).

Wilson (2003) was the first to study the impacts of harvesting and its sediment production on the Cascapédia River. Her objective was to investigate the relation between forestry practices and the quality of potential spawning habitat (i.e. the fine sediment content) in second to fifth order streams in the Cascapédia watershed. While no general relation between basin-wide equivalent cut area (ECA, the equivalent area that would need to be harvested in the current year to account for the hydrological recovery of a basin with time since harvest) and substrate fine sediment (‹ 2 mm) content values was found, a weak, but significant, positive relationship was found for reaches with a channel gradient ‹ 1%. These reaches were more susceptible to fine sediment accumulation in the substrate when ECA and road density in the 1 km radius upstream of a site were greater than 40% and 4 km/km^2, respectively (Figure 1) (Wilson, 2003). Wilson's (2003) study of a road failure site found no significant difference in the riffle fine content upstream or downstream of the failure, despite the identification of roads as the largest sediment contributor to streams (Wemple *et al.*, 1996).

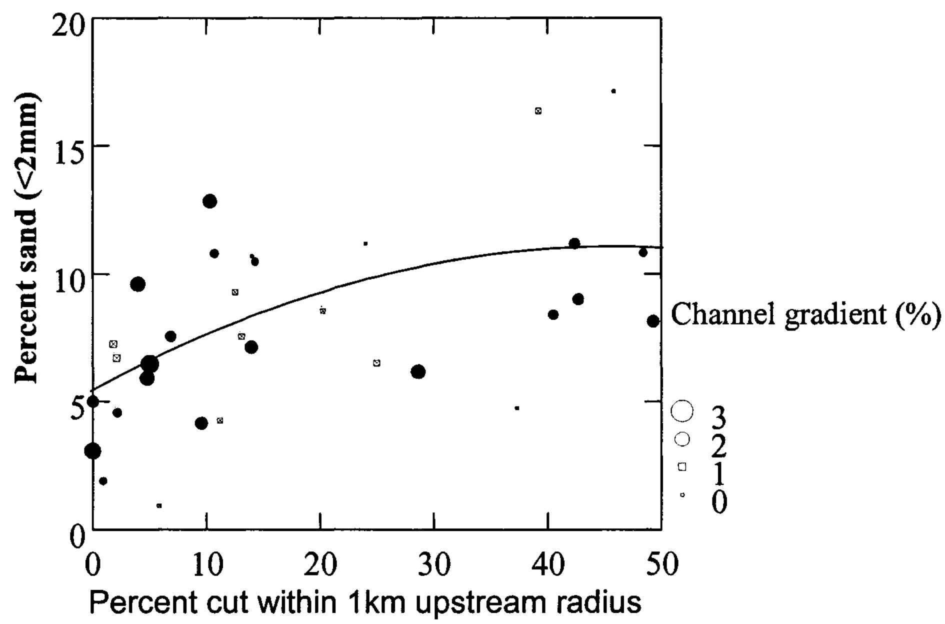


Figure 1. Scatterplot of percent sand versus percent cut within a 1 km upstream radius (Wilson, 2003). The best fit line is a smoother.

II.1.3 Stream morphology and characteristics

Channel geometry

Stream morphology is affected by the volume and timing of water distribution, the volume, timing, and character of sediment introduced into the stream, the nature of the river's bed material, local geological history, climate, land use, and riparian vegetation (Church, 1996). Changes in runoff affect streamflow, which when combined with changes in sediment load, can alter a stream's morphology. This has repercussions on fish and the macroinvertebrate populations they feed on because their diversity is negatively related to the fine sediment (< 2 mm) content in the substrate (Richards and Host, 1994). Alluvial systems can recover from a temporary disturbance to flow or sediment inputs, but will not necessarily return to the previous equilibrium dictated by hydraulic geometry (Phillips, 1990; Trenhaile, 1998). This concept is described below.

In undisturbed rivers, there is an allometric relationship between discharge and channel width, depth, and velocity (Knighton, 1984; Church, 1996; Merigliano, 1997), described as hydraulic geometry relations (Leopold and Maddock, 1953). These relationships are represented by the equations:

$$w = aQ^b \qquad d = cQ^f \qquad v = kQ^m \qquad \text{(1a, b, c)}$$

W is the water surface width, d is the mean water depth, v is the mean velocity, and Q is discharge. Drainage area can be used as a surrogate for discharge when the latter cannot be obtained (Castro and Jackson, 2001). These hydraulic geometry relations, as well as other downstream changes in channel form, are shown in Figure 2. The sum of the parameters b, f, and m is one, and the product of a, c, and k is also one (Merigliano, 1997; Trenhaile, 1998). When discharge is used in equation 1a, the exponent b varies between 0.1 and 0.5 (Leopold and Maddock, 1953; Morisawa and LaFlure, 1979; Trenhaile, 1998). It varies between 0.36 and 0.51 when basin area is used (Castro and Jackson, 2001; Doll *et al.,* 2002). Relationships lying outside the hydraulic geometry ranges predicted from regional drainage curves are usually indicative of watershed alterations (Rosgen, 1996). Wilson (2003) calculated the hydraulic geometry relation of stream width versus basin area for 48 second to fifth order tributaries of the Cascapédia River (80% were third and fourth order) and obtained a strong, significant relation ($r^2 = 0.80$, $P < 0.0005$), with an exponent of 0.46, which falls within the range of published results (e.g. Church, 1996; Miller *et al.*, 2000). However, stream width varied considerably for equal-sized basin areas because of factors such as stream density and soil erosion potential (Wilson, 2003).

Channel width can also be predicted by stream order. However, given the irregular nature of drainage networks, stream order can sometimes be misleading and inaccurate since two links of the same order are required to create the next order (Church, 1996). This problem can be avoided by using the stream's link-magnitude, where each link is assigned the value of the number of links upstream of it (Morisawa, 1957; Church, 1996). Nevertheless, the problem with these methods is that headwater streams are often omitted on small-scale maps, which affects the stream order and link-magnitude assigned to each stream.

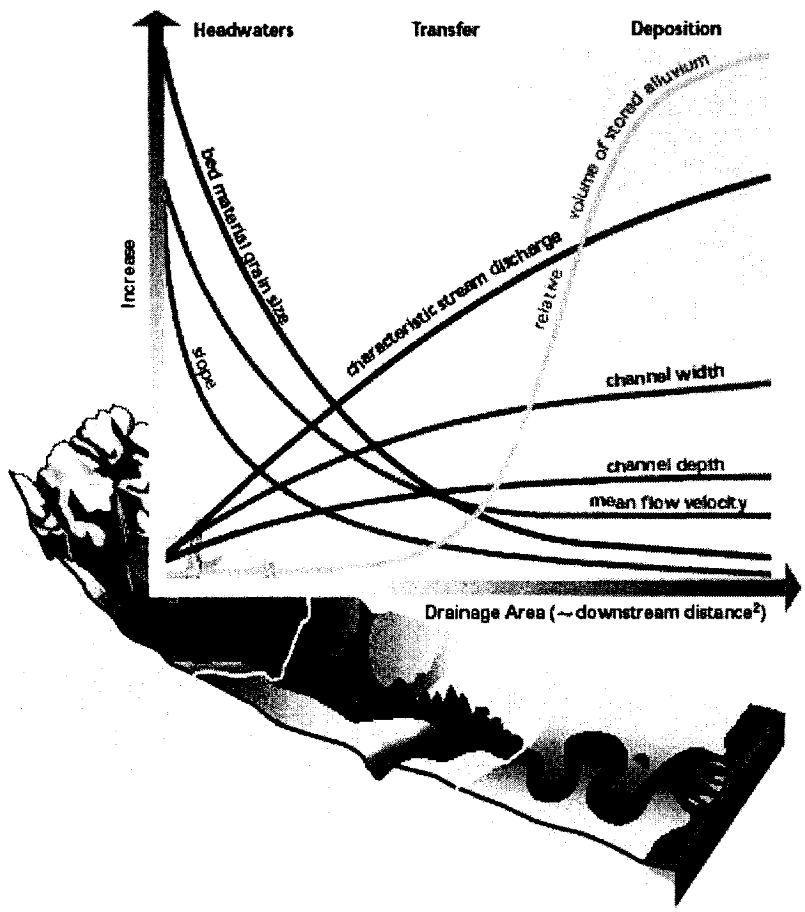


Figure 2. Schematic representation of theoretical downstream changes in stream characteristics as basin area increases (FISRWG, 1998).

Stream width is also a function of streamflow timing and magnitude, sediment size and type, and bed and bank materials (Trenhaile, 1998). Width can be altered by processes affecting any of these, such as direct channel disturbance, changes in riparian vegetation, changes in streamflow regime (due to watershed changes), or changes in the sediment regime (Morisawa and LaFlure, 1979; Church, 1996; Rosgen, 1996; Barrett *et al.*, 1998).

Land use changes can destabilise streams. A stream's first response to land use change is usually bed degradation, although the channel banks can also be eroded (Thorne, 1991). Bed and bank toe scouring increase bank height and angle, reducing bank stability. This leads to bank failure, usually when bank material strength is weakest and weight is at its maximum. Streamflow washes the failed material away such that bed and bank toe scouring can reoccur and widen the channel further. Maximum widening is determined by the flow's ability to continue this process (Thorne, 1991). For example, streams in harvested watersheds ranging from 32 to 1000 km^2 can be 25 to 250% wider than streams in undisturbed areas (Lyons and Beschta, 1983).

Much like channel width, discharge, velocity, and channel slope also change as basin area increases (Figure 2). Generally, channel width increases concomitantly with basin area, which explains the increase in discharge (Q). Discharge is calculated as:

$$Q = \text{Velocity} * \text{Cross-sectional area of the stream} \qquad (2)$$

Discharge increases in the downstream direction despite the downstream decrease in velocity, which is linked to the decrease in channel slope. Velocity (V) is calculated as:

$$V = (R^{2/3} * S^{1/2})/n \qquad (3)$$

Where R is the hydraulic radius, S is slope, and n is the Manning coefficient of roughness. Channel slope also decreases at tributary junctions to compensate for the increases in channel width and discharge at these locations (Gordon *et al.,* 1992). Following from this, shear stress usually decreases in the downstream direction, and is thus negatively related to basin area, because it is calculated as:

$$\tau = \gamma RS \qquad (4)$$

Where S is slope, γ is gamma (9800 kg/m^2sec^2), the product of gravity and the density of water, and R is the hydraulic radius (in m). The decrease in shear stress also explains the downstream decrease in bed material grain size (Figure 2, Gordon *et al.,* 1992; FISRWG, 1998). Therefore, these factors (discharge, velocity, channel slope, and shear stress) play a role in the downstream changes in sedimentology.

Stream water characteristics

Harvesting can also change stream characteristics such as dissolved oxygen content, temperature, and nutrient content. This has repercussions on benthic and salmonid community structures (Phillips, 1971). Logging debris and increased fine sediment in the river can reduce dissolved oxygen content, increase turbidity, and decrease redd reproductive success by smothering and entombing the eggs (Campbell and Doeg, 1989).

An increase in light exposure raises stream temperature (Hartman *et al.*, 1996), which, when coupled with an increase in sediment and nutrients in the stream can increase primary production and change the macroinvertebrate community structure. Normally, this has a negative impact on fish feeding patterns (Hall and Lantz, 1969; Hall *et al.*, 1987 in Hartman *et al.*, 1996), but it can enhance fish growth temporarily (e.g. Carnation Creek, Hartman *et al.*, 1996; Tschaplinski, 2000). Increased light exposure can be avoided by leaving a buffer strip along the stream's riparian zone (Campbell and Doeg, 1989). Clearcutting can decrease the amount of stable large woody debris (LWD) in the river, increasing stream velocity, bank erosion, and sediment deposition. At Carnation Creek, channel width increased twofold in areas where stable LWD declined (Tschaplinski, 2000). Conversely, Faustini and Jones (2003) reported that streams with LWD are wider by up to 50% when compared to streams with no LWD.

II.2 Salmon habitat requirements

Atlantic salmon are anadromous, returning from the sea to their native rivers to spawn in October or November (Parkinson *et al.*, 1999). Despite their wide distribution, Atlantic salmon have similar habitats (Mäki-Petäys *et al.*, 2002). They spawn in gravel beds called redds, which are located immediately upstream of riffles. Redd water velocities average 20 to 60 cm/s and water depth ranges from 20 to 30 cm (Fleming, 1996; Bardonnet and Baglinière, 2000). Eggs are buried to depths of 10 to 50 cm in substrates with a mean diameter of 15 to 150 mm (Bjornn and Reiser, 1991; Fleming, 1996; Bardonnet and Baglinière, 2000), which prevents predation (Parkinson *et al.*, 1999; Soulsby *et al.*, 2001), but increases their vulnerability to excess sedimentation. Salmonid reproductive success is closely linked to spawning habitat quality, which controls egg survival. Salmonids are most sensitive to habitat quality limitations during the spawning and incubation seasons (Parkinson *et al.*, 1999). The main physical controls over this habitat are water depth, velocity, and substrate characteristics (Soulsby *et al.*, 2001).

Successful embryo incubation requires that water percolate through the redd to provide dissolved oxygen at a rate of 2 to 8 mg/L (Silver *et al.*, 1963; Kondolf, 2000). The percolating water also ensures metabolic waste disposal (Parkinson *et al.*, 1999). While embryo mortality is higher in redds with low oxygen concentrations and flow velocities

(Phillips, 1971), embryos can reduce their respiration rate when their oxygen supply is limited. However, this reduces their chances of survival since they are often hatched too small or too weak to compete effectively with other fry (Silver *et al.,* 1963).

Salmonid habitat is considered mediocre when sediments less than 2 mm constitute over 15% of the substrate (Anderson, 1998) and poor when these same sediments exceed 20% of the substrate (Petersen and Metcalfe, 1981). When fine sediments (‹ 2 mm) exceed this level, embryo survival declines (Soulsby *et al.,* 2001) because the flow velocity and oxygen content in the spawning gravels are decreased (Silver *et al.,* 1963; Parkinson *et al.,* 1999; Kondolf, 2000). Sediment deposition in the substrate is the leading factor in the low reproductive success of salmon (Parkinson *et al.,* 1999). At Carnation Creek, clogging of interstices by sediment reduced Chum salmon fry production by 50% (Tschaplinski, 2000). Furthermore, once hatched, fry emerge from the bed. However, if the substrate's pores are filled with too much fine sediment of 1 to 10 mm, emergence is impeded and fry are smothered or entombed (Phillips, 1971; Parkinson *et al.,* 1999). The detrimental effects of sediment deposition in the substrate can be reversed by large floods (floods › 50% of bankfull flow), which mobilise the deposited sediment, or by a subsequent reduction in sediment injection into the stream if the eggs have not been permanently damaged (Parkinson *et al.,* 1999).

While most of the literature concludes that harvesting has deleterious effects on salmon, there are instances when harvesting was beneficial for the fish. In Carnation Creek, the absence of a buffer led to stream temperature increases, allowing the fish to grow faster. This produced sea-ready smolts in one year rather than two. However, this bigger size and better survival in fresh water are not always translated to similar results in the ocean. (Tschaplinski, 2000)

II.3 Geomorphological research using Geographic Information Systems (GIS)

GIS models are designed to allow the calculation of multiple spatially-based metrics in a short period of time (Purdum, 1997). The use of GIS for manipulating the large amounts of data associated with fluvial systems is increasing (Aspinal, 1993; Priestnall and Downs, 1996). However, its users tend to be hydrologists and not geomorphologists

(Gurnell and Montgomery, 1998), perhaps because of the scale limitations of digital elevation models (DEM) (Eash 1993) from which other data are often derived. In a DEM, the cells of the flow grid representing the river may not always give the correct channel patterns (Priestnall and Downs, 1996) or have the desired precision for detailed study (Downs and Priestnall, 1999), which can be a drawback for fluvial geomorphologists.

Rivers may undergo geomorphological changes due to many factors, including extreme climatic events, river channelisation, and land use changes (Downs and Priestnall, 1999). A river's sensitivity to these factors depends on basin topography (e.g. steeper slopes are more prone to erosion than milder slopes), on the relative positions of the activity within the basin (e.g. how close the harvesting is to the river), and on temporal factors (e.g. time since the harvesting operation). Analysing the impacts of the complex interactions between these factors is easier within a GIS because of its data storage flexibility, rapidity of calculation, easy parameter modification, treatment of spatially-explicit data, easy display of results, and automated calculations, all of which decrease the likelihood of human error (Downs and Priestnall, 1999; Moglen and Beighley, 2002).

Studying geomorphology in a GIS allows the user to study different scales (Priestnall and Downs, 1996), although the choice of scale affects how results are interpreted (Aspinall, 1993; Downs and Priestnall, 1999; Bregt *et al.,* 2002). The scales typically used in a GIS are: the catchment scale (encompassing the entire basin), the river corridor scale (the river and a small buffer area around it), and the local scale (the area directly upstream of a site - e.g. 1 km radius upstream of a site) (Downs and Priestnall, 1999). Each of these scales has advantages and disadvantages, and can mask impacts detected at the other scales (e.g. at the catchment scale, local impacts may be eclipsed). Geomorphologists must understand the limitations of a GIS, especially in terms of the scale of the research, to know what can and cannot be inferred from the GIS (Downs and Priestnall, 1999).

Within a GIS, basin characteristics such as DEMs, flow grids, drainage basin outlines, equivalent cut area (ECA), road densities, channel gradient, and stream densities can be derived. ECA is often used to quantify harvesting activity because it accounts for the hydrological recovery of a site (Wei and Davidson, 1998) by assigning a recovery factor to each harvest year such that older cuts have a smaller effect on the hydrology of the system than newer cuts.

Despite the advantages of using GIS, users must remember that the complexity of natural river systems is difficult to represent in its entirety in a GIS. Integrating this complexity into a GIS is one of the biggest challenges to their use in modelling fluvial behaviour and habitats. A middle ground must be reached between having a manageable data source and an accurate, abstract representation of the river system. Data accuracy must be maintained in a suitable spatial and temporal framework to maintain a functional and efficient model of data representation. Users must also understand the limitations and errors inherent in digital data. The choice of map scale is also important when measuring variables such as stream length, where headwater stream reaches are sometimes omitted in small-scale maps, reducing channel length. (Downs and Priestnall, 1999, 2003)

III STUDY OBJECTIVES

III.1 General statement of objectives and rationale

The increased harvesting activity in the Cascapédia watershed has demonstrated how conflicts can occur when two resources located in close proximity are exploited by different groups of people, each having their own set of potentially conflicting goals. The conflict in the Cascapédia is the perceived increase in river flashiness and turbidity of the river, which some believe is associated to an increase in harvesting intensity. As stated in the introduction, a 'before-after' study on turbidity or flashiness was not possible due to the lack of data from the pre-harvesting period. However, an increase in turbidity suggests higher sediment levels in the water, whose source may be harvested parcels, roads (Chamberlain *et al.*, 1991; Grant and Wolff, 1991; Plamondon, 1993), or stream bed and banks (Knighton, 1984; Rosgen, 1996). Therefore, this study proposes to focus on the question of turbidity and 1) determine if stream banks are widened in association with harvesting intensity and if this is a source of sediment and 2) determine if there is an association between the variations in the sedimentology along four mainstem segments and the harvesting intensity in the watershed.

Forestry companies seek to harvest the maximum allowable cut, which is the maximum timber volume that can be harvested indefinitely from an area without reducing the production capabilities of the forest (Gouvernement du Québec, 1986). Provincial regulations set this limit at an ECA of 50% (Langevin and Plamondon, 2003). With this method, harvested parcels are weighted with a time attenuation factor to account for the hydrological recovery of the basin with time since harvest (Wei and Davidson, 1998). These measures are meant to minimise the adverse consequences harvesting can have on channel morphology (Thorne, 1991) and potential spawning habitat by increasing the amount of fine sediment (sediment $<$ 2 mm) in the river's substrate (Tschaplinski, 2000). A decline in the quality of the Cascapédia's spawning habitat could reduce the salmon population, which would in turn affect the sport fishing industry, a large employer in the region. The goal of this research is to determine if there is an association between harvesting and variations in the morphology and sedimentology of the Cascapédia River.

Objective 1:

Studies report that peak flows increase in basins of up to 50 km^2 when harvesting exceeds 25% of the total basin area (e.g. Lewis *et al.* 2001; Caissie *et al.*, 2002). However, to determine if peak flows have increased in association with harvesting requires data prior to the start of the harvesting activity, which began in the early 1900's in the Cascapédia watershed (Alcock, 1935) and are not available. Therefore, this study examines stream morphology, which would have to adjust to accommodate to an increase in peak flow (Morisawa and LaFlure, 1979; Thorne, 1991). Changes in peak flow are usually observed in watersheds where %ECA exceeds 25% (Lewis *et al.,* 2001). One quarter of the sites (30 of 110) visited in the Cascapédia watershed have %ECA at or above this level.

Furthermore, Article 2 of the "Règlements sur les normes d'interventions dans les forêts du domaine publique" requires the preservation of a 20 m buffer on both sides of all perennial streams to protect these from harvesting activities (Government of Quebec, 2003), leaving intermittent streams unprotected. While intermittent streams are usually located in the headwaters of the watershed and do not support fish populations (Hudson, 2001), widespread harvesting impacts occurring in the headwaters can accumulate as they propagate downstream (Church, 1996; Kondolf *et al.,* 2002) into reaches with potential salmonid habitat (i.e. sediment eroded in the headwaters travels through the watershed and accumulates with the sediment eroded in other sections of the watershed). Potential habitat in the Cascapédia is found downstream of headwater tributaries, in pool-riffle reaches with channel slopes $\leq$1.7% and fine sediment contents $\leq$20% (Wilson, 2003). Because impacts can travel downstream, it is important to determine if harvesting is associated with changes in headwater streams to better understand how these changes can affect downstream channel morphology.

Given this context, the first objective is to test if the morphology of low-order tributaries is associated with harvesting intensity, once natural variations are taken into account. The hypothesis is that many low-order tributaries of the Cascapédia have been widened due to the harvesting activities in their basins, increasing the amount of sediment injected into the stream (Chamberlain *et al.,* 1991) and thus increasing the turbidity of the water. While an increase in turbidity could also be due to an increase in sediment from harvested parcels and roads (Chamberlain *et al.*, 1991; Grant and Wolff, 1991; Plamondon, 1993), stream widening is studied because it is easier to measure and analyse than collecting sediment samples from parcels and roads following rain events. Furthermore, provincial guidelines require the presence of 20 m buffers around streams and roads are built according to strict guidelines to minimise erosion and sediment production (Gouvernement du Québec, 2003b). The literature reports that harvesting can increase the peak flows of headwater streams (Brandt *et al.*, 1988; Chamberlain *et al.*, 1991; Lewis *et al.*, 2001). Thus, to adjust to these higher flows, the stream banks of the headwater streams in the Cascapédia may have been eroded, injecting sediment into the river and widening the streams. The flow then transports the injected sediment further downstream, increasing the turbidity of the water because of its higher sediment concentrations. If the flow's sediment transport capacity is exceeded, deposition occurs on the river bed, which can degrade its quality as salmonid habitat. This has implications for the spawning and emergence success of the salmon population. Low-order streams with basins smaller than 25 km^2 were chosen for three reasons. Firstly, these streams are in the headwaters of the watershed and are most susceptible to harvesting impacts (Church, 1996). Secondly, the close proximity of these streams to the harvested parcels should minimise any delays between harvesting and changes to morphology. Thirdly, this study's methodology (described in Chapter V) is only suitable at this scale.

To achieve the first objective, the initial task is to determine which landscape structure variable is most closely associated to the variations in stream width. The residuals (or remaining variations) from this model can then be tested against the harvesting metrics to establish if there is an association between the two. Using residuals is effective because it removes the variation in stream width associated to landscape structure variables and simplifies the analysis by allowing the creation of single variable models (i.e. a model between the residuals and an independent harvesting variable).

Objective 2:

The second part of this study focuses on determining if the sediment injected into the river deposits in potential salmonid spawning habitat and changes the river's sedimentology. When sediments with a diameter of $<$ 2 mm comprise over 15% of the substrate, spawning habitat quality is decreased (Petersen and Metcalfe, 1981; Anderson, 1998). While a 'before-and-after' comparison of the fine sediment content in the potential spawning habitat of the Cascapédia would be ideal, no information is available regarding the quality of the habitat prior to logging in the watershed. Similarly, a comparison study of the riffle fine sediment content between an undisturbed control basin and a harvested basin would also have been more direct (Slaymaker, 2000). However, no undisturbed basins exist to serve as a control, either along the mainstem of the Cascapédia or in the watersheds surrounding it. Therefore, a watershed comparison study could not be undertaken. The best alternative is to determine if there is an association between variations in sedimentology and harvesting intensity, once the natural variations in sedimentology are accounted for. The goal of this part of the study is thus to investigate the relation between harvesting operations in the Cascapédia watershed and the riffle fine sediment content and median sediment diameter of four fourth and fifth order segments of the river, once the effects of reach-scale variations in basin area, geology, local channel slope, local bankfull shear stress, and channel width have been taken into account. Harvesting operations are represented by the metrics equivalent cut area and road density. Channel slope and shear stress are used because they interact to control sediment transport and deposition (Gordon *et al.,* 1992; Gomez, 1995). Basin area, geology, and channel width are used because of the theoretical relation between these and sedimentology (Church, 1996; Rosgen, 1996). Note that for the purposes of this study, fine sediments always refer to sediments with a diameter $<$ 2 mm.

Therefore, the second objective of this study is to determine if variations in the sedimentology of potential spawning habitat are associated to harvesting activities in the Cascapédia watershed. Potential spawning habitat is located upstream of riffle crests, in substrate with a median surface sediment size of 15 to 150 mm (Bjornn and Reiser, 1991; Bardonnet and Baglinière, 2000). The hypothesis is that once the variations in riffle fine sediment content associated to large-scale landscape structure and reach-scale variables are accounted for, a portion of the remaining variation will be related to metrics quantifying the intensity of harvesting (ECA, road density) at the catchment, local or corridor scale. The remaining variation is represented in the form of residuals, which indicate the difference between the predicted model value and the observed value.

Residuals represent the amount of variation that the model cannot predict and will be used to test other variables, in this case, the harvesting metrics, without the difficulties associated with multivariate models.

III.2 Significance of the research

The significance of this research is threefold. Firstly, along with the other CIRSA projects, this research will help establish a baseline of scientific data regarding the state of health of the Cascapédia River. Secondly, results obtained for the Cascapédia watershed concerning potential fish habitat sensitivity to harvesting operations will add to the existing pool of literature, particularly to systems where Atlantic salmon is the dominant species. Thirdly, significant evidence of a relation between harvesting operations and variations in stream morphology and sedimentology will encourage further studies of these research questions to better understand how streams respond to harvesting.

III.3 Chapter organisation

Each of the objectives is explored in two chapters. The first objective, which focuses on low-order tributaries, is developed in Chapters V and VI while the second objective, which studies the mainstem segments of the river, is explored in Chapters VII and VIII. Chapter V studies the question of how basin area, stream length, and local stream slope affect stream characteristics, in particular stream width. Chapter VI tests whether the estimates of harvesting metrics are related to the width residuals (i.e. the portion of the variation in stream width not explained by the landscape variables) obtained in Chapter V. Chapter VII analyses the relation between the large-scale landscape structure variables basin area and geology, as well as the reach-scale variables local channel slope, local shear stress, channel width, and average point bar width and variations in the riffle fine sediment content and median pavement diameter of four segments of fourth and fifth order tributaries of the Cascapédia. Chapter VIII uses the residuals obtained from the models in Chapter VII to investigate any links between these and the estimated harvesting metrics.

IV STUDY SITE

IV.1 General Information

The study site for this thesis is the Cascapédia River, whose 3200 km^2 watershed is located in the Gaspé Peninsula, Québec, Canada (Figure 3). The Cascapédia is a salmon-run river managed by the Cascapédia Society. Its sport fishery is known internationally, attracting fisherman from all over the world. It is a large employer in the region, employing locals as guides and wardens, and helps to keep local outfitters in business.

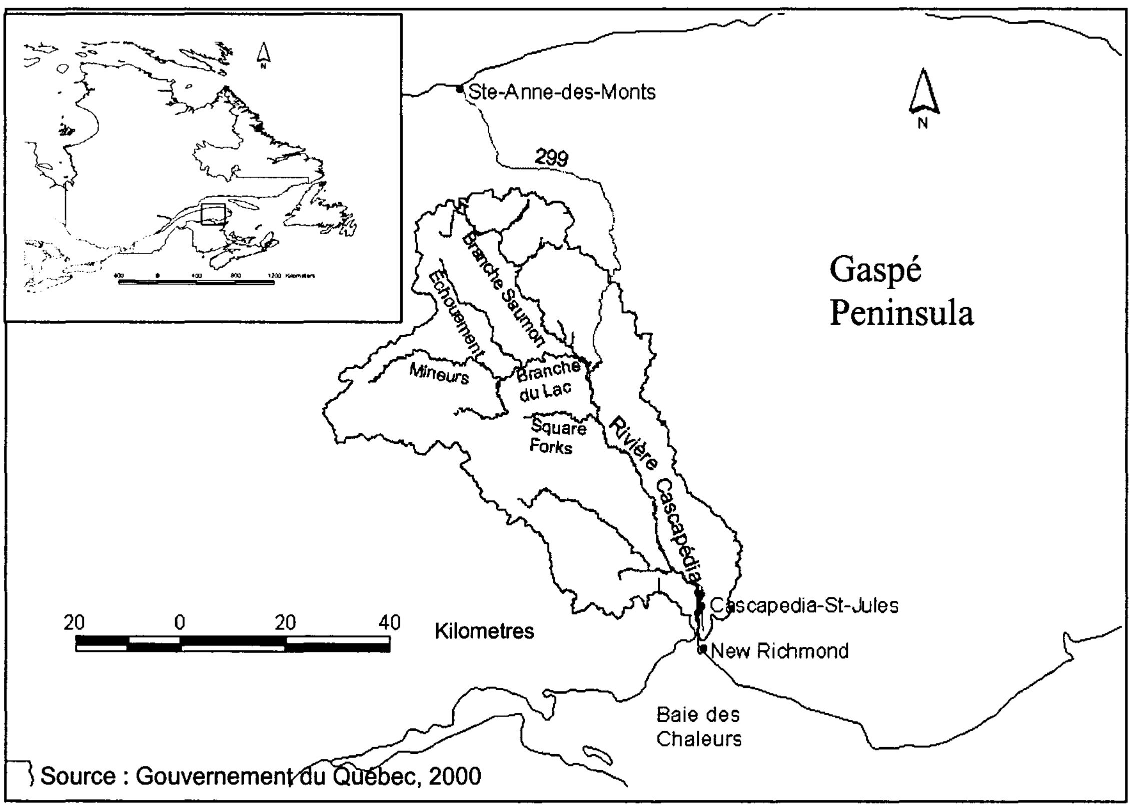


Figure 3. Location of study site, the Cascapédia River, located on the Gaspé Peninsula, in Eastern Quebec.

IV.2 Physiography

The Cascapédia River's headwaters are on the southern side of the Chic Choc Mountains, which form the northernmost portion of the Appalachian Mountains (Gouvernement du Québec, 1999). The river is composed of two main branches - Lac and Saumon. The headwaters of the Saumon Branch flow from Lake Cascapédia, located in the Parc

National de la Gaspésie. The river's mouth discharges into the Baie des Chaleurs (Figure 3). The sections of the watershed located in the Parc de la Gaspésie are protected from harvesting. The Northwest section of the watershed lies within the Dunière and Matane wildlife reserves, but these areas are not protected from harvesting. The geology of the Gaspé Peninsula is composed of folded overthrust sediments with metamorphic and igneous intrusive rocks (Alcock, 1935). The surficial deposits are mostly till, colluvium, and weathered material (Gouvernement du Québec, 1999). There are also a few lakes in the Cascapédia watershed, most notable of which is Lac Huard, fed by the Inlet tributary and located at the head of Lac Branch.

For the first objective of this study, which is to determine if there is an association between the width of low-order streams and harvesting intensity, low-order tributaries with basin areas up to 25 km^2 and whose watersheds are harvested to some degree were sampled throughout the watershed. A basin area no larger than 25 km^2 was the main criteria for tributary selection. This was judged to be the upper limit of the basin area size at which the methodology, explained in the following chapter, was effective and practicable. The stream orders of the sampled tributaries vary from first to fourth. The second objective (to establish if variations in riffle sedimentology are related to harvesting intensity) focuses more closely on Lac Branch, a fifth order stream, and two of its major tributaries, Échouement and Mineurs (Figure 3), for two reasons. Firstly, these mainstem segments were chosen because harvesting is more prevalent in the Lac Branch watershed than in the Saumon Branch watershed since the headwaters of the latter lie in the Parc National de la Gaspésie, where harvesting is prohibited, therefore keeping overall harvesting percentages below the 20% usually required to detect impacts (Swanson *et al.*, 1996; Plamondon, 1993; Caissie *et al.*, 2002). Secondly, access to field sites from Highway 299 is made easier from the multitude of logging roads in the Lac Branch region of the basin. Following some road design failures over the highly erodible Lake Branch formation in the mid-1990's, new logging roads in the watershed are currently built according to the improved designs described in the "Saines pratiques en voirie forestière", a forestry road best practices guideline established to reduce sediment injection to streams from roads (Gouvernement du Québec, 2001).

IV.3 Climate and Vegetation

The Cascapédia watershed is in a maritime climate region with mild to hot summers (temperatures average around 20°C) and cool to cold winters (temperatures below -15°C). It receives close to 1100 mm of precipitation a year (Government of Canada, 2001; Gouvernement du Québec, 2003a). The mean annual discharge near the mouth of the river is 61 m^3/s and the mean annual daily maximum is 535 m^3/s (Government of Canada, 2000). This maximum is usually reached during the spring freshet, which typically occurs in May or June.

According to the Gouvernement du Québec (2002), 95% of the Gaspésie-Iles-de-la-Madeleine region is forested land. The Cascapédia drainage basin is mainly composed of mixed forest, where the dominant species are balsam fir, white spruce, and birch (Gouvernement du Québec, 2003c). Harvesting in the Cascapédia watershed has been ongoing since the early 1900's (Alcock, 1935). In the period of 1995-99, 10.4 Mm^3 of softwood was harvested (88% of allowable cut) and 1.1 Mm^3 of hardwood was harvested (35% of allowable cut) in the area (Gouvernement du Québec, 2002). Harvesting is mainly through whole-tree and careful harvest around regeneration clearcutting (Gouvernement du Québec, 2000).

V EFFECTS OF LARGE-SCALE LANDSCAPE STRUCTURE VARIABLES ON STREAM CHARACTERISTICS, IN PARTICULAR CHANNEL WIDTH

V.1 Introduction

This part of the study is concerned with whether an increase in low-order tributary stream width is linked to an intensification of harvesting activities in their watersheds, once natural variations in width are accounted for. The assumption is that stream enlargement results from bank erosion, which is initiated by higher flows and injects sediment into the river. Flow transports the sediment through the watershed, where it deposits in the substrate if the flow's transport capacity is exceeded. However, hydraulic geometry equations dictate that stream width varies with discharge (Leopold and Maddock, 1953; Merigliano, 1997) or basin area (Castro and Jackson, 2001). In addition, bed material grain size and stream slope also generally vary downstream and with basin area. Therefore, before analysing the association between harvesting activities and variations in stream width, the natural variations in width associated to the landscape structure variable basin area, to the local stream slope, and to stream bed sediment size distributions must be accounted for. Thus, the objective of this chapter is to determine the effects of these variables on the stream characteristics of low-order tributaries of the Cascapédia River, in Eastern Quebec.

For the purposes of this part of the study, the stream characteristics of 104 first to fourth order tributaries of the Cascapédia River with basin areas < 25 km^2 were measured. Width was chosen as the principal morphological index of stream expansion rather than depth for several reasons. As the most easily observable stream dimension, width is easy to measure, requires little equipment, the methodology is easily replicated, and it is an indicator of excess sediment production. Furthermore, many hydrologic and geomorphic interpretations can be derived from stream width and changes to width (Rosgen, 1996). In alluvial channels, erosion is greatest on the more susceptible parts of the channel boundary (Gordon *et al.,* 1992), and can be greater on the banks, which are composed of fine sediment, than on the cobble bed (Knighton, 1984). Riffles and pools also create a greater variation in the mean depth of a channel with similar basin area (Rosgen, 1996). Therefore, channel width is a simpler indicator of morphological change than depth.

Chapter V analyses the variations in stream width associated with basin area, median sediment diameter at the sampling site, local channel slope, watershed geology, and stream order. The residuals from the strongest of these models will be analysed in Chapter VI to examine whether these are associated to harvesting intensity. Residuals are used because they represent the unexplained portion of the variation in the dependent variable, and help in the identification of streams with abnormally wide or narrow widths when compared to the model (Wharton, 1995).

V.2 Methods

V.2.1 Measuring local stream characteristics

To achieve the first objective, 104 first to fourth order tributaries were visited in the summers of 2002 and 2003 (Figure 4). Study sites were selected based on the ease of accessibility by road. Measurements of width (described below), stream bed sediment size quartiles, channel slope, and riparian zone side slope were taken at each site, at least 20 metres upstream of the road and stream junction (Appendix I). Site locations were recorded in Universal Transverse Mercator (UTM) coordinates, with a NAD 1983 datum and later converted to Modified Transverse Mercator (MTM), Quebec's map projection, using ArcView's Projection Utility. ArcView is the geographic information system (GIS) software used to analyse the data.

At each site, four distinct estimates of width were measured at five cross-sections: wetted width (W1), alluvial width (W2), bankfull width (W3), and nearest woody vegetation to the stream width (W4). An example of each of these widths is shown in Figure 5. The five cross-sections were located at least ten metres apart. Abnormally wide or narrow sections and sections with LWD were omitted from measurement because they are not representative of the stream (Faustini and Jones, 2003). For the 53 sites visited in 2003, the widths were measured both upstream and downstream of the road to determine the impact of roads on downstream channel width. Again, the measures were taken at least 20 metres away from the junction of the stream and the road. An average of each width was calculated and a composite width (CW) was calculated as the average of the alluvial, bankfull, and nearest woody vegetation widths (W2, W3, and W4) to facilitate analysis.

Wetted width was not included in the average because some of the streams were dry when sampled. With no way to determine when the streams dried up, a relationship could not be established to standardise wetted width to sampling date and water level.

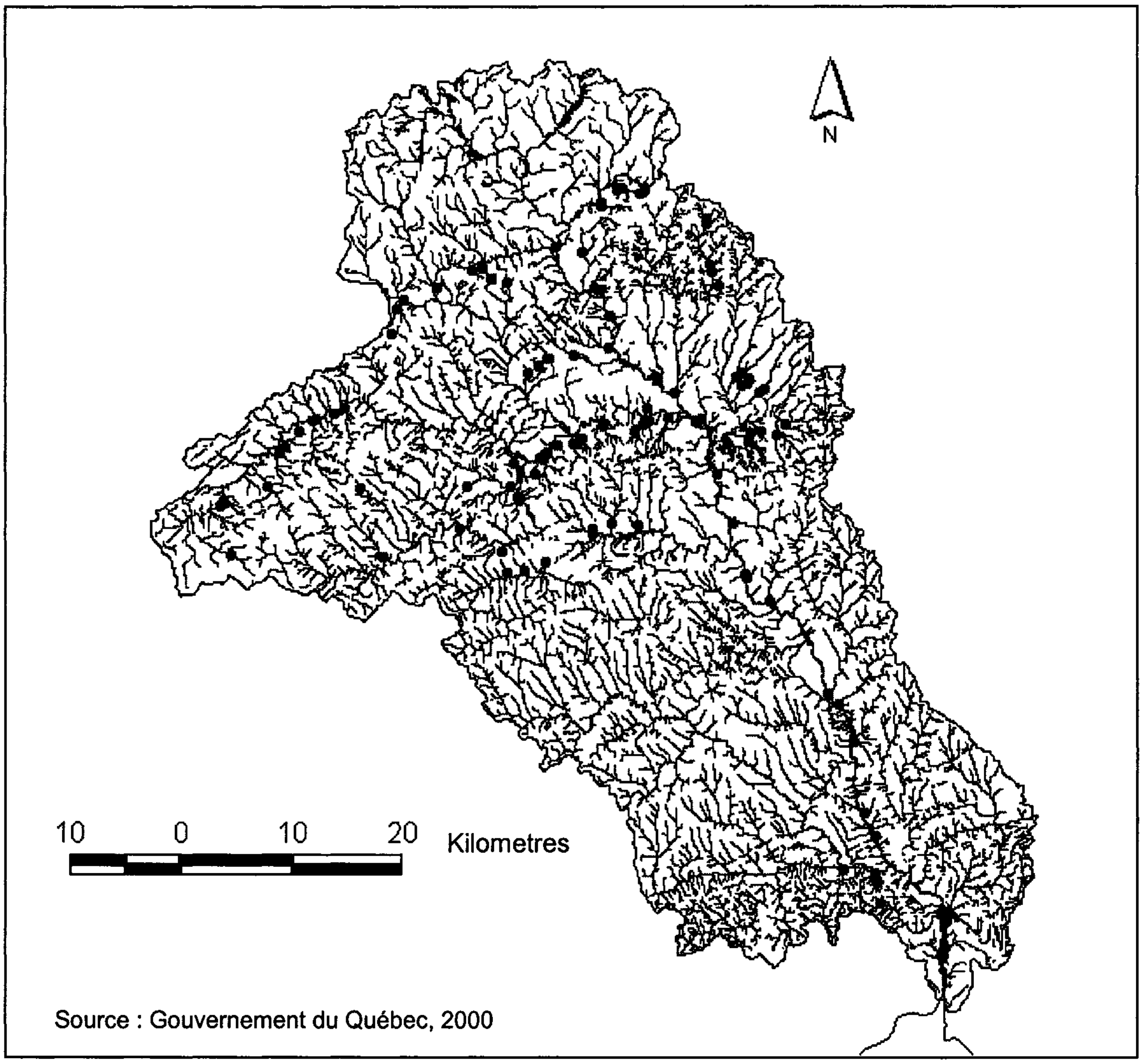


Figure 4. Location of low-order study sites throughout the Cascapédia watershed.

Local stream slope was measured over a distance of 10 metres using an abney level. The abney is a hand-held level with a tubular spirit level connected to a vertical scale graduated from 0° to 90° and with a vernier that can be read to 5 minutes of arc. The observer aimed at an object located at eye level (either a rod or another observer), adjusted the vernier until the spirit level was centred on the horizontal index line, and measured the inclination angle. The two observers stood upright in the thalweg, at a distance of at least 10 metres, whenever possible. In some cases, the density of fallen logs and branches prevented using this distance, and distances between five and ten metres were used. In these cases, extra vigilance was required to ensure the region sampled was representative of the stream's profile (i.e. not abnormally steep or flat). Local stream slope was measured twice at each site and averaged. For sites visited in 2003 (n = 53), the riparian zone side slopes were measured in the same manner, over a distance of five metres, with the observer standing on top of the bank and measuring the slope of the riparian zone perpendicular to the stream (Figure 6).

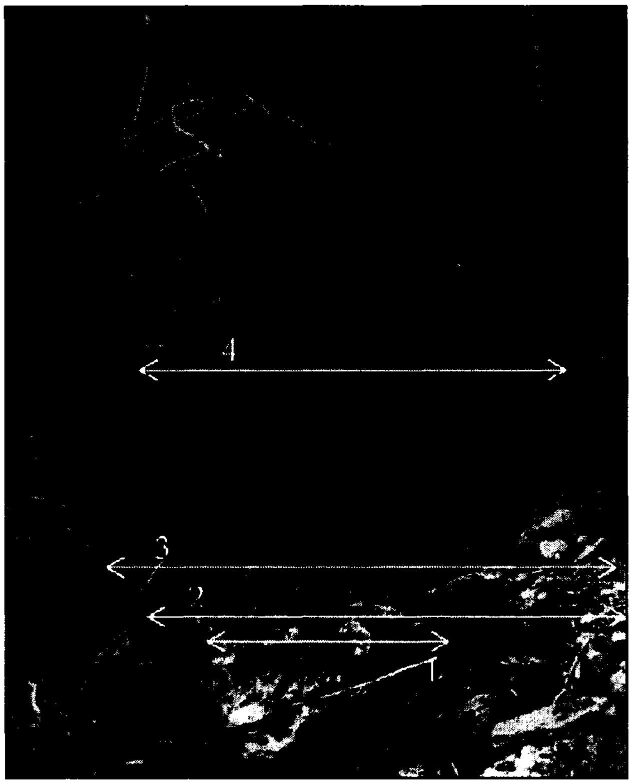


Figure 5. Example of the four types of widths measured at each site: wetted (1), alluvial (2), bankfull (3), and nearest woody vegetation to the stream (4).

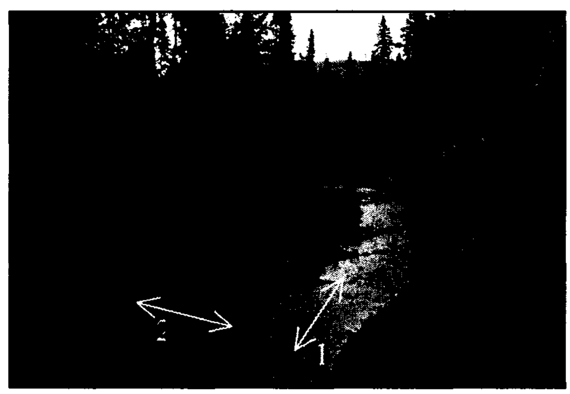


Figure 6. Photograph showing the location of stream slope (1) and riparian zone side slope (2) measurements.

To determine median sediment size (D50), a Wolman sample of 50 rocks was taken along each stream's thalweg. While less than the suggested 100 stone count of Wolman (1954), samples of 40 and 50 stones have been used in the past (Church, 1987; Thompson and Hoffman, 2001). Samples were taken according to the Wolman (1954) methodology, where the intermediary axis (b-axis) of all rocks at a predetermined distance along the thalweg was measured (Rosgen, 1996; Kondolf *et al.,* 2003). The distance between the sampled sediments varied between 30 and 100 cm (for a total sample zone of 15 to 50 m along the channel), depending on the visual estimate of the coarseness of the bed made prior to sampling. This distance was always greater than twice the visual estimate of the D90, to prevent large sediments from being sampled twice (Church, 1987). Sediments in coarser stream beds (e.g. D90 = 40 cm) were measured at greater intervals than sediments in finer beds (e.g. D90 = 10 cm).

V.2.2 Estimating large-scale landscape structure variables using a GIS

Digital model

Once the field data were collected, the MTM site locations were added to an existing database. This database is a 1:20000 topographic model in ArcView format provided by the Québec Ministry of Natural Resources (MNR). The model of the Cascapédia watershed includes a digital elevation model (DEM) and layers of roads, streams, geology, and forestry parcels. The forestry parcels indicate the last year each parcel was harvested. Using the DEM of the Cascapédia basin, each site's watershed was delineated using ArcView's Hydro extension. The delineated watersheds were then used to calculate the basin size, mean basin slope, stream order, link magnitude, which is calculated as the sum of the number of segments found upstream of a segment (Gordon *et al.*, 1992), and stream density of each site.

V.2.3 Statistical analysis

Regression analysis

Once the stream characteristics were measured and the landscape structure variables calculated, a regression analysis was conducted to predict the variance of the former based on local channel slope, D50, and the landscape structure variables basin area and stream order. Each variable was modelled independently and all possible predictor combinations were tested to obtain the best predictive model. Models were evaluated first on significance and then on strength (i.e. P was considered before r^2). A $P < 0.05$ was considered significant (i.e. where the slope indicates a true trend). The strongest of the significant models is used to obtain the residuals analysed in Chapter VI. The model with the highest r^2 is used to account for the largest proportion possible of the natural variation in stream characteristics before testing the relation of the residuals of these characteristics to the harvesting metrics.

V.3 Results

V.3.1 Analysis of the determinants of variations in stream characteristics

This section examines if landscape structure variables and/or local variables can explain the variance in stream characteristics, in particular stream width (their distributions are shown in Table 1). Composite width is used because changes in alluvial, bankfull, or vegetation width can all be indicative of changes in channel morphology (Rosgen, 1996). By using the average of these three measures, the analysis is simplified (one analysis instead of three) without compromising the chance for a significant result. The variables basin area, stream order, D50, and local channel slope are used because their relations to stream characteristics are established (see section II.1.3) and can thus be used to assess the significance of the results obtained with the Cascapédia dataset (Table 2, Figure 7 to Figure 9, Figure 11, and Appendix II). Of the many models tested, those with the greatest significance are listed in Table 2 and will be referred to throughout Chapters V and VI. All the models are listed in Appendix II.

Table 1. Distribution of the basin area and stream characteristics sampled at each study site in the Cascapédia watershed.

Variable	# of cases	Minimum	Maximum	Range	Median	Mean	Standard Deviation
Basin area (km^2)	104	0.03	23	23	4.0	5.3	4.3
Width (m)	104	1.0	7.5	6.5	2.9	3.2	1.4
Channel slope (%)	104	0.02	48.4	48.4	3.4	4.6	6.2
D50 (mm)	104	2	136	134	29	34	28

Table 2. Models relating composite stream width to various landscape variables. * indicates a significant relation at the 5% level.

Variable	Equation	R^2 (P)
Composite width versus:		
Basin area	$1.7 \cdot \text{Area}^{0.40}$	**0.549 (0.000)***
Channel length	$1.4 \cdot \text{Length}^{0.38}$	**0.501 (0.000)***
D50 (mm)	$1.15 \cdot \text{D50}^{0.26}$	**0.306 (0.000)***
Stream order	$0.84 + 0.93 \cdot \text{Order}$	**0.319 (0.000)***
Link-magnitude	$1.84 + 0.16 \cdot \text{Magnitude}$	**0.477 (0.000)***
Geology – alluvial deposits (%)	$3.4 \cdot \text{AD}^{-0.06}$	**0.063 (0.012)***
Geology – weathered deposits (%)	$1.3 \cdot \text{WD}^{0.22}$	**0.121 (0.000)***
Basin area and D50	$1.02 \cdot \text{Area}^{0.42} \cdot \text{D50}^{0.14}$	**0.657 (0.000)***

As predicted from theoretical models, there is a negative relation between basin area and channel slope (Figure 2) in the Cascapédia dataset (Figure 7a). This is contrary to Carragher *et al.*'s (1983) result that slope and basin area in basins of up to 10 km^2 are unrelated. As basin area increases, local channel slope decreases (Figure 7a) and stream order increases (not shown, but this is implicit in the definition of stream order). The theoretical, negative relation between sediment size and basin area (Figure 2) is not found in the Cascapédia dataset, where a slightly positive relation exists between these two variables (Figure 7b).

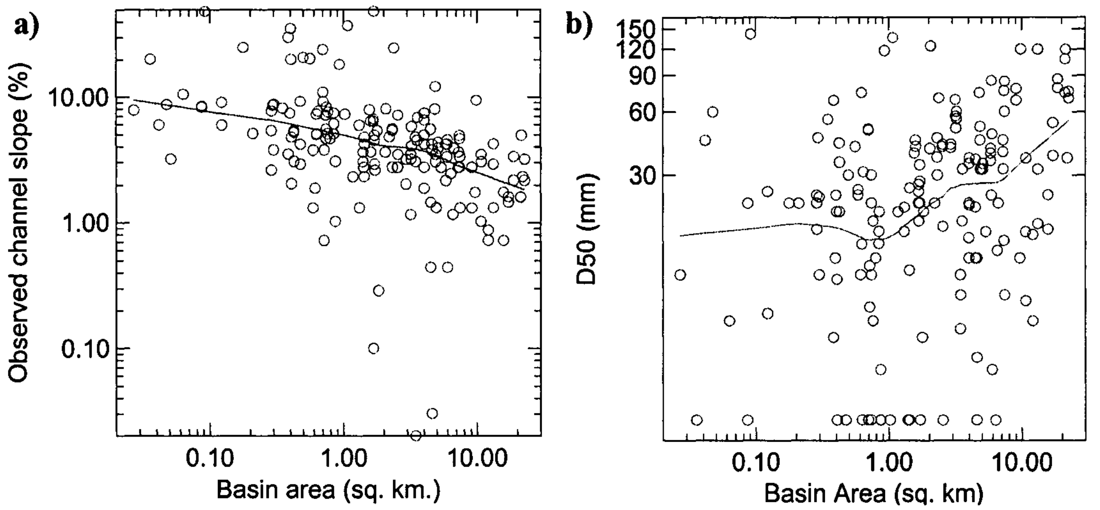


Figure 7. Change in a) channel slope (%) and b) surface D50 as basin area increases. The line of best fit is a Lowess smoother, which does not presuppose the shape of the function. It runs along the x values and finds the predicted values from the weighted average of nearby y values (Cleveland, 1979).

Stream width is related to many natural variables, the first which is discussed here is sediment size. Thompson and Hoffman (2001) reported a positive relation between sediment size and stream width, despite the fact that theoretical models show grain size decreasing with an increase in channel width. However, in basins of up to 5 km^2, sediment size may increase in conjunction with basin area because stream discharge cannot carry large sediments (Carragher *et al.,* 1983). In the Cascapédia dataset, there is indeed a positive relation between width and D50 (the median sediment diameter) (Figure 8a) ($r^2 = 0.306$, $P < 0.0005$). There is also a positive relation between width and D10 (the bed material size for which 10% of the sediment is finer) (width = $2.2 \cdot D10^{0.23}$, $r^2 = 0.257$, $P < 0.0005$) (Figure 8b). Therefore, D10 and D50 are both related to channel width.

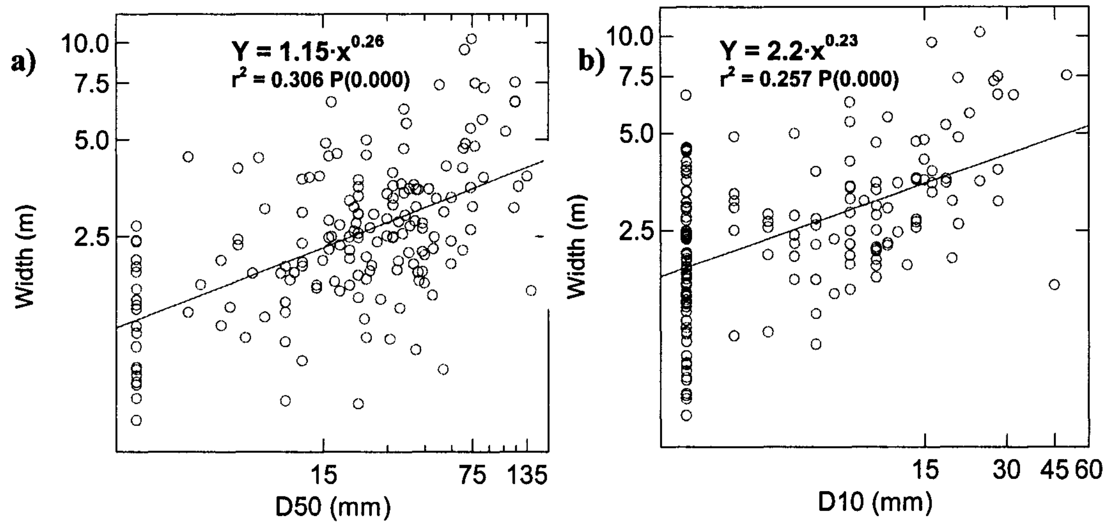


Figure 8. Variation in width following increases in a) D50 (mm) (median sediment size) and b) D10 (mm) (the sediment size for which 10% of the sediment is finer). The line of best fit represents the linear regression.

Composite width (hereafter referred to as width) is also positively related to drainage basin area. Hydraulic geometry relations predict that stream width will increase with basin area (Figure 2, Church, 1996) and published studies confirm this theory (Richards *et al.,* 1996; Merigliano, 1997; Miller *et al.*, 2000; Castro and Jackson, 2001). The Cascapédia dataset also follows this trend ($r^2 = 0.549$, $P < 0.0005$, Table 2, Figure 9).

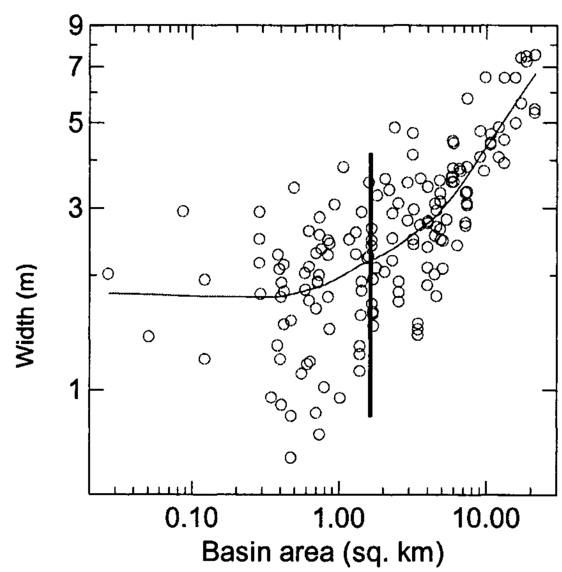


Figure 9. Change in composite width (m) as area (km^2) increases for all sites. The line of best fit is a Lowess smoother. The black vertical line is the lower limit of the use of composite width (1.75 km^2).

The exponent (0.40, Table 2) obtained from the hydraulic geometry model using basin area is similar to the exponent obtained by Miller *et al.* (2000) (0.34), who studied the relation between width and basin areas of 1 to 100 km^2 ($r^2 = 0.47$). It is also similar to the range in exponents of 0.38 to 0.51 found by Castro and Jackson (2001), who studied basins of 80 to 7500 km^2 and to the value of 0.38 obtained by Sweet and Geratz (2003). Moreover, it is also similar to the 0.46 value obtained by Wilson (2003), who studied streams in basins of 7.5 to 350 km^2 in the Cascapédia watershed. Figure 9 shows that the variance in width is greatest in the basins ‹ 1.75 km^2, especially for those sites between 0.3 and 1.75 km^2 (shown by the vertical line in Figure 9). This is due to the greater range in vegetation width (W4) for the small harvested tributaries where the closest woody vegetation is further away from the stream (Figure 10). This occurs for one of two reasons. First, no buffer zones were left after the harvesting, suggesting these are intermittent streams (Gouvernement du Québec, 2003b). Secondly, blowdowns may be more frequent in these watersheds, although no mechanism explains why this would be so. Thus, to account for the change in relation, a separate analysis using bankfull width (W3) was conducted for sites with basin areas ‹ 1.75 km^2. The analysis of these smaller sites is presented in the next sub-section.

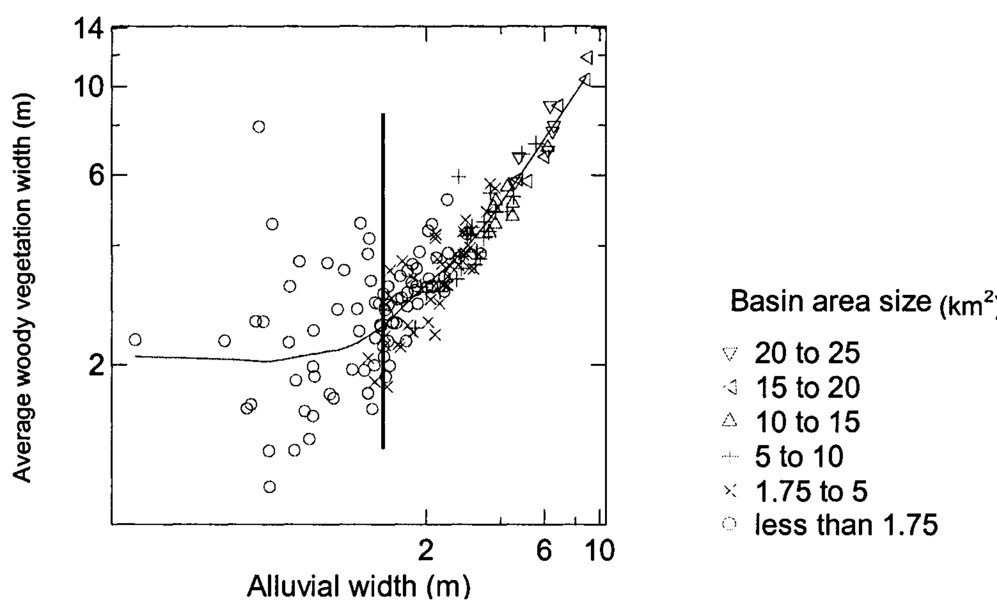


Figure 10. Variation of average woody vegetation width (m) as average alluvial width (m) increases, by basin area class. The black vertical line represents the width at which alluvial and vegetation widths no longer vary in phase.

Stream width was also modelled against average basin slope, stream length, stream density, observed riparian zone side slope, local channel slope, and geology. None of these could account for the variance in stream width as well as basin area (Table 2, Appendix II), although stream length is almost as strong ($r^2 = 0.50$ versus 0.55 for basin area, Table 2, Figure 11). The strength of the stream length relation may be because length is proportional to basin area (Shreve, 1974; Moon, 1980). Link magnitude was also moderately strong ($r^2 = 0.477$, $P < 0.0005$) (Table 2).

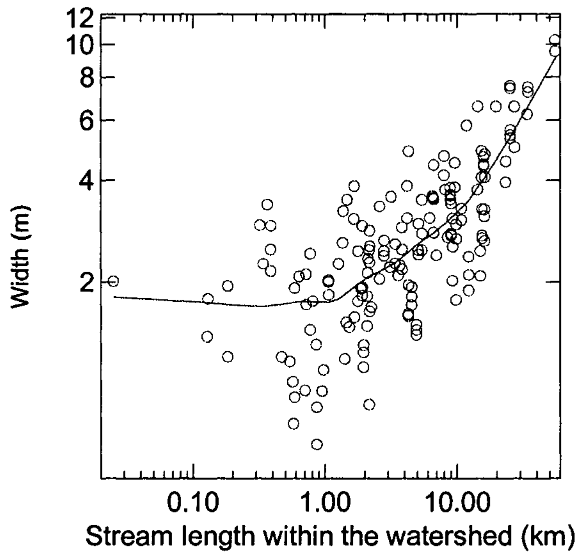


Figure 11. Change in composite width (m) as stream length within the watershed increases. The line of best fit is a Lowess smoother.

Having tested each independent variable separately, a multivariate analysis was run to determine if any variable combination could more fully explain the variance in stream width. When the strongest variables – basin area and length – are modelled together, the model is not stronger due to the correlation between the two variables (Moon, 1980), which is evidenced by the low tolerance values (0.181) of each variable (tolerance values below 0.2 indicate strong multicollinearity) (Wilkinson *et al.*, 1992). Basin area and D50 were then tested and yielded a significantly stronger relation ($r^2 = 0.657$, $P < 0.0005$) (Table 2). Other variables were then added individually to this model to determine if they could strengthen it. Even though stream order ($r^2 = 0.319$, $P < 0.0005$, Table 2) and stream magnitude ($r^2 = 0.477$, $P < 0.0005$, Table 2) explain some of the variance in stream width, neither of these added to the strength of the model based on basin area and D50.

The same is true for the remaining variables (geology, average basin slope, stream density, and riparian side slopes). Therefore, the basin area and D50 model best explains the variations in channel width of this dataset, completing the analysis for basins of 1.75 to 25 km^2. The residuals from this model (width = $1.02 \cdot Area^{0.42} \cdot D50^{0.14}$, Table 2, Figure 12) express the unexplained variations in channel width, once basin area and bed texture are accounted for. These will be analysed in chapter VI to determine if they are associated to the intensity of harvesting activities.

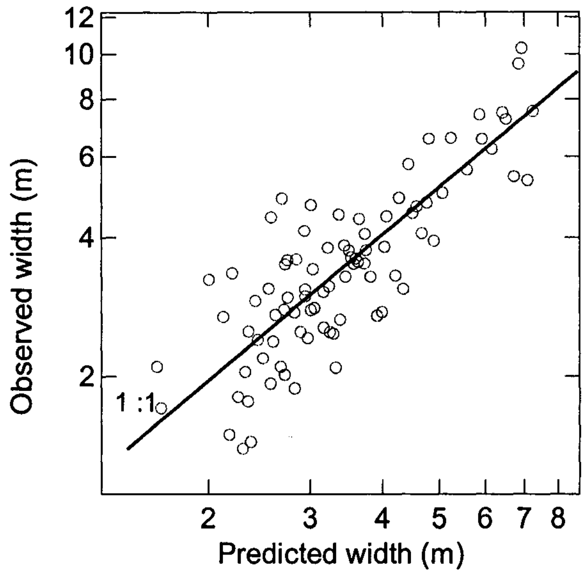


Figure 12. Scatterplot of observed widths versus the predicted widths, using the basin area and D50 model. The difference between the points and the 1:1 line is the residual.

Streams in basins with areas smaller than 1.75 km^2

For streams located in basin areas smaller than 1.75 km^2 (n = 64), bankfull width (W3) was used in the analysis instead of composite width for two reasons. First, composite width has a greater variance at any given basin size in this subset because of the greater variance between alluvial and vegetation width (Figure 9, Figure 10). When composite width is modelled against basin area, no significant relation emerges ($r^2 = 0.006$, $P < 0.229$). However, when bankfull width is used, a weak, but significant relation emerges ($r^2 = 0.050$, $P < 0.022$) (Table 3, Figure 13b). Second, there is a change in the trend of the relation between basin area and composite width in the small basins (i.e. the best fit line in Figure 9 is almost completely horizontal). Previous studies (Thornes, 1974; Carragher *et al.,* 1983) report that the rate of change in the stream width of small headwater basins (no basin size given) is not related to the rate of change in stream width of larger basins because their discharge is not large enough to change channel morphology. Thus, changes in width are negligible for these small basins, where the local control on channel width may be differences in soil texture or vegetation strength.

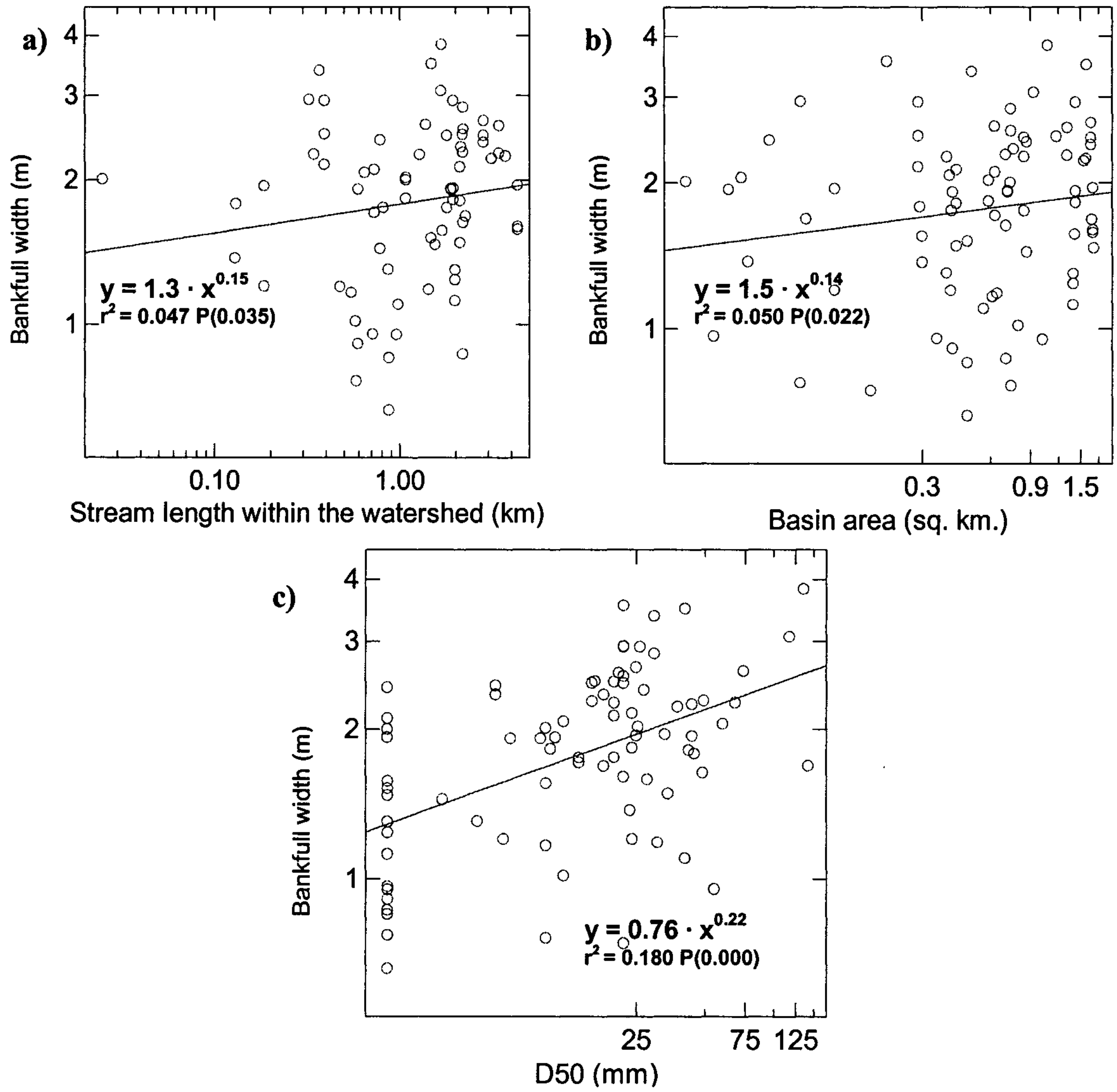


Figure 13. Variations in bankfull width with increasing a) stream length, b) basin area, and c) D50 for Cascapédia watersheds with areas less than 1.75 km^2. The lines indicate the linear regression of each relation.

The analysis performed on the basins of 1.75 to 25 km^2 was repeated on streams in basins of ‹ 1.75 km^2 (Table 3 and Appendix II). Of all the variables tested, three yield significant relations (basin area, D50, and stream length, Figure 13). These three variables produced some of the stronger models in the larger basins (Table 2), although the relations are weaker for the small basins. Stream length, which explained 50% of the variance in stream width in the larger basins, only significantly explains 5% of the variance for basins < 1.75 km^2 (Table 3, Figure 13a). Similarly, D50 explains 18% of the variance in the bankfull width of channels in small basins (Table 3, Figure 13c), but it explained 35% of the variance in composite width in basins of 1.75 to 25 km^2 (Table 2). These weak relations may be due to the streams' small discharge, associated to their small areas (0.03 to 1.75 km^2), which may not be enough to move sediment and create an equilibrium channel morphology (Carragher *et al.,* 1983; Plamondon, 1993). The remaining variables did not yield significant models (See Appendix II). Stream order and link magnitude, which explained 31% and 48%, respectively, of the variance in the width of the medium-sized tributaries were not tested on the smaller streams because their range (1 to 3 for stream order, but with only 5% classified as order 3, and 1 to 6 for link magnitude, with 85% classified as 1 to 3) was considered too small to yield significant relations.

Table 3. Models relating bankfull width to various large-scale landscape structure variables for streams in basins < 1.75 km^2. * indicates a significant relation at the 5% level.

Variable	Equation	R^2 (P)
Bankfull width versus:		
Basin area	**$1.5 \cdot Area^{0.14}$**	**0.050 (0.022)***
Stream length	**$1.3 \cdot Length^{0.15}$**	**0.047 (0.035)***
Basin slope (%)	**$0.78 \cdot Basin\ Slope^{0.25}$**	**0.039 (0.043)***
Channel slope (%)	$1.65 \cdot Channel\ slope^{-0.13}$	0.023 (0.066)
Basin area and D50	**$0.8 \cdot Area^{0.15} \cdot D50^{0.23}$**	**0.242 (0.000)***
Stream length and D50	**$0.79 \cdot Length^{0.13} \cdot D50^{0.20}$**	**0.200 (0.000)***

Various multivariate models were also tested to find the strongest relation to bankfull width. Basin area and D50 yield the strongest relation (P < 0.0005), although this model is weaker (r^2 = 0.245, Table 3) than the model for the medium-sized basins – 1.75 to 25 km^2 (r^2 = 0.657, Table 2). The residuals of the basin area and D50 model were saved and used in Chapter VI to test for a relation between the remaining variation in width and harvesting intensity of the small tributaries.

V.4 Discussion

V.4.1 Determinants of variations in stream morphology

These results show there is a greater variance in the relation between width and basin area for basins < 1.75 km^2 than for basins of 1.75 to 25 km^2 (Figure 9). One possible reason for the change in trend is the wider range of local channel slope typically found in small basins compared to the medium-sized basins (i.e. basins of 1.75 to 25 km^2, in this case) (Rosgen, 1996). Figure 7a shows how local channel slope varies significantly more in the small basins (2 to 40%) than in the medium-sized basins (0% to 15%). First and second order streams have a wider range of slopes (Figure 14) and 70% of these found in basins of < 1.75 km^2. This explains why the data from these basins were analysed separately.

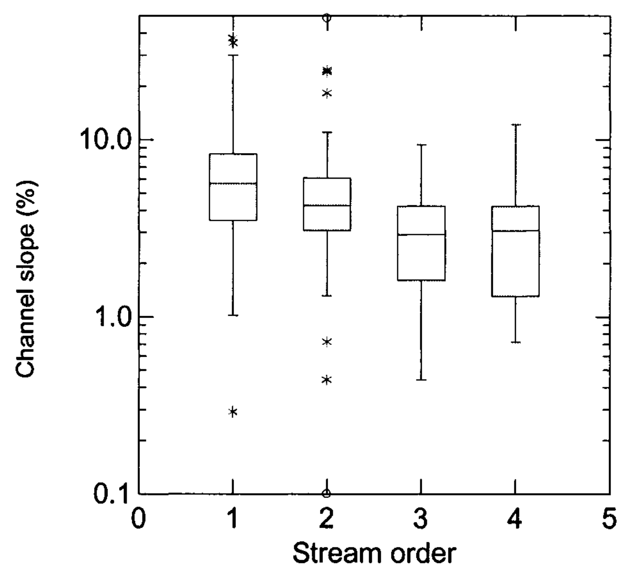


Figure 14. Channel slope distribution for basins with stream orders of 1 to 4.

Streams in basins larger than 1.75 km^2 (i.e. medium-sized basins)

The analysis of tributaries in watersheds greater than 1.75 km^2 reveals that basin area and D50 best predict the variations in channel width. The practicalities of this model and some complications to using hydraulic geometry equations are discussed below.

First, the analysis shows basin area and D50 have the strongest relation to width in basins larger of 1.75 to 25 km^2 ($r^2 = 0.657$). Therefore, there is a landscape structure and a local component to explaining stream width. This model is practical because both variables are easily obtained. D50 is acquired from Wolman particle sampling, which requires little equipment and has an established, accepted methodology (Wolman, 1954). Basin area is derived from digital data, as are the other variables that yielded significant relations (stream length, stream order, and link magnitude). If the data are not available in digital form, the contour lines from topographic maps can be digitised and interpolated into a DEM. This can be used in conjunction with digitised stream vectors to delineate watersheds within a GIS. If this cannot be done, stream length can be used as an alternative to basin area, as its relation to stream width is almost as strong (r^2 of 0.50 versus 0.55, respectively). When drainage density is about 1 km/km^2, stream length and basin area are interchangeable. Basin area, stream order, and stream length can also be calculated manually from topographic maps, provided the scale used is large enough to identify all headwater streams (Church, 1996).

Despite its strength, the basin area and D50 model leaves over 30% of the variance in stream width unexplained. While a portion of this may be linked to harvesting (the analysis of the next chapter), other variables such as local channel depth or discharge may explain some of the remaining variation. These were excluded from this study because they do not remain constant throughout the summer season and a relation between the time of sampling and channel depth could not be established, as was done by Wilson (2003). A balance must also be reached between the energy expended to measure variables and their value in the analysis. Thus, including channel depth and/or discharge as an independent variable in the model should be tested on a small group of basins to determine its role in explaining variations in channel width prior to being applied to all sites.

There are also complications associated with predicting watershed characteristics based on hydraulic geometry relations (Merigliano, 1997), including not having all the required predictors. For example, if discharge data are not available, basin area can be used as its surrogate in the hydraulic geometry relations, although it yields weaker relations than those between discharge and stream width (Gordon *et al.,* 1992; Castro and Jackson, 2001). Compare the r^2 of 0.55 obtained for width versus area for this dataset versus Jowett's (1998) r^2 of 0.86 for width versus discharge (in basins of 8 to 3210 km^2 with discharges varying from 0.6 to 204 m/s^3). Castro and Jackson (2001) calculated four regional hydraulic geometry regression equations for sites in the Pacific Northwest using both discharge and basin area. They found that discharge explained 76 to 87% of the variance in width and that area explained 49 to 83% of the variance. Therefore, it is conceivable that discharge data could explain as much as 30% more of the variance, leaving only 15% unexplained. However, Sweet and Geratz (2003) obtained an r^2 of 0.95 when modelling width and basin area, for basins of 1.6 to 472 km^2 in North Carolina's coastal plains. Therefore, discharge may not necessarily increase the strength of the relation, although the wider range in basin area in Sweet and Geratz (2003) dataset may have contributed to the stronger relation.

Furthermore, theoretical downstream adjustments to channel morphology are not always found in nature, as seen with the Cascapédia dataset, where the expected downstream fining of sediment as basin area increases is not found (Church, 1996; FISRWG, 1998). Rather, there is a weak, positive relation between the sediment size (D50) of the sampled tributaries and basin size, which ranges from 0.03 to 23 km^2 (Figure 7b). Carragher *et al.* (1983) suggest this trend may be hydrologically-driven, with the smaller basins not having a large enough discharge to move even the smallest sediments. If these particles are not transported, the D50 should be reduced.

Streams in basin areas smaller than 1.75 km^2 (i.e. small basins)

Because of the change in trend and greater variance between alluvial width and vegetation width in basins $<$ 1.75 km^2 (Figure 10), these basins were analysed separately using bankfull width (W3) rather than composite width. A significant model was found between bankfull width and basin area and D50 of these basins. However, the relation is not as strong as the one found for the medium-sized basins (r^2 = 0.25 versus 0.66, respectively). Several possibilities for this are discussed briefly below.

The weaker model of the small basins may be due to the smaller range in the predictor values, which may not capture the essence of the relations. For example, consider the range of total stream length of the small basins (0.1 to 4 km) when compared to the range of the medium-sized basins (1.4 to 55 km), or the range in basin area (1.72 km^2 versus 23 km^2, respectively). In addition, stream width varies from 1 to 3.8 m in the small basins and is more than doubled in the medium-sized basins (1 to 10.25 m).

Secondly, errors are introduced into the analysis when basin areas are delimited using topographic maps and aerial photographs. The Cascapédia watershed's DEM was constructed from contour lines with a +/- 5-metre accuracy, thus any point on the map is subject to this error. In the basins of 1.75 to 25 km^2, a change of +/- 5 m on the watershed boundaries makes little difference on the total basin area and its position within the watershed. However in the small basins, a change of +/- 5 m in basin boundaries can lead to a considerable change in basin area. This is particularly important in areas of small or rounded peaks, where the drainage divide changes depending on where the contours are located on the map. These delineation errors may explain why the model for basins $<$ 1.75 km^2 was weaker.

Another hypothesis is that the variable responsible for the greater disparities in the width of the small basins was not measured. This variable could play a more muted role in medium-sized basins, which would explain why a stronger relation was obtained for these. Possible variables responsible for variations in stream width that were not considered for this research include soil depth, conductivity, and antecedent moisture content (Hudson, 2001; Sidle *et al.*, 2001), precipitation events (Caissie *et al.*, 2002), and the age structure of the vegetation growing at the time of harvest (Plamondon, 1993). Future studies should test these variables for their relation to stream width variations.

To conclude, different variables can explain portions of the variance in stream width. Some, such as basin area and stream length, explain portions of the variance in both datasets (basins of 1.75 to 25 km^2 and basins smaller than 1.75 km^2), although the relations are stronger in the medium-sized basins (Table 2, Table 3). For the two datasets, the basin area and D50 model was strongest (width = $1.02 \cdot \text{Area}^{0.42} \cdot \text{D50}^{0.14}$, $r^2 = 0.657$, $P < 0.0005$ for the medium-sized basins and width = $0.8 \cdot \text{Area}^{0.15} \cdot \text{D50}^{0.23}$, $r^2 = 0.242$, $P < 0.0005$ for the small basins). These residuals were analysed separately in Chapter VI.

VI ANALYSING THE RELATION BETWEEN CHANNEL WIDTH AND HARVESTING OPERATIONS

VI.1 Introduction

Chapter V considered the relation between landscape structure variables such as basin area, local channel slope, basin geology, and stream length and stream characteristics, in particular stream width, for 104 low-order tributaries of the Cascapédia. The variance in stream width was best explained by the basin area and D50 of each site for streams in basins of 1.75 to 25 km^2 ($Width = 1.02 \cdot Area^{0.42} \cdot D50^{0.14}$, $r^2 = 0.66$, $P < 0.0005$). This model leaves 34% of the variance unexplained. For streams in basins < 1.75 km^2, the best relation was between bankfull width and basin area and D50, although this model is weaker ($width = 0.8 \cdot Area^{0.15} \cdot D50^{0.23}$, $r^2 = 0.24$, $P < 0.0005$) and leaves 76% of the variance unexplained. The objective of this chapter is to determine if harvesting operations at the 60 m buffer and watershed scales, represented by the harvesting metrics equivalent cut area and road density, are related to any of the remaining width variations of these tributaries. The remaining variance is expressed as the residuals from each basin area and D50 model. Each set of residuals is analysed independently. This chapter also considers how sedimentology and stream width differ at road-stream junctions by comparing these measures upstream and downstream of road junctions.

Low-order streams were studied because they are the most easily altered by harvesting due to their high responsiveness to changes in their riparian vegetation and surrounding watershed (Chamberlain *et al.,* 1991; Church, 1996). Thus, higher harvesting intensities can increase peak flows (Harr and McCorison, 1979; Lewis *et al.,* 2001). If this has occurred, stream banks should have widened to adjust to these flows (Thorne, 1991; Church 1996; Rosgen, 1996), and the eroded sediment is injected into the river and transported downstream. If the flow's transport capacity is exceeded, deposition can occur on the river bed, especially on mildly-sloped segments, potentially degrading salmon habitat (Bjornn and Reiser, 1991). Sediment production and runoff were not measured directly because there were no data from the pre-harvesting period. Therefore, the pre-harvest stream widths could not be determined and compared to the current widths. Instead, hydraulic geometry equations were used to determine the proportion of the variation in stream width that is related to basin area and D50. This chapter focuses on the analysis of the remaining variance (i.e. residuals) from these relations.

VI.2 Methods

VI.2.1 Calculating the harvesting metrics in a GIS

To represent the harvesting operations, metrics were compiled from the GIS model described in Chapter V, which contains data layers on roads and forestry parcels. These layers were used to calculate the harvesting metrics of road density (measured in km/km^2), equivalent cut area (ECA, expressed as a %), and linear distance (in km) from the sample site to the nearest recently harvested parcel (0-5 years). Road density and %ECA were calculated at the watershed and 60 m buffer scales. The 60 m buffer is a corridor that runs the length of the tributary and all of its branches. It encompasses 60 m on either side of the stream, for a total buffer width of 120 m. While the first goal was to determine the degree of compliance to the required 20 m buffers on either side of permanent streams, provincial regulations explicitly state that aerial photographs cannot be used to determine compliance because of the difficulties in accurately measuring buffer widths using air photos (Gouvernement du Québec, 2003b, 2003c). Therefore, the analysis focuses on the watershed and 60 m buffer scales.

Equivalent cut area

The equivalent cut area of each watershed was calculated from the forestry parcel layer of the database, where an attribute table lists the last year each forestry parcel was harvested. Harvest years are assigned one of eight attenuation factors (AF) (Table 4), which were then allocated to the forestry parcels. The AF represents the equivalent area that would need to be harvested in the current year to yield the same hydrological response as the cut of the designated age class (Wei and Davidson, 1998). Harvesting perturbations have a higher AF than thinning interventions, for the same age classes, because harvesting creates a potentially greater change in streamflow and hydrological processes such as evapotranspiration (Chamberlain *et al.*, 1991). The %AF was then multiplied by the area of the parcel to which it was assigned to obtain an ECA for each parcel. The ECA of all the parcels contained in a watershed were summed to give total ECA (in km^2). This was then divided by the total watershed area to obtain a %ECA. The %ECA of streams in small basins is also sensitive to the basin delineation errors discussed in Chapter V, as well as to the quality of the air photos, which affect basin area delineation and forestry parcel delineation. A %ECA was also calculated separately for each AF category, to test for a timing effect or delay between harvesting and changes to stream morphology. These categories are referred to as ECA(AF#), e.g. %ECA(85) refers to the cuts with an AF of 85, where the attenuation factor of 85 has been applied to the area of the parcel. The other seven AF categories were also treated in this manner, where the respective AF was applied to the parcels.

Table 4. Attenuation factors used to classify forestry parcels, based on intervention year and by perturbation (from Langevin *et al.*, 2001).

	Attenuation Factor		
Age of intervention/ Perturbation	Plantations and Harvesting	Thinning	
		Precommercial	Commercial
0 – 5	85	60	25
6 – 10	65	50	10
11 – 15	55	35	0
16 – 20	45	25	0
21 – 25	35	0	0
26 – 30	25	0	0
31 – 35	10	0	0
› 36	0	0	0

Because the harvesting metrics were not normally distributed (see Table 5), the values were logged (Castro and Jackson, 2001). However, this excluded sites with null values from the dataset, since there is no log of 0. This problem can be avoided in one of two ways. First, a 'trace' amount can be added to the zeroes (e.g. add 0.01% to an ECA of 0%). While this has been successful (e.g. Pess *et al.,* 2002), the selected trace amount governs where sites will lie in the log space of the data distribution. This affects the results by influencing the model's slope, and should be avoided whenever possible (Gordon *et al.*, 1992). Consequently, the subset of sites with non-zero values can be used. For the purpose of clarity, the latter alternative was used in this study.

Road density

The impact of roads on stream width was studied at two scales. From the digital database, each watershed's road density was calculated at the basin-wide and 60 m corridor scales. Originally, a distinction between the types of road present in each watershed was attempted to study how the density of different types of road (e.g. primary, secondary, tertiary, abandoned, etc.) affect stream width. Unfortunately, the road database was incomplete, with many road segments having no assigned road type. Field verification also showed errors in the database's classification system. Therefore, road densities weighted by road type could not be calculated and a more general overall road density was used, where all roads were given the same weight.

VI.2.2 Statistical analysis

Once calculated in the GIS, the harvesting metrics were used in a regression analysis to establish their relation to the width residuals obtained from the model of composite width versus basin area and D50 for basins of 1.75 to 25 km^2 (i.e. medium-sized basins) (Table 2) and from the model of bankfull width versus basin area and D50 for the small basins (Table 3). References to residuals refer to the residuals calculated from these two models, which are discussed separately below. The goal of this chapter is to determine if there is a relation between harvesting metrics and the width residuals, which is determined by the P value of the relations. These are considered significant when $P < 0.05$. Therefore, when discussing the relations, interest is placed on the significance of the model and the direction of the slope rather than on the strength of the model (i.e. the r^2 value) and its predictive abilities.

As mentioned in Chapter V, the widths of the 53 sites visited in 2003 were measured upstream and downstream of the road crossing from which the streams were accessed. These measurements were compared using a paired t-test to determine if roads have an immediate impact on stream width and sediment size distribution.

VI.3 Results

VI.3.1 Analysis of the relation between harvesting intensity and the remaining variance in channel width

The harvesting intensities (%ECA) of the 104 tributaries range from 0 to 48% at the watershed scale and 0 to 55% at the 60 m buffer scale (Table 5). Road densities range from 0 to 3 km/km^2 in the watershed and 0 to 8 km/km^2 in the 60 m buffer (Table 5). The medians of all the metrics except watershed %ECA are smaller than the mean, indicating positively skewed distributions. The models of width residuals versus the harvesting metrics for basins of 1.75 to 25 km^2 are shown in Table 7 (relations are considered significant when $P < 0.05$). For the purpose of clarity, only relations with a $P < 0.10$ are shown in the tables. All other relations are included in Appendix III.

Table 5. Distribution of harvesting metrics for the low-order tributaries sampled in the Cascapédia watershed.

Variable	# of cases	Minimum	Maximum	Range	Median	Mean	Standard Deviation
Watershed:							
%Equivalent Cut Area (ECA)	104	0	48	48	19.8	19.5	13.8
%ECA(85)	104	0	43.1	43.1	4.1	8.5	10.8
Road density (km/km^2)	104	0	3.1	3.1	1.3	1.4	0.9
Distance to ECA(85) (km)	81	0	2.8	2.8	0.2	0.6	0.7
%Slope ECA(85)	81	1.7	14.8	13.2	7.4	7.7	2.5
60m buffer:							
% Equivalent Cut Area (ECA)	104	0	54.6	54.6	8.5	12.2	10.9
%ECA(85)	104	0	54.6	54.6	1.4	4.8	7.9
Road density (km/km^2)	104	0	8.4	8.4	0.5	1	1.2
%Slope ECA(85)	75	2.0	31.3	29.3	8.5	9.1	1.5

Medium-sized basins

Prior to analysing the relation between the residuals and harvesting metrics, an analysis of the data distribution showed only five sites out of 39 had intensely harvested basins (i.e. %ECA > 25%) and with D10's > 10 mm (Recall from Chapter V that D10 was related to channel width (Figure 8b)). A %ECA value of 25% was chosen to represent high intensity harvesting because increased peak flows related to harvesting activities are often detected at this intensity (Caissie *et al.,* 2002). This analysis compares intensely harvested sites (ECA > 25%) to sites with low to moderate harvesting values. Thus, a conservative approach was used where data were not extrapolated from sites with D10 $\leq$ 10 mm, where harvesting intensities range from 0 to 48%, to sites with D10 > 10 mm where the range is 0 to 25%. The remaining analysis is performed only on sites with a D10 $\leq$10 mm (removing approximately 30% of the sites), to ensure the resultant models are robust. To ensure consistency in the analysis, the area and D50 model obtained in Chapter V (Table 2) was recalculated using the subset of sites with a D10 $\leq$10 mm to determine if the model's coefficients would change (Table 6). When the standard errors are taken into account, the basin area and D50 coefficients are not significantly different. Consequently, Chapter V's results remain unchanged and the models do not need to be recalculated. The residuals from the basin area and D50 model in Table 2 were used in the analysis, omitting sites with a D10 › 10 mm.

Table 6. Comparing the coefficient intervals of the two models relating width to basin area and D50, the median sediment diameter. Model 1 is for all sites and model 2 is for sites with a D10 ≤10mm. D10 is the sediment size for which 10% of the sample is smaller.

Dataset	Equation	Standard Error	Confidence interval
All sites	$1.02 \cdot Area^{0.42} \cdot D50^{0.14}$	Area 0.04 D50 0.03	0.38 to 0.46 0.11 to 0.17
Sites with D10 ≤10mm	$1.2 \cdot Area^{0.42} \cdot D50^{0.08}$	Area 0.05 D50 0.03	0.37 to 0.47 0.05 to 0.11

Table 7. Models relating width residuals to harvesting metrics for the sampled Cascapédia streams located in medium-sized basins. * denotes a significant relation at the 5% level.

Variable	Equation	r^2	P
Residual width versus:			
Basin-scale metrics:			
%Equivalent Cut Area - ECA(85)	$0.86 \cdot ECA(85)^{0.06}$	0.046	0.072
%ECA(85) + Slope ECA(85) parcels (%)	$1.25 \cdot ECA(85)^{0.06} \cdot Slope^{-0.09}$	0.040	**0.062**
Number of road-stream junctions	$0.93 * \#of\ junctions^{0.06}$	0.024	0.082
60 m corridor buffer metrics:			
Road density (km/km^2)	$\mathbf{0.99 \cdot road\ density^{0.09}}$	**0.106**	**0.011***
%Equivalent Cut Area - ECA(85)	$\mathbf{0.86 \cdot ECA(85)^{0.09}}$	**0.141**	**0.006***
%ECA(85) + slope ECA(85)(%)	$0.85 \cdot ECA(85)^{0.09} \cdot Slope^{0.01}$	0.121	0.023

Equivalent Cut Area

The first harvesting metric tested against the width residuals was %ECA (equivalent cut area). Larger positive residuals (i.e. greater widths than predicted by the basin area and D50 of a site) should be associated with higher %ECA (i.e. more intense perturbations), if there is a harvesting impact (Jackson *et al.*, 2001). However, the %ECA at the watershed and 60 m buffer scales do not explain any of the variance in the width residuals of the low-order tributaries sampled (Table 7, Figure 15). Note that the residuals from the power law models are expressed in log units. The residuals thus represent multiplicative changes from the model's predicted value. A residual value of 0.1 represents a width 26% greater than it should be according to the basin area and D50 model, a value of 0.2 indicates the stream is 58% larger, and so forth (Figure 15a).

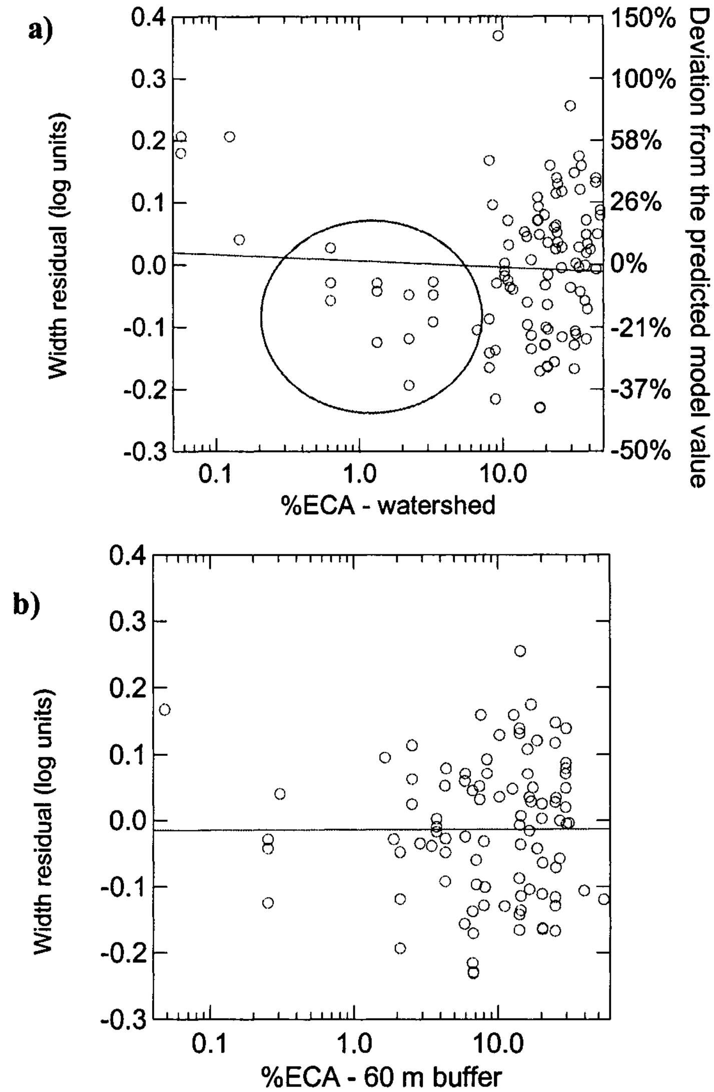


Figure 15. Scatterplot of width residuals obtained from the basin area and D50 model versus % equivalent cut area (%ECA) in a) the watershed and b) the 60 m buffer. The linear best fit lines are shown.

Each attenuation factor category was then analysed independently to determine if there is a time delay in the harvesting impacts or if one five-year period is more closely associated to the residuals than another (Table 4). The harvest intensity of the most recently harvested parcels (%ECA(85)) yields a significant model at the 60 m corridor scale ($r^2 = 0.141$, $P < 0.006$, Table 7, Figure 16). This may be because the soil has yet to recover and the hydrological impacts are greater in the years immediately following harvesting (Trenhaile, 1998; Wei and Davidson, 1998). This model shows that streams that are wider than predicted by their basin area and D50 are positively related to the intensity of harvesting activities within a 60 m distance on either side of the stream in the last five years (%ECA(85)). Sites with negative residuals should be associated to a low %ECA, but this is not always the case at the watershed scale. Conversely, at the 60 m scale, all but four of the sites with negative residuals (16, 152, 213, and 252) have %ECA(85) values below 10% (Figure 16b). This may explain why the relation is significant at this scale and not at the watershed scale.

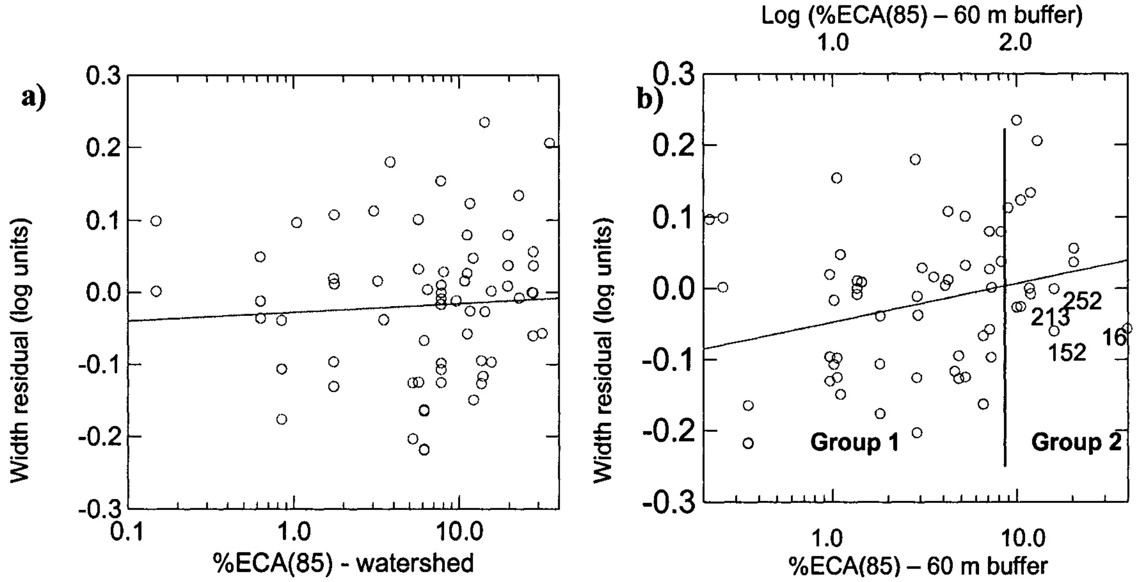


Figure 16. Scatterplot of width residuals versus % equivalent cut area with an attenuation factor of 85 (%ECA(85)) a) in the basin and b) in the 60 m buffer. Group 1 represents site with a %ECA(85) below 8.3% while Group 2 includes sites with a %ECA(85) value above 8.3%. The linear best fit line is shown.

Two approaches can be used to determine the average increase in width associated with the harvesting intensity of the last five years in the 60 m buffer (Figure 16b): the slope of the model (Table 7) and a comparison of the average residual value of two groups representing sites with low %ECA and sites with high %ECA (groups 1 and 2 in Figure 16b). Each of these is explained briefly. The slope of the %ECA(85) model indicates that when the harvesting intensity changes by one log unit, the residual value increases by 0.09 log units, or 23% (Table 7). (The slope is from the regression model of the residuals versus the log of the harvesting intensity. Therefore, it must be transformed (as $10^{0.09}$) to yield a percentage value). Thus, the model predicts that a tenfold increase in harvesting will lead to a 23% increase in width, for harvesting intensities ranging from 0 to 55%.

To determine the average increase in stream width using the second method, the dataset was divided in two groups, using an %ECA(85) of 8.3% as the threshold (Figure 16b). This value was selected using a regression tree, where an algorithm searched the predictor variable (%ECA(85) – 60 m buffer) for a way to split the dataset in two, using the smallest overall within-group sum of squares for the dependent variable (Wilkinson *et al.*, 1992). A two-sample t-test was used to compare the mean of the two groups and is significant at 5% ($P < 0.018$). The mean residual of group 1 (-0.031) indicates that sites in this group are, on average, 7% narrower than predicted by their basin area and sedimentology (Figure 17). In contrast, the sites in group 2 are, on average, 16% wider (mean residual = 0.066) than predicted by the same model (Figure 17). The streams in group 2 are approximately 25% wider than those in group 1. However, given the scatter in the data (Figure 16b) and the errors associated with the field and mathematical methodologies, the threshold used to separate the groups in this case is purely mathematical, given that there is no clear break in the trend in Figure 16b. Hence, the more conservative approach is to use the slope, although, in this case, both methods are in agreement (23% and 26%).

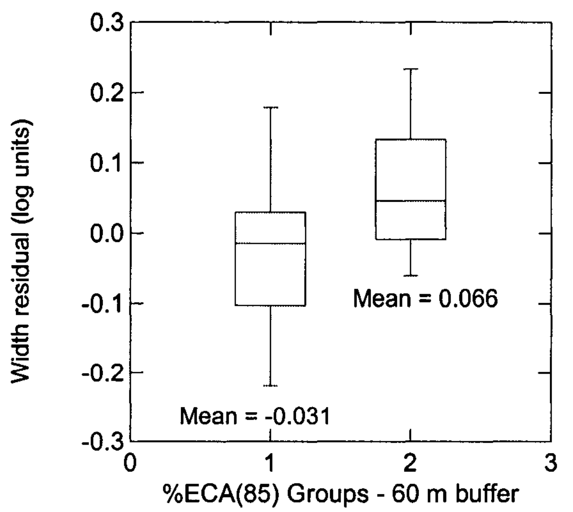


Figure 17. Boxplot comparing the average residual values of sites with a low % equivalent area cut (ECA(85) - group 1) and sites with a high % equivalent area cut (%ECA(85) - group 2). The sites in each group are shown in Figure 16.

Since the %ECA(85) at the 60 m scale is significantly related to the width residuals (Table 7), each year of this category (1997 to 2002) was modelled separately to determine if a particular year yields a stronger relation. The only year to return a significant model at the 5% level is 1997 (Table 8). The slope of this model (0.1) indicates that stream width increases by an average of 26% for each increase in one log unit of slope (i.e. for each tenfold % increase). This is similar to the average increase in width obtained by the %ECA(85) model at the 60 m scale (23%).

Similarly, at the watershed scale, the harvesting intensity in 2002 (%ECA(02)) is significantly related to the stream width residuals (Table 8, Appendix III). This year has the smallest range in %ECA (0 to 15%) when compared to the other five years in the AF = 85 category (0 to 40%). However, while it is possible that the harvesting activities in a particular year can have a greater impact than those in another, the weak relations between these two suggest other factors are involved. The remaining harvesting metrics were not significant at the 5% level (Table 7, Appendix III).

Table 8. Models relating width residuals to individual attenuation factor (AF) classes at the 60 m and watershed scales. * denotes a significant relationship.

Variable	Equation	r^2	P	n
Width residual versus:				
%Equivalent Cut Area - ECA(01) – 60 m	$0.98 \cdot ECA(01)^{0.03}$	0.092	0.076	25
%Equivalent Cut Area - ECA(00) – 60 m	$2 \cdot ECA(00)^{0.1}$	0.269	0.059	11
%Equivalent Cut Area -ECA(97) – 60 m	$\mathbf{0.8 \cdot ECA(97)^{0.1}}$	**0.195**	**0.012***	**27**
%Equivalent Cut Area -ECA(02)	$\mathbf{1.01 \cdot ECA(02)^{0.04}}$	**0.236**	**0.001***	**42**

Roads

The next metric to analyse is road density. A significant, positive relation ($r^2 = 0.11$, $P < 0.011$) exists between the road density in the 60 m buffer and the width residuals (Table 7, Figure 18b). This relation is significant because all but one of the sites (site 29) with road densities > 2.5 km/km^2 have positive residuals. Similarly, with the exception of site 27, all sites with densities < 0.2 km/km^2 have negative residuals. As with the %ECA(85) model at the 60 m buffer scale, the slope of the road density model (0.09) shows a 23% increase in stream width as road density in the 60 m buffer increases tenfold (Table 7). A significant relation does not exist between the width residuals and the remaining road density metrics (road density at the watershed scale, Figure 18a, and number of road-stream junctions, Table 7).

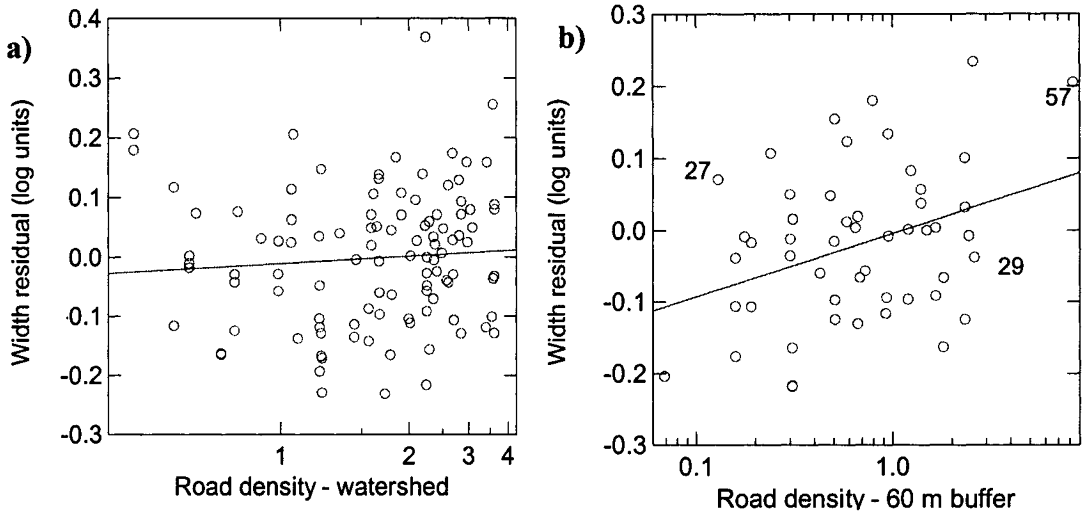


Figure 18. Change in width residuals from the basin area and D50 model as road density increases in (a) the watershed and (b) the 60 m buffer. The linear line of best fit is shown.

Small basins

In Chapter V, two models were created to explain the variance in channel width: one for streams with basin areas of 1.75 to 25 km^2 and a second for basins smaller than this. This section deals with the model created for basin areas < 1.75 km^2 (width = 0.8 · Area$^{0.15}$ · D50$^{0.23}$, r^2 = 0.242, P < 0.0005, Table 3), now referred to as small basins. The regression analysis run on the larger basins was repeated for the small basins, using this second set of residuals.

In the small basins, the only significant relation is between the width residuals and the slope of the recently harvested parcels (AF = 85) (Figure 19, Table 9, Appendix III). Theoretically, the increase in terrain slope increases the speed of runoff, thus creating higher flows immediately following a precipitation event. These higher peak flows would increase bank erosion and be associated to streams with higher positive residuals. This is supported by the results of Brandt *et al.* (1988), who found higher flows in basins of < 2 km^2. Moreover, if the slope of the recently harvested parcels is added to the original model of basin area and D50 (Table 3), the model explains 63% of the variance in stream width (i.e. an additional 39% of the variation is explained by this model than by basin area and D50 alone). However, the relation is improved because there are fewer sites with recently harvested parcels than there are sites in the original model (n = 33 versus n = 63, respectively). Sites without a %ECA(85) metric are not included in the regression because there is no %ECA(85) slope and there is no log of 0 (see section VI.2.1). No other ECA metric yields a significant model for streams in basins ‹ 1.75 km^2.

Table 9. Models relating bankfull width to the harvesting metrics at the 60 m and watershed scales for the Cascapédia streams in small basins. * indicates a significant result.

Variable	Equation	r^2	P
Residual width versus:			
Watershed metrics:			
%Equivalent cut area - ECA(55)	$0.70 \cdot ECA(55)^{0.14}$	0.279	0.067
%Slope of ECA(85) parcels	$\mathbf{0.30 \cdot Slope^{0.54}}$	**0.185**	**0.008***
Distance to ECA(85) parcel (m)	$0.74 \cdot Distance^{0.05}$	0.075	0.070
60 m buffer metrics:			
Road density (km/km^2)	$1.03 \cdot \text{road density}^{-0.05}$	0.043	0.072
%Equivalent cut area - ECA(85)	$0.93 \cdot ECA(85)^{-0.03}$	0.025	0.097

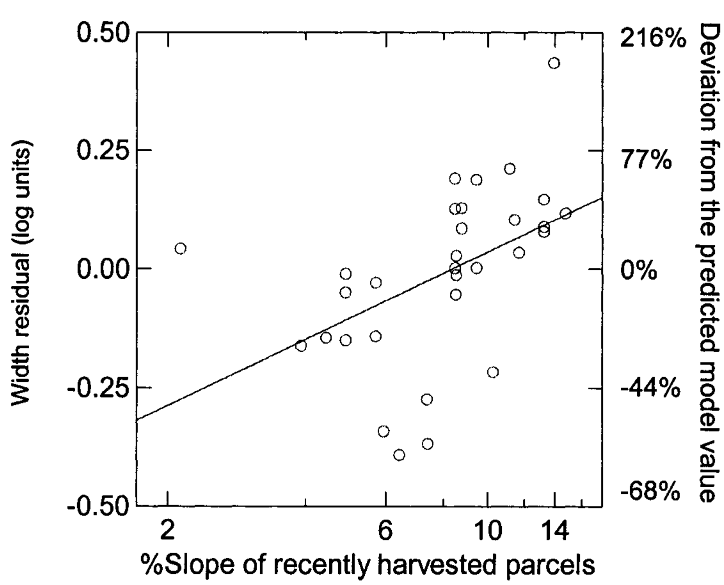


Figure 19. Variation in width residuals as the slope of the most recently harvested parcel (attenuation factor of 85) increases in basins of 1.75 km^2 or less. The linear best fit line is shown.

For the basins of ‹ 1.75 km^2, no significant relation exists between road density and width residuals, either at the watershed or 60 m buffer scales (Figure 20). At both scales, the sites with the lowest road density have residuals close to 0. Similarly, at the 60 m buffer scale, the two sites with the highest road density also have residuals close to 0, while theoretically, these should have had large, positive residuals indicative of streams that are wider than predicted by their basin area and D50.

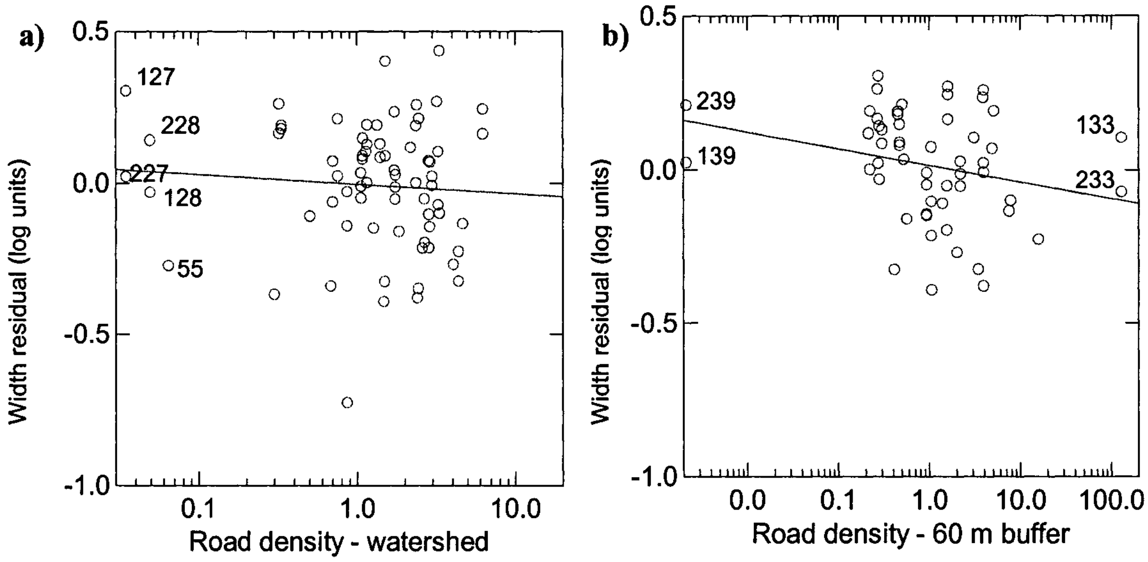


Figure 20. Variation in width residual as road density increases in a) the watershed and b) the 60 m buffer for sampled streams in basins of 1.7 5 km^2 or less. The linear line of best fit is shown.

VI.3.2 Analysis of the association between road-stream junctions and stream characteristics

Having tested for the effects of road density at the buffer and watershed scales, the next analysis determines how road-stream junctions are associated to local width and stream sedimentology, given that road stream crossings are the primary source of erosion and sedimentation in streams, especially following precipitation events (Spillios and Rothwell, 1998; Grace, 2002). At each site visited in 2003, width measurements were taken at least 20 m upstream and downstream of the road and river crossing. The five cross-sections were taken over 50 to 150 m of the stream. At this scale, comparison of the variables measured upstream and downstream of the road junction on the same stream using paired t-tests shows that there is no significant difference between the averages of width, slope, or sediment distribution (Table 10). The median widths of the upstream and downstream sites (shown as the middle line in the box of Figure 21) are almost identical in every basin size category. The range of values is greater in the sites downstream of the road, demonstrated by the whiskers in Figure 21. However, both upstream and downstream sites have outliers with widths greater than 7 metres, shown by the asterisks.

Table 10. T-test results of the upstream and downstream average values of width, channel slope, and sediment size (D10, D50, and D90). N = 23.

Variable	Upstream Average	Downstream average	r^2 (P)	Student's t	95% confidence interval of mean difference
Widths (in m)					
Wetted (W1)	2.5	2.4	0.968 (0.000)	1.576	-0.035 to 0.290
Alluvial (W2)	2.9	2.8	0.970 (0.000)	0.645	-0.130 to 0.253
Bankfull (W3)	3.1	3.2	0.963 (0.000)	-0.560	-0.291 to 0.164
Vegetation (W4)	4.1	4.1	0.965 (0.000)	-0.348	-0.314 to 0.222
Composite (CW)	3.4	3.4	0.972 (0.000)	-0.158	-0.226 to 0.193
Stream slope (%)	4.2	3.9	0.532 (0.000)	0.494	-0.809 to 1.335
D10 (mm)	7.2	7.1	0.619 (0.000)	0.126	-1.947 to 2.208
D50 (mm)	30.6	29.9	0.778 (0.000)	0.274	-4.975 to 6.540
D90 (mm)	83.2	82.8	0.554 (0.000)	0.053	-13.25 to 13.97

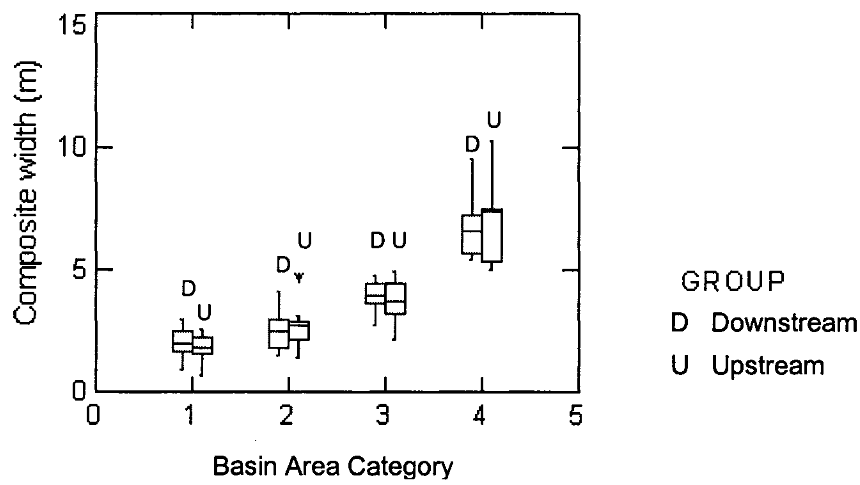


Figure 21. Box and whisker plot of upstream and downstream composite widths (m), by basin area category. Category 1 includes basins of 0 to 1.75 km², category 2 comprises basins of 1.75 to 5 km², category 3 includes basins of 5 to 15 km², and category 4 contains basins of 15 to 25 km².

VI.4 Discussion

VI.4.1 Relation between harvesting metrics and width residuals

Medium-sized basins (1.75 to 25 km²)

Harvesting is associated to increases in stream width (Kondolf *et al.*, 2002). Indeed, a portion of the variance in width unexplained by basin area and stream sedimentology is related to the harvesting metrics in the Cascapédia dataset. On average, stream widths are increased by approximately 25%. However, the models are not strong enough to predict how a *particular* stream will react to harvesting. When added to the original basin area and sedimentology model of Chapter V, only one of the significant harvesting variables adds to the strength of this model (%ECA(2002), Table 11). Indeed, while all four models are significant overall (i.e. $P < 0.0005$), %ECA(1997) and road density, both in the 60 m buffer, are not significant ($P > 0.05$, Table 11). Hogan *et al.* (1998) found a significant relation between stream width and harvesting intensity. Streams in basins of 30 to 75 km^2, harvested at 57%, were wider than streams in undisturbed basins, although the authors do not state by how much. Lyons and Beschta (1983) also found 25 to 250% increases in channel width associated with harvesting intensity, although they also noted a decrease in width 10 years after the perturbation. This cannot be tested in the Cascapédia watershed because harvesting is ongoing. These results likely indicate that current provincial regulations do not sufficiently protect streams from harvesting impacts, given that metrics at the 60 m scale are related to stream width residuals. Below, two reasons that may explain why harvesting is associated to a stream enlargement in certain tributaries of the Cascapédia are discussed, along with possible reasons why certain metrics failed to produce significant models.

Table 11. Multivariable models relating large-scale landscape structure variables, harvesting metrics, and stream width. The P is the significance of the 3rd variable in the model and not the overall model significance. All models are highly significant (0.000). ECA is equivalent area cut.

Variable	Equation	r^2	P
Width versus:			
Basin area, D50, and	$1.02 \cdot Area^{0.42} \cdot D50^{0.14}$	0.657	0.000
%ECA(85) – 60 m	$\mathbf{1.04 \cdot Area^{0.43} \cdot D50^{0.1} \cdot ECA(85)^{0.05}}$	**0.648**	**0.044***
%ECA(2002)	$\mathbf{1.24 \cdot Area^{0.4} \cdot D50^{0.09} \cdot ECA(2002)^{0.03}}$	**0.704**	**0.003***
%ECA(1997) – 60 m	$0.86 \cdot Area^{0.62} \cdot D50^{0.04} \cdot ECA(2000)^{0.01}$	0.670	0.672
Road density – 60m (km/km^2)	$0.97 \cdot Area^{0.42} \cdot D50^{0.15} \cdot Road\ density^{0.02}$	0.664	0.092

Firstly, stream enlargement may be explained by the timing of the delivery of snowmelt and soil water movement, as shown by Burton (1997). An increase in snow accumulation and melt, particularly in small and moderate size basins, will lead to an increase in flow (Plamondon, 1993; Slaymaker, 2000). Higher flows can engender bank erosion as the stream attempts to adjust its morphology (Harr and McCorison, 1979; Burton, 1997), which is affected by the channel's sustained high flows (Whitaker *et al.,* 2001). Stream buffers wider than 60 m, where harvesting activities are prohibited, could delay the delivery of melted snow to the stream, thus reducing the impacts of higher flows (Purdum, 1997).

Secondly, buffers help maintain channel morphology (Slaymaker, 2000). Two problems may be related to the buffers in the Cascapédia watershed. First, the effective width of the buffers may not be the required 20 m in all tributaries. Second, the 20 m regulation may not be adequate to protect the river's morphology. The consequences of this include the accumulation of logging debris which can cover the stream completely (Jackson *et al.*, 2001). This was observed at certain of the sampled sites, although no quantitative data on debris quantities were collected. Large woody debris accumulations can also alter the channel, slowing velocities and forcing water to flow through a matrix of debris, increasing the fine sediment content upstream of the obstruction. Removing bank vegetation can also widen a channel because of a weakening of the channel banks (Chamberlain *et al.*, 1991; Hartman *et al.*, 1996; Tschaplinski, 2000; Kondolf *et al.*, 2002). Blowdowns also need to be considered (where trees are thrown over by strong winds) because this can reduce a buffer's effective width (Jackson *et al.*, 2001). A qualitative assessment of photographs taken at the sampled sites shows blowdowns may have occurred at several of these, reducing the width of the buffers. Perhaps the 20 m buffer regulation should be an *effective* width. Future studies should determine the average width of blowdowns. This width should then be added to the minimum buffer width requirement so that once blowdowns have occurred the remaining width of the buffer is the required 20 m.

The next issue of interest is the weakness of the relations, which may be linked to the harvesting metrics estimated from the GIS database. These metrics (e.g. %ECA, linear distance from a site to the closest recently harvested parcel) may not have been significantly related to width residuals for several reasons. The first may be that errors in harvested parcel photo interpretation are large enough to impact the delineation of forestry parcels with respect to the location of the streams in the digital database. However, this is unlikely except for the smallest basins, which were considered separately. Furthermore, the %ECA(85) category yielded a weak, but significant result at the 60 m buffer scale ($r^2 = 0.14$, Table 7). Thus, any error associated with watershed and harvested parcel delineation does not always obscure the relations, although it may have been large enough to render the models of the other attenuation factor categories insignificant at the 5% level.

Secondly, the overall ECA metric assigned to a watershed may not be a good indicator of morphological impacts. The assumptions behind the attenuation factor categories assigned to the year of harvest used to calculate %ECA simplify and generalise the underlying hydrological recovery processes. Assigning a mean attenuation factor (AF) based on perturbation year may not accurately represent local conditions since some areas recover from harvesting more quickly than others, which cannot occur in this AF system. One suggestion is to structure the AF categories to include the growth rate of the resident species at the time of harvest to better represent field conditions. Perhaps there should also be a more gradual decrease in the value of the attenuation factor categories. Rather than going from an AF of 85 to an AF of 65 between the fifth and sixth year since harvest, the addition of intermediary categories of 80, 75, and 70 may better represent the recovery process. Wei and Davidson (1998) used a more progressive method of calculating ECA, assigning individual years an attenuation factor and giving systems 40 to 45 years to recover to 80%. The AF classification used for the Cascapédia dataset gives the system 36 years to recover completely (Langevin *et al.*, 2001), despite the difficulties in accurately predicting the hydrological effect of altering vegetation and the time to recovery (Campbell and Doeg, 1989). Finally, ECA may also become more meaningful if it includes the time of year of harvest and the climatic conditions of the days prior to the harvest.

The weakness of the relations may also stem from factors which were not considered in the analysis. Precipitation, which affects runoff and peak flows (Beschta *et al.*, 2000), could be added to strengthen these models. Precipitation intensity is rarely evenly distributed throughout a large watershed (Wei and Davidson, 1998). Furthermore, inter-annual changes in precipitation should also be considered. Since the sites were sampled throughout the Cascapédia watershed (Figure 4), it is likely that the precipitation intensity varied across it and could explain why there is a range in how the sampled tributaries responded to recent harvesting operations.

Roads

While road density is significantly related to the width residuals, the relation is strongest in cases where the road density within the 60 m buffer is less than 0.2 km/km^2 or greater than 2.5 km/km^2, which occurs in 30% of the Cascapédia dataset. This data thus confirm that roads can be a major source of sediment in harvested areas (Campbell and Doeg, 1989). Road density in the 60 m buffer does not increase the strength of the width prediction from basin area and sedimentology because it is not significant in the multivariate model (Table 11). Watershed road density may not be significantly related to stream width because it has a smaller range that the density in the 60 m buffer (0 to 3.1 km/km^2 versus 0 to 8.4 km/km^2, respectively). Furthermore, watershed road density is related to watershed %ECA (Figure 22a), which was also not significantly related to the width residuals. Conversely, the road densities at the 60 m buffer scale are not strongly related to the harvesting intensity in the buffer (Figure 22b). This relation between road density and %ECA at the watershed scale may explain why there is also no relation between watershed road density and the width residuals.

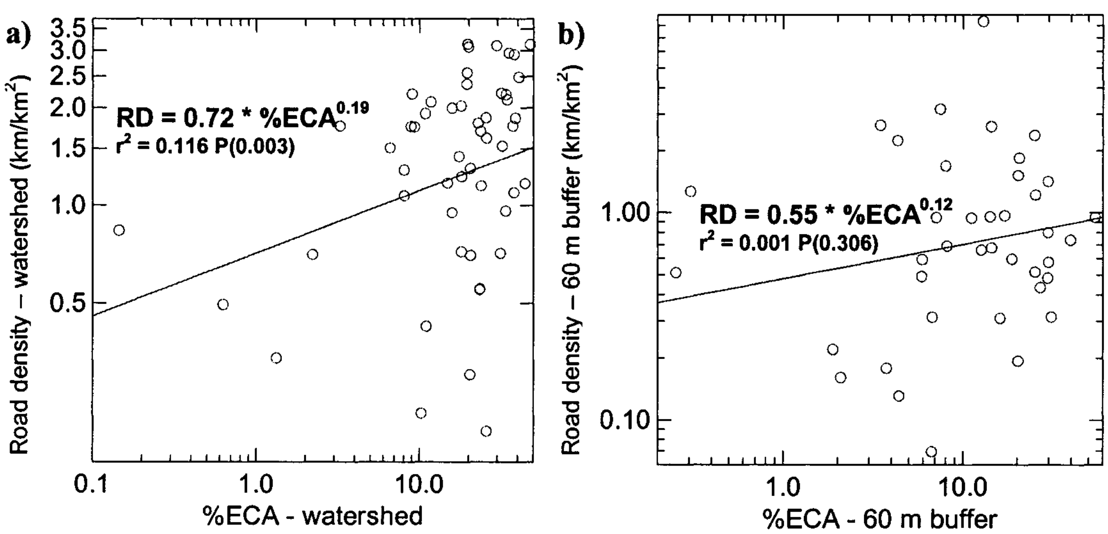


Figure 22. Relation between road densities and % equivalent cut area (%ECA) in a) the watershed and b) the 60 m buffer for study basins of 1.75 to 25 km^2. The linear line of best fit is shown.

Furthermore, harvesting does not occur simultaneously throughout the basin, but rather in sectors of the watershed. Certain roads experience concentrated traffic for a few days and then are left unused for the remainder of the year. A combination of heavy traffic and a large rain event would increase the chances of sediment production and the likelihood of runoff being redirected, via drainage ditches, to the river, increasing its flow or the possibility of road failure. Improper maintenance of road drainage structures is a major factor contributing to road-related failures (Slaymaker, 2000). Consequently, road conditions should be reflected in the model. In addition, the database should be updated to ensure all road segments are included and classified. This is especially relevant for skid trails because of the fine sediment production potential of their non-gravel surfaces.

Data on road use in the Cascapédia watershed were not available and data on road type were incomplete; therefore these analyses could not be performed. Including rain events in the database requires an elaborate system of weather stations and close monitoring of precipitation events throughout the watershed. Data collection can be difficult in large watersheds, especially in heterogeneous terrain. Therefore, if future studies are to attempt this analysis, the endeavour should be undertaken for a small portion of the basin to determine its effectiveness in explaining any of the remaining variations in stream width before being applied to the watershed as a whole.

Small basins (0.03 to 1.75 km^2)

That the only significant relation in the small basins at the 5% level is the relation between the width residuals and the slope of the recently harvested parcels located in the 60 m buffer (Table 9) was unexpected, especially since previous research on the hydrological responses of watersheds to harvesting intensity has yielded significant results in basins $<$ 2 km^2 (Brandt *et al.,* 1988; Hudson, 2001; Jackson *et al.,* 2001). The headwater creeks with basin areas $<$ 2 km^2 studied by Hudson (2001) experienced the greatest increases in peak flow, to which the channel would have to adjust its morphology. Several reasons may explain the scarceness of significant relations in the small basins of the Cascapédia watershed. Four of these are discussed below.

First, the errors in harvest parcels and/or basin areas in the model (due to contour line interpolation and air photo interpretation) may be large enough, relatively, in these small basins to hide or mask any significant relations (i.e. these errors add enough uncertainty to the predictor values to reduce the significance of the relations to below 5%). This theory could be tested on a subset of watersheds through a field verification of forestry parcel and basin boundaries with a high-precision GPS, although this is time-consuming. The benefit to having this information is that average error values could then be included in the analysis. It is also imperative to include small streams in future research because they affect the quality of downstream habitat by bringing water, nutrients, and wood debris to the larger streams and they are the most easily impacted by changes brought about from harvesting (Chamberlain *et al.*, 1991; Church, 1996).

Secondly, published studies have reported that the peak discharge in small basins may not be high enough to initiate bank erosion (Plamondon, 1993). A critical stream length or basin area may have to be reached before the stream's discharge is large enough to trigger bank erosion, which may not have been reached in the small watersheds of this study (Carragher *et al.,* 1983). However, studies in watersheds of < 2 km^2 have recorded significant changes in peak flow responses following harvesting in 30% of their basins (Beschta *et al.*, 2000; Hudson, 2001). Since 25% of the small basins sampled had %ECA values at or above 30%, some of these streams were expected to have increased peak flows, which would be detected by stream enlargement (Rosgen, 1996). Other studies showed that over 70% of a small basin has to be harvested for peak flow increases to occur (Brandt *et al.*, 1988). Since only two of the 64 tributaries were harvested above 70%, this may explain why the streams in this study did not show any change related to harvesting. Therefore, the literature reports that different levels of harvesting are required to create an increase in peak flows, illustrating how other factors and/or stream characteristics may be involved.

This introduces a third possibility, which is that another stream characteristic is altered in association to harvesting intensity. Stream characteristics other than width may be more sensitive to harvesting. Measuring maximum discharge or maximum water depth may yield a clearer picture of the relation between harvesting and changes in stream morphology. Peak flow measurements can be used with width and channel slope to calculate discharge and shear stress to provide an indication of the stream's sediment transport capacity. Thus, perhaps stream enlargement should only be used as an indicator of increased peak flows associated to an intensification of harvesting activities in basins larger than 1.75 km^2.

Furthermore, other factors may play a major role in determining the width of streams in small basins and have a more muted effect in larger basins. Some of the factors known to impact streamflow are snow accumulation and melt (Brandt *et al.,* 1988; Plamondon, 1993; Buttle *et al.,* 2000; Hudson, 2001; Caissie *et al.*, 2002), stream bank material and slope (Thorne, 1991), slope aspect (Thorne, 1991; Church, 1996; Rosgen, 1996), and indigenous vegetation (Plamondon, 1993; Church, 1996). Compliance to the buffer width regulations should also be verified to determine if non-compliance is a problem, given that it leads to the largest damages to streams (Slaymaker, 2000).

Roads

Roads are known to accelerate storm runoff and increase peak flows in basins smaller than 1 km^2 (Harr and McCorison, 1979; Chamberlain *et al.,* 1991), although there was no relation between road density and the variance in width residuals in the small basins. The problem may be one of oversimplification. More representative road density metrics could be calculated. Since road use is positively linked to sediment production, road density could be weighed by the number of trucks using each road every day (Reid and Dunne, 1984). It may also be useful to have a database where roads are divided into categories and assigned a code for potential impacts, based on use, width, age, level of maintenance, time of use, and slope. One study (King and Tennyson, 1984) found an impact from roads only when these had very high cut slopes. This information was not available for this study, and therefore could not be tested, although it could prove useful in determining any existing relation between roads and the remaining variance in width.

VI.4.2 Local sediment production from roads

The lack of a significant difference between the widths, channel slope, and D50 upstream and downstream of the road junction indicates (Table 10) one of two possibilities: either roads have no impact at this scale or this methodology cannot detect an impact associated to current logging road practices at the local scale. A more detailed study of the sediment production from roads is required before it can be stated with certainty that roads do not affect local stream morphology, either by facilitating the introduction of flow to the stream, leading to an enlargement, or by introducing fine sediment into the stream and affecting the quality of the substrate at the point of entry or further downstream as the sediment is transported by flow and subsequently deposited (Reid and Dunne, 1984; Campbell and Doeg, 1989; Slaymaker, 2000; Lewis *et al.,* 2001; Grace, 2002). Spillios and Rothwell (1998) used freeze-core sampling and found increased fine sediment levels, especially clays (sediment with a diameter $<$ 0.0625 mm), downstream of road-stream crossings. The use of Wolman sampling, where all sediments with diameters smaller than 2 mm were agglomerated into the 2 mm category, may explain why no significant results were found. Furthermore, roads may impact width further downstream than the 150 m measured in this study or at the slope change immediately downstream of the culverts (i.e. in the first 20 m from the road junction). These factors should be considered in future studies.

Moreover, studies often report road sediment production, which was not measured in this study. Reid and Dunne (1984) reported a link between road length and road slope on sediment production from the roads. They discovered that roads injected more fines into the stream. If this had been the case for the Cascapédia sites, the D10 would have been smaller downstream of the road junction (Table 10). Perhaps sediment was injected into the stream, but has since been washed away, accumulating downstream (Campbell and Doeg, 1989). Therefore, the impact may not be seen in the sediment size, but rather in a stream widening over a larger scale rather than in the section immediately downstream of a road junction. Therefore, more detailed studies should be undertaken, dealing specifically with roads and their possible impacts on stream width.

VII ANALYSIS OF THE DETERMINANTS OF MAINSTEM RIFFLE SEDIMENTOLOGY

VII.1 Introduction

Having completed the analysis of the first objective, the following two chapters detail the analysis performed for the second objective. The goal of these chapters is to determine if a relation exists between harvesting metrics and the riffle sedimentology of four fourth and fifth order segments of the Cascapédia River, in terms of median pavement diameter ($D50_p$) and fine sediment content ($\%fines_{sp}$), once variations due to natural variables such as basin area and local stream slope are accounted for. These segments were selected because of the presence of potential salmonid spawning habitat (i.e. riffles with sediment substrates of 15 to 150 mm) (Bjornn and Reiser, 1991; Bardonnet and Baglinière, 2000). Spawning habitat is considered mediocre when fine sediments (sediment $<$ 2 mm) constitute over 15% of the riffle substrate and poor when fines exceed 20% of the substrate (Petersen and Metcalfe, 1981; Anderson, 1998). For the purpose of this research, fine sediments are defined as sediments with a mean diameter $<$ 2 mm. The aim of this chapter is to remove the variations in $D50_p$ and $\%fines_{sp}$ associated to the large-scale landscape structure variables basin area and geology, and to the reach-scale variables channel slope, local shear stress, channel width, and average point bar width, given that $D50_p$ and $\%fines_{sp}$ vary with these variables (Church, 1996; Thompson and Hoffman, 2001). The general relations between these variables are reviewed below.

In theory, as basin area increases, there is a decrease in sediment size and an increase in fine sediment content (Figure 2, Church, 1996; FISRWG, 1998). However, this downstream fining trend can be offset 1) by tributaries or landslides that inject large sediment into the channel, 2) in areas of reduced valley width, or 3) by bedrock outcrops. Watershed geology is also related to a stream's natural sediment input (Barrett *et al.,* 1998). For example, soils composed of glacial tills are usually coarse and have carbonates that render soil particles resistant to detachment (Swanson *et al.,* 1986). Steeper channel slopes are usually associated with higher shear stresses and both of these variables are associated with larger D50 values and lower fine sediment contents (Gordon *et* al., 1992; Rosgen, 1996; Thompson and Hoffman, 2001). Shear stress generally declines as basin area increases because of the concurrent decrease in channel slope (Figure 2, Gordon *et al.*, 1992). In addition, channel width tends to increase in the downstream direction (Rosgen, 1996) and is usually associated with a decrease in shear stress because of the concomitant decrease in water velocity (Gordon *et al.*, 1992). This should increase the substrate's fine sediment content. Finally, point bar widths are expected to affect $D50_p$ and subsurface fine sediment content because they are a source of sediment. Wider bars should be associated with higher fine sediment contents and lower $D50_p$ values in the riffles located immediately downstream of the bar.

Therefore, the objective of this chapter is to analyse the relations between the above-mentioned large-scale landscape structure and reach-scale variables and the variations in the pavement D50 and riffle substrate fine sediment content along four mainstem segments of the Cascapédia River. Given the theory outlined above, the main hypothesis is that in undisturbed conditions, riffle fine sediment content should increase in the downstream direction and pavement D50 should decrease.

VII.2 Methods

VII.2.1 Field measurements

Site selection

Four segments, each of 6 to 8 kilometres in length, were selected for this study (Figure 23). These were selected based on ease of accessibility (required for frequent visits) and the presence of potential salmonid spawning habitat, defined as sites with a visually estimated D50 at the crest of the riffle between 15 and 150 mm (Bjornn and Reiser, 1991; Bardonnet and Baglinière, 2000). The remaining mainstem segments (Figure 23) were not sampled because they did not satisfy the selection criteria. The segment upstream of Haute Mineurs was excluded because it has few riffles and a small estimated D50 (<10 mm). The section between the two Mineurs was not sampled because rock walls on both sides of the river prevented access. Furthermore, the river bed is composed mostly of bedrock and large sediment with diameters larger than 50 cm. The segment upstream of Échouement was not sampled because of the lack of access points. Finally, the segment downstream of Lac was not chosen due to its frequent bedrock outcrops.

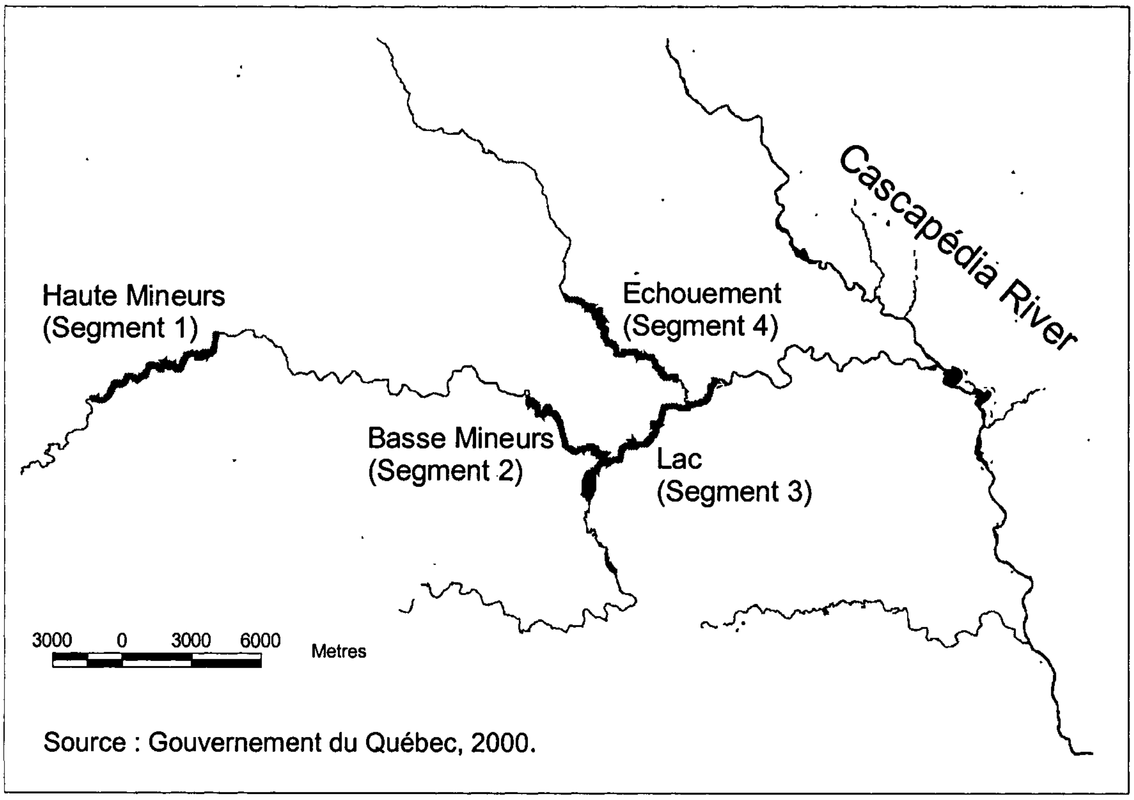


Figure 23. Location of study segments along the mainstem channels of the Cascapédia River.

Fieldwork – Collecting reach-scale variable measurements

Once the four segments were identified, their long profile was obtained by surveying riffle crest positions using an engineer's level. When riffle-to-riffle shots were not possible, intermediary points were taken to establish the vertical and horizontal distance between riffles. These intermediary points were not entered in the river bed long profiles created from the surveys (see Figure 24, section VII.3.1). The survey data were then used to obtain the mean segment slope, local channel slopes, and total distance surveyed.

While surveying, the bankfull depth at each riffle was measured to estimate a bankfull water surface long profile for each segment. Point bar tops indicate the lowest levels of bankfull flow. Thus, terraces were identified as banks higher than their associated point bar top and omitted from the water surface long profile since they usually represent bankfull levels at a time when the river bed was less incised than at present (Rosgen, 1996; Sweet and Geratz, 2003). To measure the bank height above the riffle crest (or thalweg), an observer would climb the bank to stand above the floodplain, usually indicated by the presence of large woody vegetation such as spruce or pine (Rosgen, 1996). The observer would then stand with an abney level at 0° inclination, point to the stadia rod positioned in the riffle thalweg and record the observed height. The height to the observer's eye was measured and removed from the observed height to yield an approximate value of local floodplain height with respect to the riffle thalweg. The accuracy of these measurements is estimated to be ± 25 cm. Because of the uncertainties in determining bankfull levels from the presence of large woody vegetation on banks, the bankfull level profile was smoothed over the segment using a fifth or sixth order polynomial (Table 12) and the local water surface slope was calculated from the derivative of this smoothed profile.

Table 12. Polynomial equations used to smooth the bed and water surface long profiles.

Site	B = Polynomial equation used to smooth the river bed W = Polynomial equation used to smooth the bankfull water surface (see Figure 30)	R^2
Segment 1 – Haute Mineurs		
B	$y(1) = -3.86E\text{-}18x^6 + 5.08E\text{-}14x^5 - 2.51E\text{-}10x^4 + 5.73E\text{-}07x^3 - 5.91E\text{-}04x^2 + 1.04E\text{-}01x + 10000$	0.955
W	$y(1) = -2.7E\text{-}18x^6 + 3.6E\text{-}14x^5 - 1.8E\text{-}10x^4 + 4.1E\text{-}07x^3 - 4.4E\text{-}04x^2 + 7.0E\text{-}02x + 10000$	0.989
B	$y(2) = 5.23E\text{-}19x^6 - 1.60E\text{-}14x^5 + 1.92E\text{-}10x^4 - 1.12E\text{-}06x^3 + 3.14E\text{-}03x^2 - 3.44E{+}00x + 10000$	0.985
W	$y(2) = 6.8E\text{-}18x^6 - 2.4E\text{-}13x^5 + 3.4E\text{-}09x^4 - 2.5E\text{-}05x^3 + 1.0E\text{-}01x^2 - 2.2E{+}02x + 210\,000$	0.997
Segment 2 – Basse Mineurs		
B	$y = 9.95E\text{-}20x^6 - 2.70E\text{-}15x^5 + 2.69E\text{-}11x^4 - 1.25E\text{-}07x^3 + 2.87E\text{-}04x^2 - 6.83E\text{-}01x + 10000$	0.999
W	$y = -8.47E\text{-}16x^5 + 1.46E\text{-}11x^4 - 8.89E\text{-}08x^3 + 2.34E\text{-}04x^2 - 6.23E\text{-}01x + 10100$	0.998
Segment 3 – Lac		
B	$y = 1.05E\text{-}19x^6 - 2.55E\text{-}15x^5 + 2.35E\text{-}11x^4 - 1.02E\text{-}07x^3 + 2.16E\text{-}04x^2 - 3.43E\text{-}01x + 10000$	0.998
W	$y = -2.95E\text{-}16x^5 + 4.24E\text{-}12x^4 - 1.59E\text{-}08x^3 - 2.13E\text{-}06x^2 - 6.67E\text{-}02x + 10100$	0.975
Segment 4 – Échouement		
B	$y = -5.03E\text{-}20x^6 + 1.18E\text{-}15x^5 - 9.38E\text{-}12x^4 + 2.61E\text{-}08x^3 - 1.05E\text{-}05x^2 - 4.37E\text{-}01x + 10000$	0.998
W	$y = -1.42E\text{-}19x^6 + 3.51E\text{-}15x^5 - 3.12E\text{-}11x^4 + 1.17E\text{-}07x^3 - 1.77E\text{-}04x^2 - 3.18E\text{-}01x + 10100$	0.976

Riffle bankfull widths were also measured along each segment. While channel width can be a sign of bank erosion and could thus be treated as a harvesting metric, the erosion could not be attributed solely to harvesting. As a result, channel width is used as a reach-scale variable because it varies naturally in the downstream direction (Figure 2). Width was measured perpendicular to the flow direction at the riffle, from the topographic break in slope or change in vegetation of one bank to the other (Castro and Jackson, 2001).

Point bar widths were also measured along each segment because they can be a source of sediment for riffles located downstream from them. The width was measured along the widest section of the point bar from the water's edge to the root of the nearest alder, which represents the lower levels of the bankfull discharge height (Rosgen, 1996; Simon and Castro, 2003; Sweet and Geratz, 2003). Average point bar width (in m) was calculated as the mean of the two point bars found immediately upstream of a riffle, assuming a normal channel pattern of alternating point bars and riffles (i.e. the two point bars had to be no more than two riffles upstream of the sampling site). While point bar width can be a surrogate indicator of bank erosion because point bar building allows a river to increase its lateral migration (Knighton, 1975) while maintaining its width (Rosgen, 1996; Repetto and Tubino, 2001), there was no means to determine if the erosion was associated exclusively to forestry activities. Therefore, point bar width is used as a reach-scale variable. Because point bar width is sensitive to the channel's water level, point bars along each segment were sampled the same day or in two consecutive days to ensure measurement consistency. Widths across different segments cannot be compared because large rain events that increased water levels by up to 1.25 metres occurred before all four segments were measured.

Once the riffle bed and bankfull flow long profiles were established from the field survey data, each profile was annotated with information on potential local controls of hydraulic energy and sediment supply conditions, which affect sediment transport and storage at each site (Figure 24). This information, including bedrock outcrops on the river bed and river banks, tributary junctions, log jams, bridges, back channels, and cliffs, was obtained from detailed field notes (with the ± 5 m accuracy of the GPS locator) or found on 1:20000 maps, which have a contour line accuracy of +/- 5 metres (Gouvernement du Québec, 1999).

Channel slope and indicative shear stress

From the long profile data, four channel slopes were calculated at each sampled riffle. Two estimates of bed slope were calculated from the riffle long profile. The first is the mean slope over five riffles (consisting of the two riffles upstream of the site, the sampled riffle, and the two riffles downstream of the site – called LS2) and the second spans nine riffles (including four upstream riffles, the sampled riffle, and four downstream riffles – called LS4). Two water surface slopes were also calculated from the smoothed bankfull water surface profile. The first is the lowess smoothed slope (LSS), calculated from the Lowess-smoothed bankfull water level measurements. The second water surface slope is the polynomial slope (PS), calculated as the local derivative of the smoothed bankfull water surface profile using a fifth or sixth order polynomial (Table 12 and shown in Figure 24). Each of these was used in the reach-scale analysis to determine their relation to variations in riffle sedimentology.

Using these channel slope estimates, an *indicative* value of bankfull shear stress was then calculated for each riffle. Knowledge of the shear stress patterns along each segment helps to detect forestry impacts by indicating where different grades of sediment would deposit naturally. The shear stress values are used as an indication of the relative pattern of formative shear stresses along each segment only, as this study was not designed to measure bankfull shear stress accurately. A shear stress study would have measured water depth and slope using stage recorders placed along the length of the segment. Reach-scale mean shear stress, τ_0, was approximated using equation 4 (section II.3.1). In this case, the bankfull depth at a given riffle was used as a proxy for the hydraulic radius, R, which is acceptable when a stream is wide in relation to its depth (Knighton, 1984). The flow depth at each site was calculated based on the differences between the polynomial equations for the bed and water surface levels (Table 12). Only one depth was calculated for each site. Four shear stress estimates were calculated for each riffle (i.e. one for each slope). The shear stresses are local shear stress (SS2, which uses local slope, LS2, in equation 4), regional shear stress (SS4, which uses regional slope, LS4), Lowess smoothed shear stress (LSSS, which uses lowess smoothed slope, LSS), and Polynomial shear stress (PSS, which uses polynomial slope, PS).

Substrate sampling

The riffle mean pavement size ($D50_p$) and subsurface fine sediment content ($\%fines_{sp}$) at potential spawning sites along the surveyed segments were obtained by bulk sampling (Kondolf *et al.,* 2003). Sites were selected according to two criteria. First, riffle sites in close proximity to log jams, fallen trees, back channels, unusually wide or narrow riffles, and other obstructions or abnormalities were avoided, as these obstacles can affect the substrate's sediment distribution, but cannot be explicitly attributed to harvesting operations. Second, the estimated $D50_p$ value of potential sample sites had to be between 15 and 150 mm (Bjornn and Reiser, 1991; Bardonnet and Baglinière, 2000).

To bulk sample, a flow isolation cell was placed in the thalweg of the river bed, slightly upstream of the riffle crest (as described in Kondolf *et al.*, 2003). Once in place, the UTM coordinates of the cell's location were recorded to identify the sampling sites on the 1:20000 digital model of the Cascapédia watershed provided by the MNR. The cell slowed the current, while still allowing it to flow through the coarse net (4 mm) in its upstream end. A fine-mesh net (63 µm) at the downstream end of the cell would catch disturbed fines when sediment was removed from the bed. The cell was placed to minimise sediment from escaping along its contact with the river bed. Spaces between the cell and the river bed were filled with rocks or sand bags to minimise sediment loss. Despite this measure, some medium and fine sand particles $<$ 500 µm are often washed away during sampling. Zimmermann (2003) compared bulk and freeze-core samples taken in the Cascapédia and found the samples of the latter had 6% more sediment $<$ 2 mm, especially fines $<$ 500 µm. Therefore, the fine sediment values obtained in this dataset are conservative estimates of the amount of fines found in each riffle.

Bulk sampling was carried out in two steps. First, the pavement (surface) of the bed was removed. This included all sediments found to the depth of the D84 (bed material size for which 84% of the sediment is finer), which was approximated visually prior to digging. The presence of algae and moss on the sediment was also used to identify surface sediment. The amount of sediment removed from the surface ranged from 10 to 35 kg (i.e. one or two 12-L buckets of sediment), varying in proportion to the size of the sediment. The sediment was sieved to half-phi classes (32, 48, 64, 90, 128 and $>$ 128 mm) in the field and weighed, removing any water in the samples. A 1 to 2 kg sample of the remaining sediments $<$ 16 mm was bagged and taken to the lab to be sieved further. Once the surface was removed and sieved, the procedure was repeated for the subsurface. Total sample sizes ranged from 50 to 100 kg (i.e. six to eight buckets), depending on the size of the riffle sediment, well above the suggested 32 kg sample size of Kondolf *et al.* (2003).

In the lab, the 1 to 2 kilogram sediment samples ‹ 16 mm saved from the bulk samples were sieved to 16, 8, 4, 2, 1 mm, 500, 250, 125, 63, and ‹ 63 μm classes. Each size class was weighed and prorated to the total amount of sediment ‹ 16 mm for its site. The weights of all 16 size classes (‹ 63 μm to › 128 mm) were converted to proportions of the total sample size to produce the sediment size distribution. This was used to calculate the median sediment diameter of the pavement and subpavement ($D50_p$ and $D50_{sp}$) and the percentage of fines in the subpavement ($\%fines_{sp}$). The armouring ratio was also calculated ($D50_p$:$D50_{sp}$) as an indication of the coarseness of the surface versus the subsurface (Knighton, 1984).

During the 2002 field season, the surface and subsurface were sampled together. Consequently, no $D50_p$ was available for these sites. In 2003, the pavements of the 2002 sites were re-sampled to obtain their $D50_p$. The 2002 D50 was then used as $D50_{sp}$. The 2002 $D50_{sp}$ may be slightly larger than the 2003 $D50_{sp}$ because the former includes pavement sediments. However, this difference is judged to be minimal since the 2002 samples consisted mostly of subsurface sediment. In 2002, 10 to 15% (one to two buckets) of the sampled sediment was from the pavement and 85 to 90% of the sample came from the subsurface. To illustrate the minimal differences between the 2002 D50 and 2003 $D50_{sp}$, the pavement and subpavement of four 2002 sites were re-sampled in 2003, showing a maximum difference of 6 mm (Table 13).

Table 13. Comparison of 2002 surface D50 and 2003 subsurface D50 ($D50_{sp}$) for selected sites.

Site	2002 D50 (mm)	2003 $D50_{sp}$ (mm)	difference in size
H05	16	15	1 mm
H08	13.5	11.5	2 mm
L12	9	9.7	0.7 mm
B06	50	44	6 mm

VII.2.2 Delineation of watershed boundaries in a GIS and statistical analysis

Once collected, the field data were entered into the digital database. Each site's UTM coordinates were reprojected into MTM (Quebec's 1:20000 map projection and the projection of the layers of the database) using ArcView's Projection Utility, and were then added as a layer to the model. Each site's watershed was delineated using

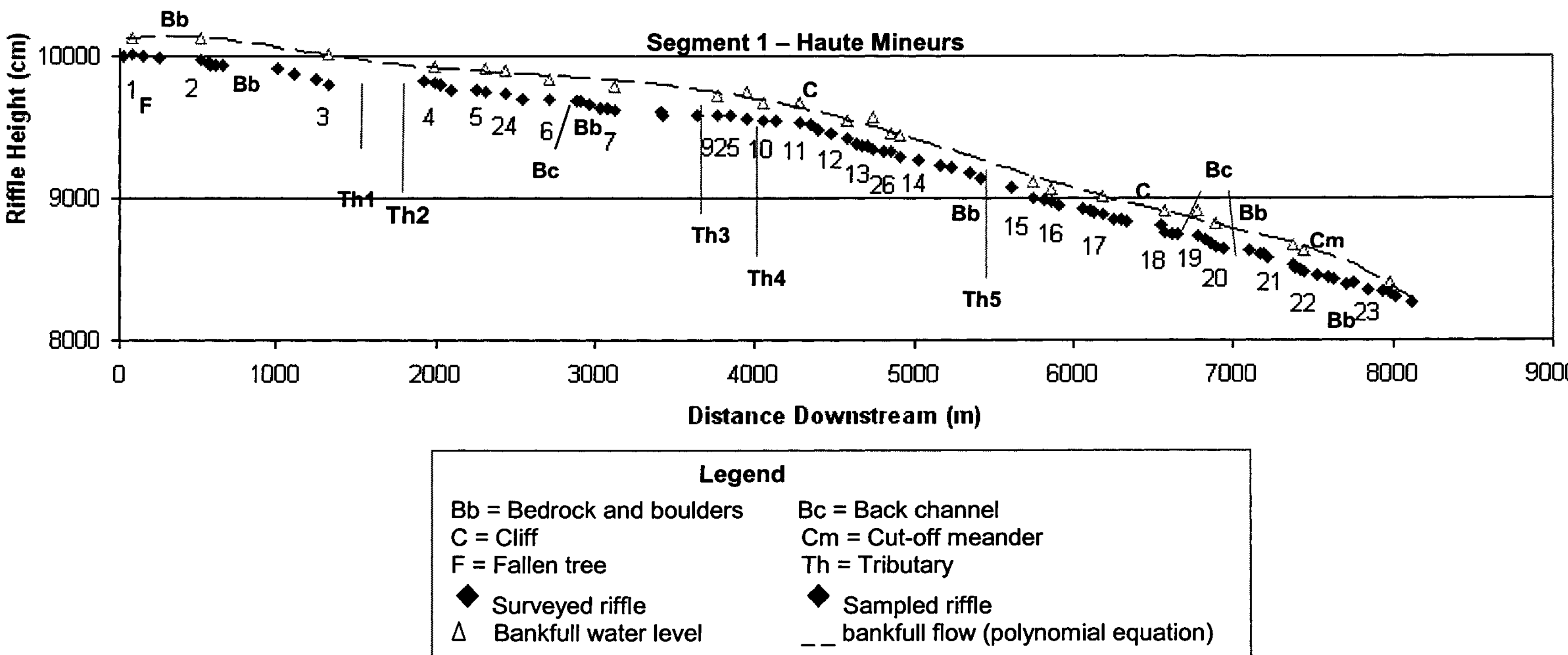
ArcView's Hydro extension and its area was calculated. The geology layer in the database was used to calculate the % of all geology deposits present in each watershed.

A statistical analysis similar to the one discussed in Chapter V (between stream width and large-scale landscape structure variables) was run for the mainstem segments in order to determine the relation between large-scale landscape structure and reach-scale variables and sedimentology. A database including the observed and estimated variables was created. Linear regressions were run separately between the two habitat variables ($D50_p$ and $\%fines_{sp}$) and large-scale landscape structure variables (basin area and geology), as well as reach-scale variables (local channel bed slope, local water surface slope, local shear stress, channel bankfull width, and point bar width). The results from this analysis are shown in the next section. For the sake of clarity and brevity, only relations with a $P < 0.10$ are shown in the tables, although relations are considered significant only if they are theoretically sound and their $P < 0.05$. Appendix V shows all the tested models. The residuals from the regressions that produced the strongest, significant relations were saved and are used in Chapter VIII to determine if harvesting is related to the remaining variance in $D50_p$ and $\%fines_{sp}$.

VII.3 Results

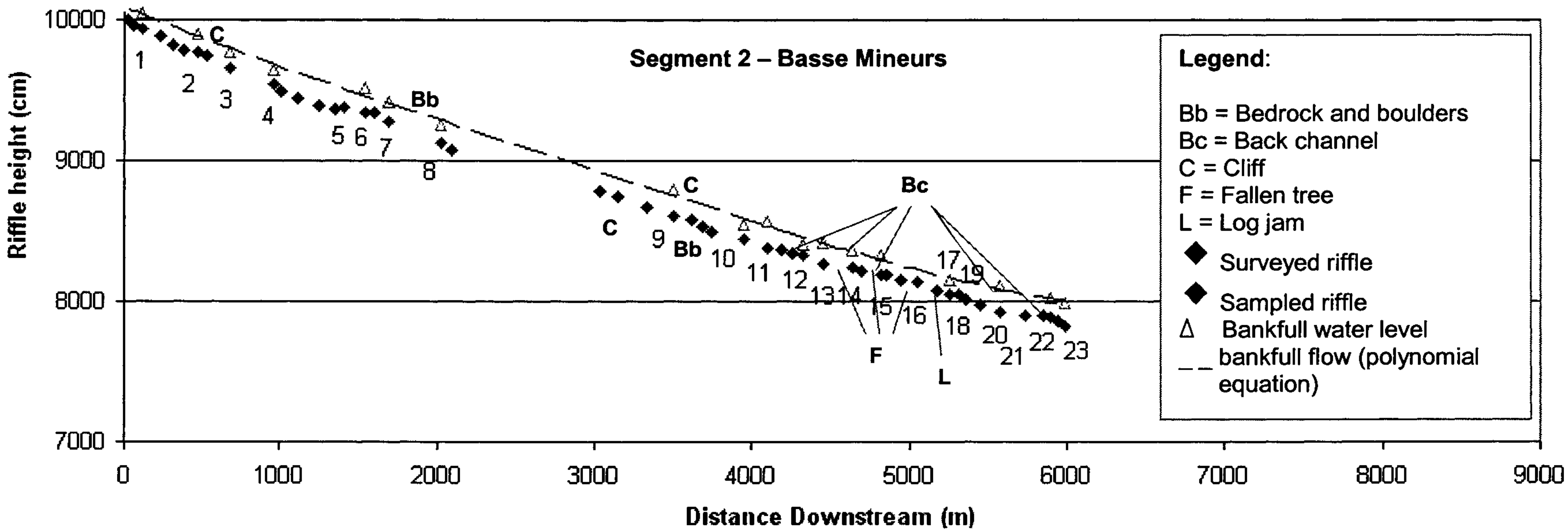
VII.3.1 Using reach-scale variables to explain downstream trends in sedimentology

The following section discusses the characteristics of each segment's river bed and bankfull flow long profiles that affect the sediment transport regime within the segment (Figure 24). Included in the discussion are the general trends observed in $D50_p$, $\%fines_{sp}$, and shear stress (Figure 25), which allows an assessment of the pattern of each segment's fine sediment and mean pavement size by considering the natural variables affecting these. Each segment is discussed separately.



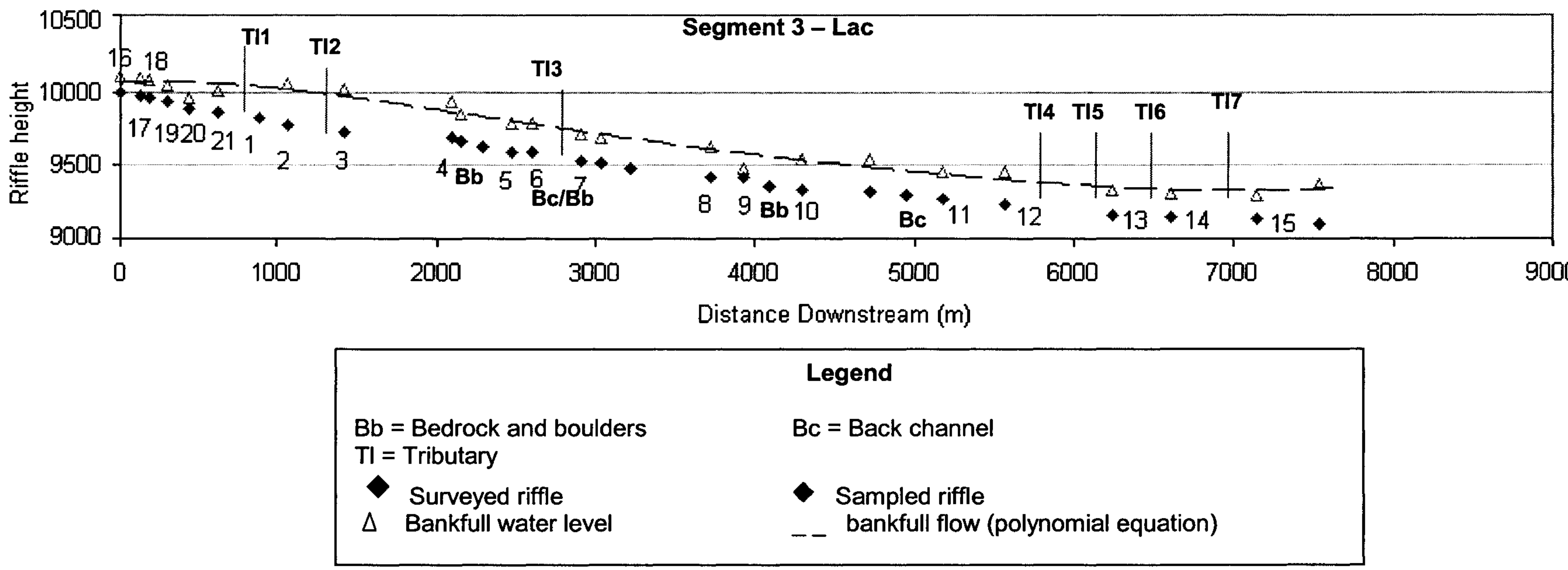
Site	H1	H2	H3	H4	H5	H24	H6	H7	H8	H9	H25	H10	H11	H12	H13	H26	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23
D50P (mm)	91	94	na	77	52	33	14	21	38	36	23	23	100	95	85	68	56	42	97	70	54	71	108	37	84	88
FinesSP (%)	14	12	16	8	16	8	17	19	23	17	15	12	5	5	7	9	7	7	8	15	5	5	6	4	10	6
Armour ratio	2.6	2.7	na	4.5	3.5	1.2	2.3	3.4	2.7	1.4	1.6	1.3	2.1	0.9	0.6	1.4	2.6	0.9	2.0	2.8	0.7	2.5	1.5	1.5	2.0	2.2
Shear stress estimates (Pa)																										
SS2	5	14	11	4	5	22	14	17	9	8	18	18	12	52	45	36	41	43	26	51	32	40	48	74	48	28
SS4	11	15	17	10	22	16	23	19	14	10	14	20	30	47	62	40	43	40	34	33	33	66	44	57	54	29
LSSS	24	23	26	18	19	19	22	21	21	20	27	27	36	37	39	52	52	42	40	44	52	50	50	51	47	38
PSS	1	19	19	16	18	19	21	22	19	14	12	10	35	52	58	61	61	32	29	25	31	40	46	66	65	21

Figure 24a. Long profile of river bed and estimated bankfull flow, showing riffles, tributaries, and natural variables affecting the sediment transport regime within segment 1. The table shows the median surface diameter ($D50_p$), subsurface fine sediment content ($\%fines_{sp}$), armour ratio, and shear stress estimates for each sampled riffle.



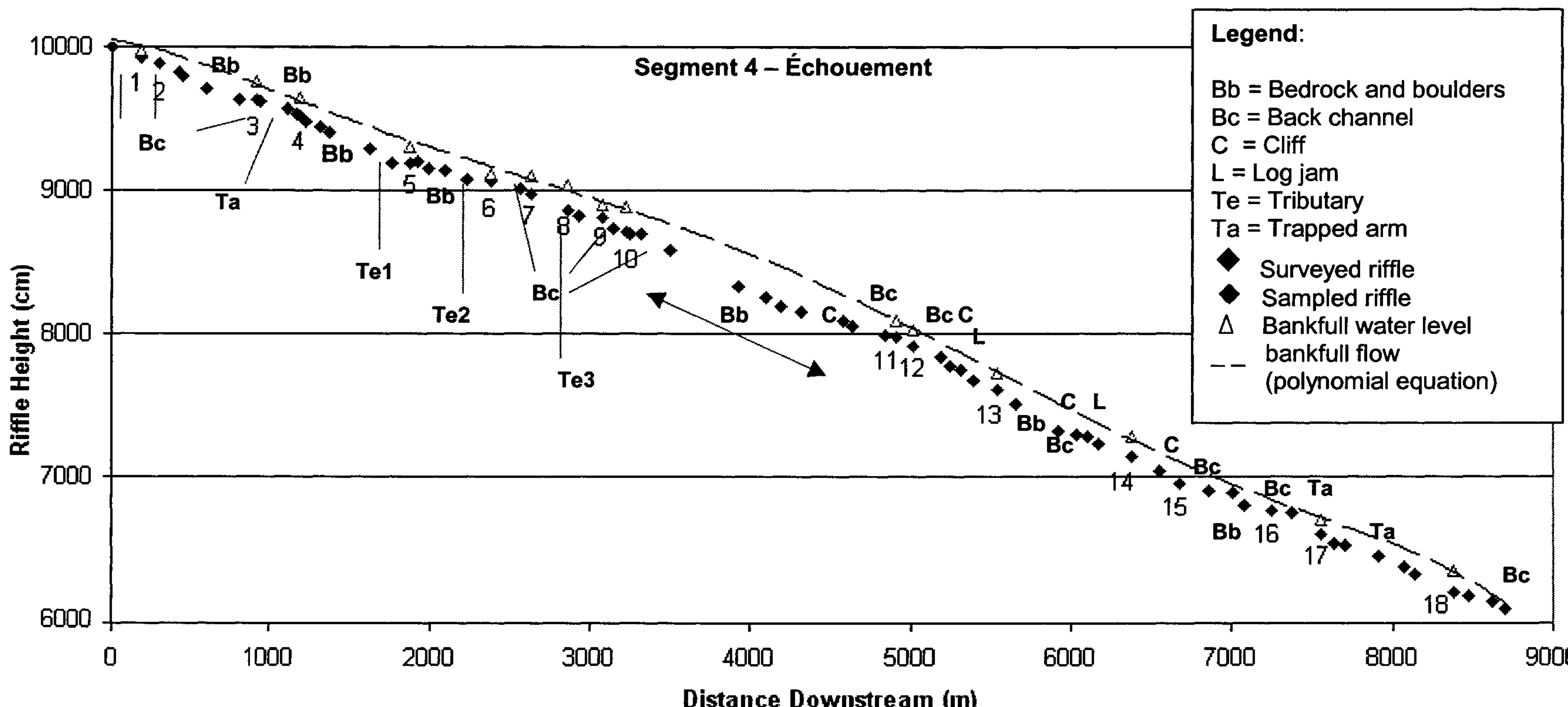
Site	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22	B23
D50P (mm)	101	157	105	79	76	130	104	106	82	122	74	84	119	64	19	21	34	55	50	45	72	54
FinesSP (%)	2	7	2	5	9	6	3	3	8	10	1	5	12	8	10	6	3	8	8	10	7	9
Armour ratio	1.8	5.5	0.8	1.7	3.4	3.0	1.7	1.0	1.6	2.0	1.4	1.2	3.7	1.4	1.3	0.5	0.7	1.8	1.4	1.1	1.3	1.5
Shear stress estimates (Pa)																						
SS2	71	51	57	51	21	41	69	58	60	58	40	33	39	38	43	41	37	66	43	32	48	103
SS4	59	57	51	43	48	59	50	55	53	62	38	30	40	40	37	37	32	54	49	53	42	48
LSSS	61	53	38	40	58	64	55	45	62	62	43	41	31	41	37	42	44	46	48	39	40	43
PSS	63	56	53	50	50	50	52	55	56	49	42	40	38	36	34	33	33	33	34	35	38	40

Figure 24b. Long profile of river bed and estimated bankfull flow, showing riffles, tributaries, and natural variables affecting the sediment transport regime within segment 2. The table shows the median surface diameter ($D50_p$), subsurface fine sediment content ($\%fines_{sp}$), armour ratio, and shear stress estimates for each sampled riffle.



Site	L16	L17	L18	L19	L20	L21	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
D50P (mm)	36	27	42	51	34	16	88	108	55	44	49	62	97	50	97	35	67	25	51	104	65
FinesSP (%)	15	9	14	9	14	10	8	9	4	10	14	3	6	8	13	7	16	26	15	9	3
Armour ratio	1.4	1.2	2.4	2.3	1.4	0.7	1.4	4.1	1.6	1.9	2.5	1.8	1.5	1.6	3.0	1.3	4.2	2.6	2.3	1.8	2.4
Shear stress estimates (Pa)																					
SS2	25	26	31	24	22	34	34	27	33	25	35	31	27	25	17	23	19	18	13	12	8
SS4	31	26	25	22	21	24	32	34	38	29	27	33	26	22	18	22	15	15	14	13	12
LSSS	13	14	15	12	14	13	5	15	16	51	44	42	40	28	18	18	19	19	18	17	16
PSS	1	4	5	8	13	18	24	27	31	33	33	32	31	26	25	22	16	14	13	14	16

Figure 24c. Long profile of river bed and estimated bankfull flow, showing riffles, tributaries, and natural variables affecting the sediment transport regime within segment 3. The table shows the median surface diameter ($D50_p$), subsurface fine sediment content ($\%fines_{sp}$), armour ratio, and shear stress estimates for each sampled riffle.



Site	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18
D50P (mm)	98	86	74	71	31	70	121	103	88	33	107	87	109	na	86	62	85	33
FinesSP (%)	13	22	8	9	14	7	10	9	7	17	9	14	7	6	2	6	6	7
Armour ratio	4.3	1.6	3.3	3.5	2.2	2.7	5.3	3.8	2.7	3.2	4.3	5.4	4.4	na	1.3	1.6	3.6	1.3
Shear stress estimates (Pa)																		
SS2	39	52	37	77	55	32	59	55	50	89	40	59	88	86	61	20	37	52
SS4	43	42	62	58	54	39	52	62	43	89	41	55	85	76	60	16	37	55
LSSS	57	66	94	104	34	28	34	40	74	74	57	51	53	53	59	57	52	62
PSS	42	48	53	50	43	45	49	53	58	62	93	92	82	58	58	47	48	60

Figure 24d. Long profile of river bed and estimated bankfull flow, showing riffles, tributaries, and natural variables affecting the sediment transport regime within segment 4. The table shows the median surface diameter ($D50_p$), subsurface fine sediment content ($\%fines_{sp}$), armour ratio, and shear stress estimates for each sampled riffle.

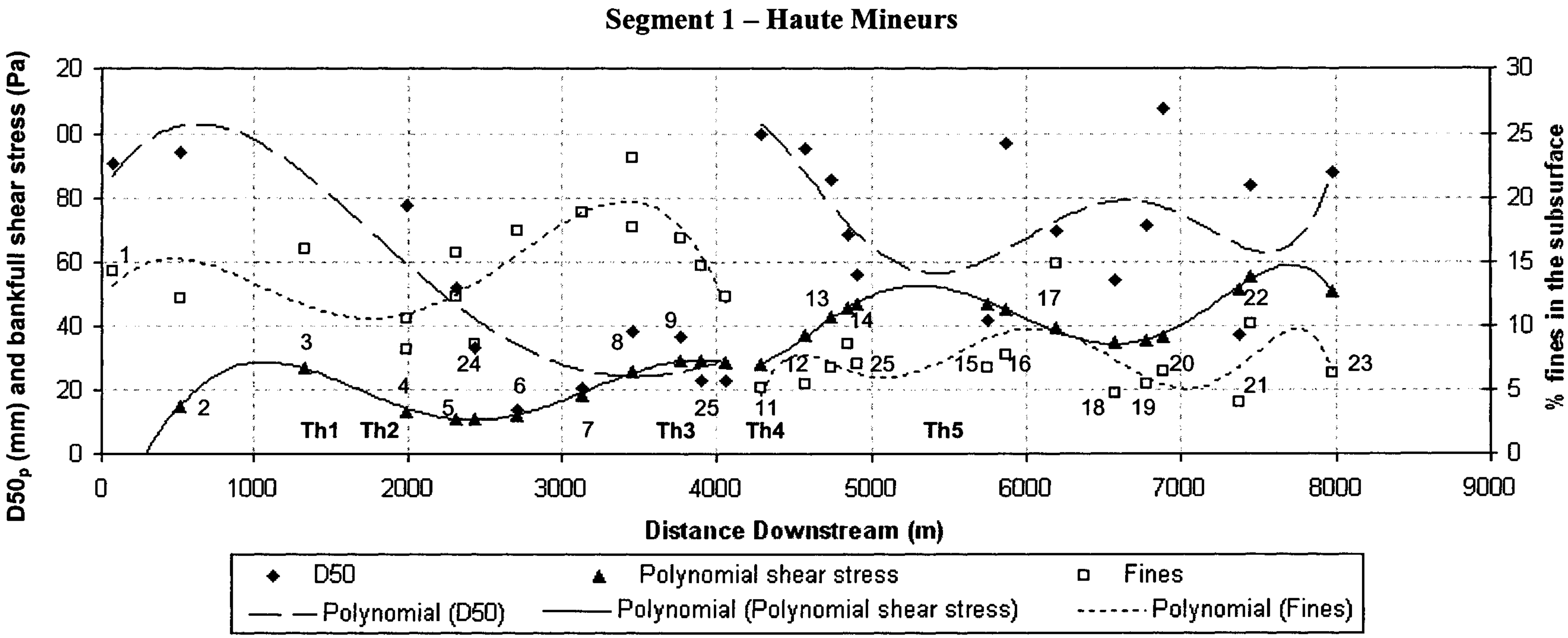


Figure 25a. Downstream changes in pavement D50 ($D50_p$), subsurface fine sediment content ($\%Fines_{sp}$), and shear stress for segment 1.

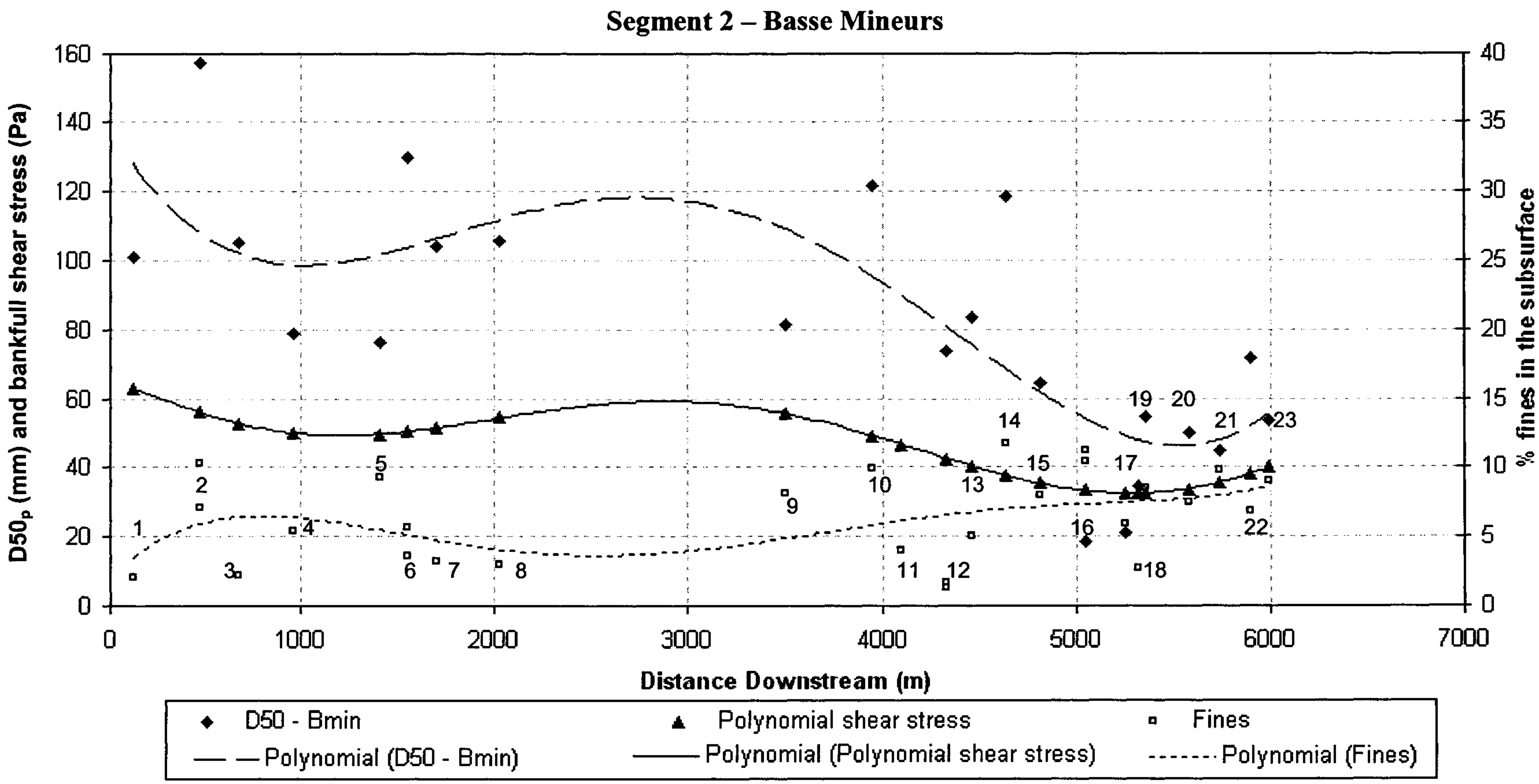


Figure 25b. Downstream changes in pavement D50 ($D50_p$), subsurface fine sediment content ($\%Fines_{sp}$), and shear stress for segment 2.

Segment 3 – Lac

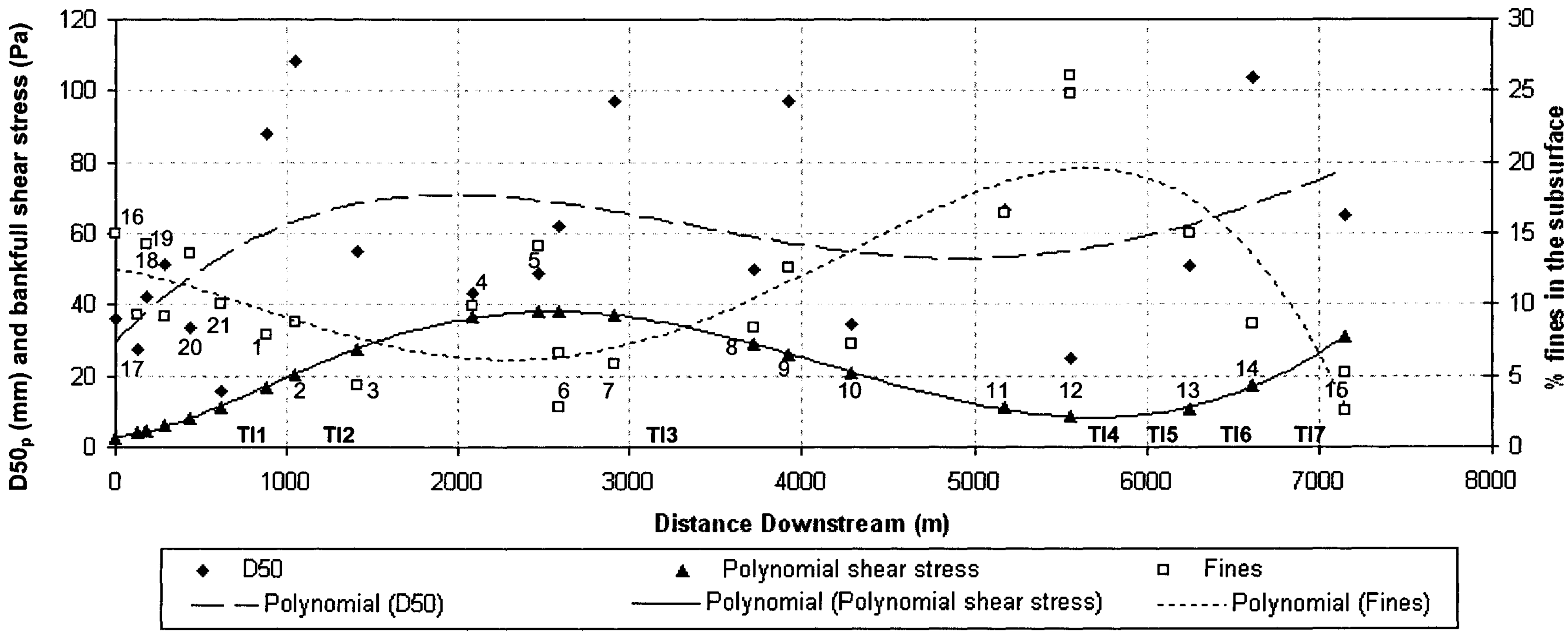


Figure 25c. Downstream changes in pavement D50 ($D50_p$), subsurface fine sediment content ($\%Fines_{sp}$), and shear stress for segment 3.

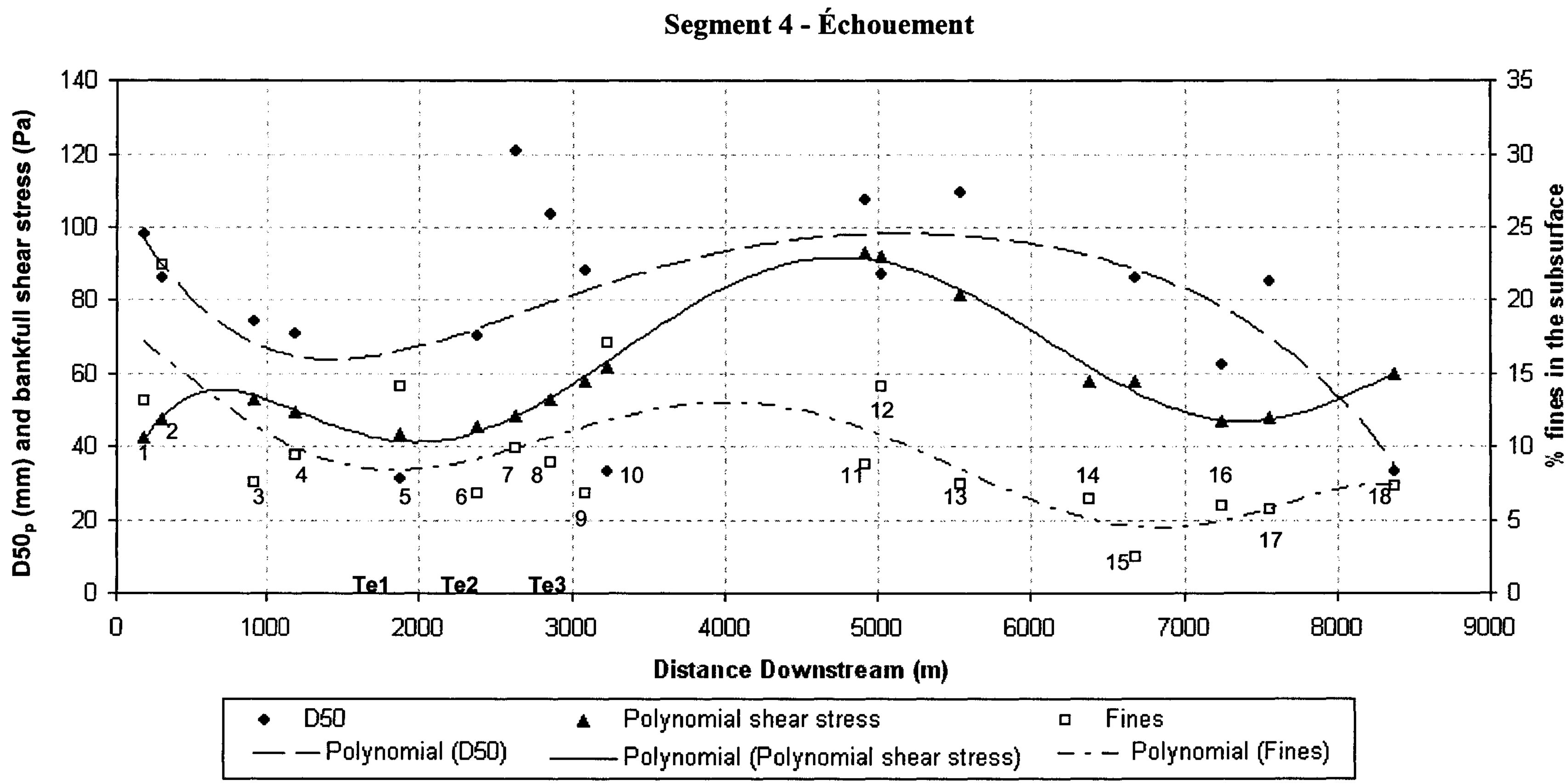


Figure 25d. Downstream changes in pavement D50 ($D50_p$), subsurface fine sediment content ($\%Fines_{sp}$), and shear stress for segment 4.

Segment 1. In segment 1, there is an increase in channel slope downstream of H11 (4300 m) (Figure 24a), where the slope doubles from 0.001 to over 0.002. H11 also coincides with the presence of a cliff to the right of the bend of the river. However, the cliff is a local disturbance and does not explain the maintained increase in slope. The slope increases more likely because of the abundance of bedrock downstream of H11, which makes it difficult for the river to adjust its shape and slope to flow (Trenhaile, 1998). According to Lane's Law, when discharge is constant, the sediment transport rate (Q_s) or size (D_s) increase to compensate for the increase in slope. Lane's Law is given as:

$$Q_sD_s \approx QS \qquad (5)$$

Q_s is the sediment discharge, D_s is the sediment size, Q is discharge, and S is stream slope (FISRWG, 1998). Indeed, sediment size increases from an average of 46 mm upstream of H11 to an average of 75 mm downstream as a consequence of the greater slope and increased sediment transport capacity (Figure 24a, Figure 25a). There are also fewer fines in the steeper half of segment 1 (7%) than in the first half (14.5%). This is consistent with both Lane's Law and the estimated shear stresses (Figure 25a), which are higher in the second half of segment 1. (To simplify Figure 25, only one shear stress trend is shown since all four trends are similar (Figure 26)). However, discharge is not constant along segment 1, being increased by tributary Th4 (Figure 24a), which should decrease slope at a constant Q_S. The increased sediment size below Th4 indicates either a reduction in fine sediment supply or an increase in the supply of large sediment.

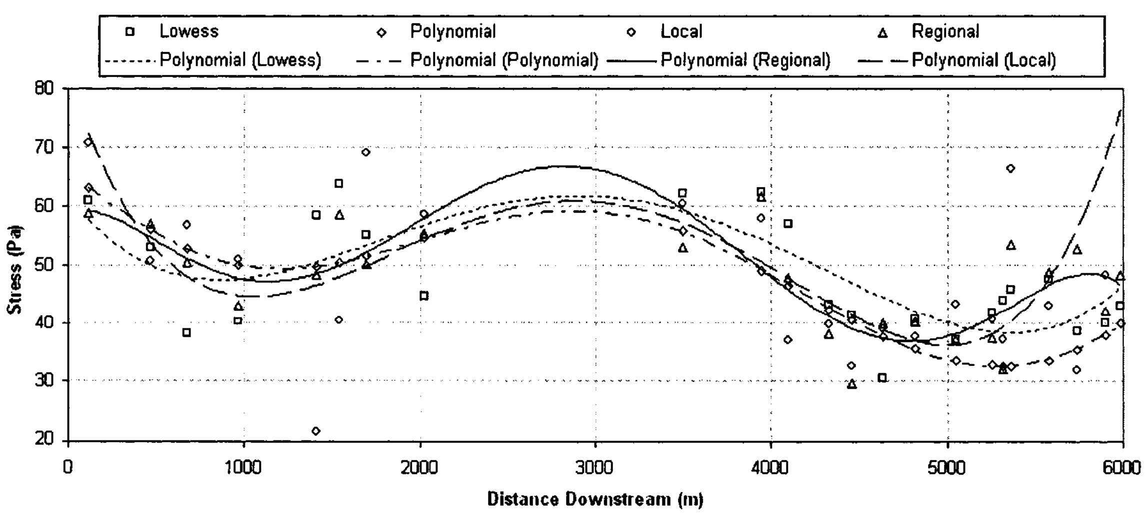


Figure 26. Variations in the four shear stress estimates (local, regional, Lowess, and polynomial) along segment 2 – Basse Mineurs.

There are nine sites along this segment with $\%fines_{sp}$ close to or above the 15% threshold considered to represent mediocre habitat (H01, 03, 05 to 09, 25, and 17) (Figure 24a, Figure 25a) (Petersen and Metcalfe, 1981). Possible reasons for these high values are discussed briefly below. While tributaries can inject fine sediment into mainstem segments, these are not responsible for the increase in subsurface fine sediment found in segment 1 because the increases in $\%fines_{sp}$ are upstream of the tributaries. Deposition may increase when there is a decrease in slope, which is followed by a decrease in shear stress (Gordon *et al.,* 1992). The channel slope along segment 1 is milder upstream of 4300 m, being mildest at sites H07 to 10 and 25, sites which also experience a decrease in D50. This may explain the higher $\%fines_{sp}$ found at these sites, as well as at site H01 (Figure 24a, Figure 25a). The high fine sediment content at H06 may be related to its smaller D50. The $D50_p$ at sites H05 and H17 are unlikely to explain the higher $\%fines_{sp}$ at these sites, given that sites with similar $D50_p$ values have much lower fine sediment contents. Furthermore, H17 has some of the highest estimated shear stresses in the entire segment, which should be able to dislodge fine sediments from the river bed. The $D50_p$ of H03 is not available; therefore, it is impossible to establish if it explains this site's high fine sediment content. Therefore, no natural variable explains the high subsurface fine sediment contents found at H03, 05 and 17. Particular attention will be paid to these sites in Chapter VIII to determine if harvesting intensity is related to their high $\%fines_{sp}$.

Segment 2. This is the shortest of the four segments (6 km) and the only segment with no tributaries (Figure 24b). Its overall segment slope of 0.0036 experiences no sharp breaks, as did segment 1 at 4300 m. Rather, there is a slight decrease in channel slope in the downstream direction, which forms a concave profile (Figure 24b). The slopes downstream of B12 are slightly below the segment average of 0.0036, varying between 0.002 and 0.0035. Two bedrock sections occur in straight reaches within the upper 4 km of the segment (e.g. between B07 and 08, Figure 24b). Downstream of kilometre 4, the channel meanders more regularly, despite a higher occurrence of fallen trees in the channel and log jams on the banks. Following from a decrease in shear stress and the armouring ratio, the average $D50_p$ is smaller (58 mm) downstream of km 4.2 (B12) than in the upstream sector (104 mm). The difference in $\%fines_{sp}$ is not as substantial (7% downstream of B12 versus 5.6% upstream) (Figure 25b). Figure 25b also illustrates how

$D50_p$ and shear stress vary together and the fine sediment content of the subsurface varies in the opposite direction, as it should (Gomez, 1995; Rosgen, 1996).

None of the sampled sites along segment 2 have fine sediment content values above 15% (Figure 24b, Figure 25b). Concurrent with theory, there is a slight increase in the riffle fine sediment content in the downstream direction, which corresponds to the downstream decrease in $D50_p$ and shear stress (Figure 2, Church, 1996). Thus, the surface D50 and substrate fine sediment trends in segment 2 are explained by the reach-scale variables and nothing suggests that the potential spawning habitat along this segment has degraded below acceptable levels.

Segment 3. The bed slope of this segment is steepest in the first 1000 m and becomes milder downstream due to the increased discharge from the Mineurs (Tl1) and Échouement (Tl4) tributaries, which enter downstream of L21 and L12, respectively (Figure 24c). With an average stream slope of 0.001, this segment has the mildest segment slope (0.0021 for segment 1, 0.0036 for segment 2, and 0.0045 for segment 4) and the greatest basin area (823 km^2), consistent with theoretically predicted downstream adjustments in channel form (Figure 2) (Brookes, 1996; Church, 1996; FISRWG, 1998). Theoretical models also show that shear stress and D50 values often vary in tandem, as they do for the most part in this segment (Figure 25c). Despite having steeper slopes, L16 to L21 have smaller $D50_p$ and lower shear stress values than the sites downstream of the junction with Mineurs ($D50_p$ of 34 mm versus 66 mm, respectively) (Figure 25c), which may be due to the lower discharge associated with their smaller basin area (200 km^2 versus 580 km^2, respectively). There are three short sections of bedrock outcrops along the middle third of Segment 3 (Figure 24c).

Seven sites along segment 3 have fine sediment contents close to or above 15% (L16, 18, 20, 05, and 11 to 13). L16, 18, and 20 may have high $\%fines_{sp}$ because they are situated immediately downstream of a lake, where water velocities are usually slower. Therefore, shear stresses are low (as seen in Figure 24c and Figure 25c) and allow fine sediments to deposit. However, most of the fine sediments should have deposited in the lake prior to reaching the stream. The higher fine content found at L05 is not explained by a smaller

$D50_p$, the presence of a tributary, or a decrease in shear stress. Thus, there may be an anthropogenic reason for the increase in fines at this site. The regional increase in fines between L11 and L13 may be explained by the decrease in shear stress (Figure 24c, Figure 25c). The high fine sediment content of L12 (26%) is explained by its wider riffle (54 m versus a 36 m average for the segment). An increase in width at a constant discharge decreases velocity and shear stress (Gordon *et al.,* 1992), which can increase sediment deposition. The channel slope also decreases at the downstream end of the segment (Figure 24c). There are three possible reasons for this. The first is the presence of four tributaries downstream of L12 which increase discharge and should be followed by a reduction in slope (Church, 1996; Rosgen, 1996), entailing a rise in fine sediment deposition. Secondly, the abundance of bedrock outcrops and steeper slope found downstream of L15 may be responsible for a trend similar to the one at H11 (segment 1), where bedrock outcrops decrease the slope from L12 to L15. This can lead to an increase in the fine sediment content. Thirdly, the increase in fines begins at L08, which is approximately 250 m downstream of tributary T13. T13 may be injecting sediment into the mainstem, where it deposits, especially in areas of low slope (such as L12).

Segment 4. Segment 4 has the steepest slope of the four segments (0.0045). It has a few short reaches where the slope becomes milder, only to increase again further downstream (e.g. between E03 and E04 and for the three riffles downstream of E10). It also has the highest frequency of log jams, cliffs, and back channels (Figure 24d). The shear stress and armouring ratio peak between E10 and E13, where the bedrock outcrops are most frequent (Figure 24d, Figure 25d). However, unlike the theoretical models, the $\%fines_{sp}$ are not lower in this section of higher shear stresses (Gordon *et al.,* 1992). This may be due to the bedrock outcrops and large woody debris, which can affect how the stream adjusts to changes in sediment production or transport (Trenhaile, 1998; Faustini and Jones, 2003). However, there are no large jams in the vicinity of E09 (at 3000 m), where shear stress increases. There are three sections along segment 4 where large woody debris has trapped a portion of the stream and redirected its flow (labelled Ta in Figure 24d). Woody debris can impede sediment transport by creating deposition zones upstream of its location and increasing degradation downstream (Hauer *et al.,* 1999). LWD also increases particle size heterogeneity and widens channels (Faustini and Jones, 2003), thereby affecting theoretical downstream adjustments of channel form. Despite this theory, none of the sites surrounding these jams have high fine sediment contents.

Along segment 4, there are four riffles with fine sediment contents close to or above 15% (E02, 05, 10, and 12). The increase in fines at these sites is local (i.e. no two consecutive riffles have a fine content at or above the 15% threshold). The high level at E02 (22%) is not explained by a low $D50_p$, low shear stress, or reduced slope (Figure 24d, Figure 25d). In fact, E03 and 04 both have lower $D50_p$ and shear stress values as well as lower $\%fines_{sp}$. The tributary located a few hundred metres upstream of E01 (not shown in Figure 24d) could be injecting fines into the stream, although if this is the case it should also affect the fine sediment content of E01. Tributary Te1 may be injecting fine sediments and increasing the $\%fines_{sp}$ at E05 (Figure 24d). The higher fine sediment contents of E05 and 10 can be attributed to their lower $D50_p$ values (31 and 33 mm, respectively) when compared to the range of the surrounding sites (70 to 107 mm) (Figure 24d, Figure 25d). However, the high $\%fines_{sp}$ and low $D50_p$ at E10 remain intriguing, given the relatively large estimated shear stress at this site. Finally, the high fine sediment content of E12 is not explained by a reduction in slope, shear stress, or $D50_p$. Therefore, no reach-scale variable explains the high fine sediment content of E02 and E12.

VII.3.2 Analysis of the determinants of variations in pavement D50

This section tests the relation between each site's $D50_p$ and the large-scale landscape structure variables basin area and basin geology, as well as the reach-scale variables channel slope, shear stress, channel width, and average point bar width. The objective is to establish how variations in $D50_p$ can be associated to changes in these variables. $D50_p$ is used rather than $\%fines_p$ because the latter are difficult to obtain via bulk sampling methods. Once the top sediment layer is removed, the water becomes cloudy with sediment, making it difficult to distinguish between surface and subsurface fines. Sediment loss also reduces the measured $\%fines_p$, further reducing the already small amount of fines found in the pavement. Because each segment has its own pattern of variables (see Figure 24, Figure 25, and section VII.3.1), each is analysed independently.

The $D50_p$ distributions and ranges in shear stress and slopes of each segment are shown in Table 14. The range in $D50_p$ values varies from a low of 90 mm in segment 4 to a high of 138 mm in segment 2 (Table 14). Despite this range, the means of the four segments are similar (57 to 80 mm). The range in area of segments 1, 2, and 4 is roughly 30 km^2 (9 to 17% of the segment's total basin area). The range is greater for segment 3 (575 km^2) because two major tributaries, Mineurs (340 km^2) and Échouement (230 km^2), discharge into Lac branch, upstream of L01 and L12 (Figure 24). Ideally, segment 3 should be divided into three segments, one for each range in basin area, but this was not possible given the paucity of sites in the smallest (n = 6) and largest (n = 3) area classes. Hence, the 21 sites located along segment 3 are studied together.

Table 14. Distribution of surface D50 and range in basin area, slope, and shear stress estimates for each study segment along the Cascapédia.

Segment	1	2	3	4
Surface D50 (mm)				
# of cases	25	22	21	17
Minimum	14	19	16	31
Maximum	108	157	108	121
Mean	62	80	57	79
Area (km^2)	134-177	318-337	247-823	185-213
Range in slope (all slopes)	0.000 - 0.007	0.002 - 0.007	0.000 - 0.003	0.003 - 0.008
Range in shear stress (SS) in Pa	5-73	18-110	2-51	16-104

Changes in $D50_p$ due to large-scale landscape structure variables

The analysis begins by testing for a relation between basin area and $D50_p$. Theoretical models for downstream adjustments in channel form predict that an increase in basin area is accompanied by a decrease in bed material grain size (Brookes, 1996; Church, 1996; FISGRW, 1998). However, this trend did not emerge in all four segments (Table 15, Appendix V). Firstly, there is no significant relation between $D50_p$ and basin area in segments 1 and 4, which is supported by the work of Thompson and Hoffman (2001), who studied watersheds with areas ranging from 10 to 365 km^2 and found no relation between basin area and D50. Secondly, segments 2 and 3 have significant relations, but these are in opposite directions (Table 15). The trend in segment 2 follows the theoretical negative relation between the two variables (Brookes, 1996; Church, 1996) ($r^2 = 0.27$, P <

0.01). In contrast, segment 3 has a positive relation between basin area and $D50_p$ (r^2 = 0.31, P < 0.005). While this may be because theoretical models apply to large changes in basin area (i.e. from a first to a seventh order stream), and not along a single segment where the change in area averages 20 km^2 as in segments 1, 2, and 4, the change in area in segment 3 is considerable (almost 600 km^2, Table 14). Thus, it should follow the theoretical model. Moreover, the fact that the models in segments 2 and 3 are in opposite directions creates doubt regarding the accuracy and relevance of basin area as a predictor of $D50_p$. Similarly, no significant, theoretically sound results were obtained for the geology categories (Appendix V).

Table 15. Models of surface D50 ($D50_p$) versus basin area for the four study segments. * indicates a significant relation at $\alpha = 0.05$.

Site	Equation	r^2	P
$D50_p$ versus basin area			
Segment 1 – Haute Mineurs	$0.002 \cdot \text{Area}^{2.01}$	0.086	0.084
Segment 2 – Basse Mineurs	$\mathbf{2.6 \cdot 10^{38} \cdot Area^{-14.51}}$	**0.271**	**0.008***
Segment 3 – Lac	$\mathbf{0.83 \cdot Area^{0.67}}$	**0.314**	**0.005***
Segment 4 – Échouement	$485 \cdot \text{Area}^{-0.36}$	0.000	0.873

Relation between $D50_p$ and reach-scale variables

Of the four reach-scale variables tested (slope, shear stress, channel width, and point bar width), only the first two yielded significant relations (Table 16, Table 17, and Appendix V). Theoretically, D50 and slope vary in tandem (Thompson and Hoffman, 2001). Of the four slopes modelled (local, regional, lowess, and polynomial), polynomial slope (PS) has the strongest and most significant relation to $D50_p$. This may be because it represents the slope of the water surface, when the water's velocity and shear stresses are highest (Table 16). If this is the case, polynomial shear stress should also be related to variations in $D50_p$. Bankfull flows are most capable of moving sediment (Sweet and Geratz, 2003). Local bed slope (LS2) and lowess smoothed slope (LSS) are not related to any of the variations in $D50_p$ (see Appendix V). Because these models conform to the theory, where slope and pavement D50 vary together (Table 16), they are more reliable than the models which appear to be stronger because they have a higher r^2, but are contrary to published theory (e.g. basin area).

Table 16. Models of the surface D50 ($D50_p$) versus channel slope for the four study segments. * indicates a significant model at the 5% level.

Site	Equation	r^2	P	Equation	r^2	P
	$D50_p$ versus Regional slope (LS4)			*$D50_p$ versus Polynomial slope (PS)*		
Segment 1	**$765 \cdot LS4^{0.42}$**	**0.148**	**0.033***	**$879 \cdot PS^{0.46}$**	**0.193**	**0.018***
Segment 2	$39810 \cdot LS4^{1.12}$	0.093	0.091	**$1.4{\cdot}10^{6} \cdot PS^{1.72}$**	**0.421**	**0.001***
Segment 3				**$815 \cdot PS^{0.39}$**	**0.184**	**0.030***

$D50_p$ is usually positively related to shear stress because as the latter increases, a larger number of smaller-sized particles can be transported downstream and coarser particles from the upstream portion of the channel can travel further downstream, increasing pavement D50 (Gomez, 1995; Thomson and Hoffman, 2001). Figure 26 illustrates how the general trends of the four shear stress estimates are similar, with a few differences, especially at the upstream and downstream ends of the segment. Polynomial shear stress (PSS) varies most closely with $D50_p$ in all four segments (Figure 25). Shear stress explains 55% of the variance in $D50_p$ for segment 2, 20% for segment 3, and 13% for segment 1 (Table 17). Polynomial shear stress has the strongest relation for segments 2 and 3. As with polynomial slope, polynomial shear stress represents the line of bankfull flow rather than of the bed, when sediment movement is greatest (Sweet and Geratz, 2003). This may explain its stronger relation to $D50_p$.

Table 17. Models relating surface D50 ($D50_p$) to shear stress for the four study segments. * denotes a model that is significant at the 5% level.

Site	Equation	r^2	P		Equation	r^2	P
	Regional Shear stress (SS4)				*Polynomial Shear Stress (PSS)*		
Segment 1	$18.5 \cdot SS4^{0.33}$	0.073	0.102	Segment 1	$12 \cdot PSS^{0.43}$	0.111	0.062
Segment 2	**$0.29 \cdot SS4^{1.43}$**	**0.238**	**0.012***	**Segment 2**	**$0.04 \cdot PSS^{1.96}$**	**0.553**	**0.000***
				Segment 3	**$23 \cdot PSS^{0.29}$**	**0.190**	**0.028***
	Lowess smoothed shear stress (LSSS)						
Segment 1	**$6.7 \cdot LSSS^{0.60}$**	**0.134**	**0.041***				

Once each independent variable was tested separately, multivariate models were run to determine if these could better explain the variance in $D50_p$. No combination of large-scale landscape structure or reach-scale variables yields a stronger, significant model that was theoretically substantiated for any of the segments. Therefore, polynomial slope (PS) is the strongest predictor of $D50_p$ for segment 1 (Table 16) and polynomial shear stress is the most significant model for segments 2 and 3 (Table 17). The residuals from these models were saved and are used in the analysis of Chapter VIII, where they are modelled against harvesting metrics. While some models were stronger than these (i.e. had a larger r^2), their trends were contrary to theory. Since no mechanism was found to explain these relations, they were not utilised. None of the independent variables modelled explained the variance in $D50_p$ along segment 4; thus, the original data are used in the analysis of Chapter VIII.

VII.3.3 Analysis of the determinants of variations in subsurface fine sediment content

This section studies the relation between variations in subsurface fine sediment content and the landscape structure variable basin area, as well as the reach-scale variables local stream slope, local shear stress, channel width, and local point bar width. The objective is to remove the variance in %fines that can be explained by these variables and save the residuals, which will be used to test for relations with the harvesting metrics (discussed in Chapter VIII). Again, each segment is analysed separately.

The average riffle fine sediment content ranges from a low of 6% in segment 2 to a high of 11% in segments 1 and 3 (Table 18). Segment 2 has the smallest range in %fines and is also the only segment where all sampled riffles have fine sediment contents ‹ 15%. Amounts above this are generally considered harmful to salmon reproductive success (Peterson and Metcalfe, 1981; Anderson, 1998). Twenty of the 88 sampled riffles are close to or above this (Figure 24, Figure 25). These sites were introduced in section VII.3.1.

Table 18. Distribution of subsurface D50 and fine sediment content for the four study segments located in the Cascapédia watershed.

	Subsurface D50 (mm)				Subsurface %fines			
Segment	1	2	3	4	1	2	3	4
# of sites	29	27	24	18	29	27	24	18
Minimum	9	14	9	10	4	1	3	2
Maximum	75	139	75	64	23	12	26	22
Range	66	125	66	54	19	11	23	20
Mean	34	51	32	27	11	6	11	10
Standard Deviation	21	26	18	13	5	3	6	5

Relation between %$fines_{sp}$ and large-scale landscape structure variables

The large-scale landscape structure variables basin area and geology were tested as predictors of subsurface fine sediment contents. Theoretical downstream adjustments in channel form predict a positive relation between fine sediments and basin area, given the concomitant decease in stream slope and shear stress as basin area increases (Figure 2) (Church, 1996; FISRWG, 1998). However, the significant relations found in segments 1 and 4 are negative (Table 19). This may be because the change in basin area is small in segments 1, 2, and 4 (Table 14) and does not span the change in basin area used in the theoretical models of downstream channel adjustments. Geology did not yield any theoretically sound models (Appendix V).

Relation between %$fines_{sp}$ and reach-scale variables

In addition to the reach-scale variables, local $D50_{sp}$ was also tested for its relation to fine sediment content. Theoretically, $D50_{sp}$ and %fines should be negatively related (Rosgen, 1996), which is the case with the Cascapédia dataset. While the subsurface fine sediment content is negatively related to both surface and subsurface D50, the relation is stronger for the latter (Table 19, Figure 27). The relation between %$fines_{sp}$ and $D50_{sp}$ is significant in all four segments, but it is strongly significant in segment 4 and only moderately strong in segment 2 (Table 19).

Table 19. Models relating subsurface fine sediment content to surface D50 ($D50_p$), subsurface D50 ($D50_{sp}$), and basin area for the four study segments. * indicates a significant relation.

Site	Equation	r^2	P	Equation	r^2	P
	%$fines_{sp}$ versus $D50_p$			*%$fines_{sp}$ versus $D50_{sp}$*		
Segment 1 – Haute Mineurs	**$53 \cdot D50_p^{-0.43}$**	**0.208**	**0.009***	**$79 \cdot D50_{sp}^{-0.63}$**	**0.714**	**0.000***
Segment 2 – Basse Mineurs	$14 \cdot D50_p^{-0.22}$	0.003	0.309	**$165 \cdot D50_{sp}^{-0.22}$**	**0.393**	**0.000***
Segment 3 – Lac	**$63 \cdot D50_p^{-0.49}$**	**0.139**	**0.041***	**$167 \cdot D50_{sp}^{-0.49}$**	**0.646**	**0.000***
Segment 4 – Échouement	$24 \cdot D50_p^{-0.24}$	0.000	0.448	**$248 \cdot D50_{sp}^{-1.08}$**	**0.848**	**0.000***
	%$Fines_{sp}$ vs area					
Segment 1	**$2 \cdot 10^8 \cdot Area^{-3.33}$**	**0.489**	**0.000***			
Segment 4	**$9 \cdot 10^{13} \cdot Area^{-5.7}$**	**0.278**	**0.014***			

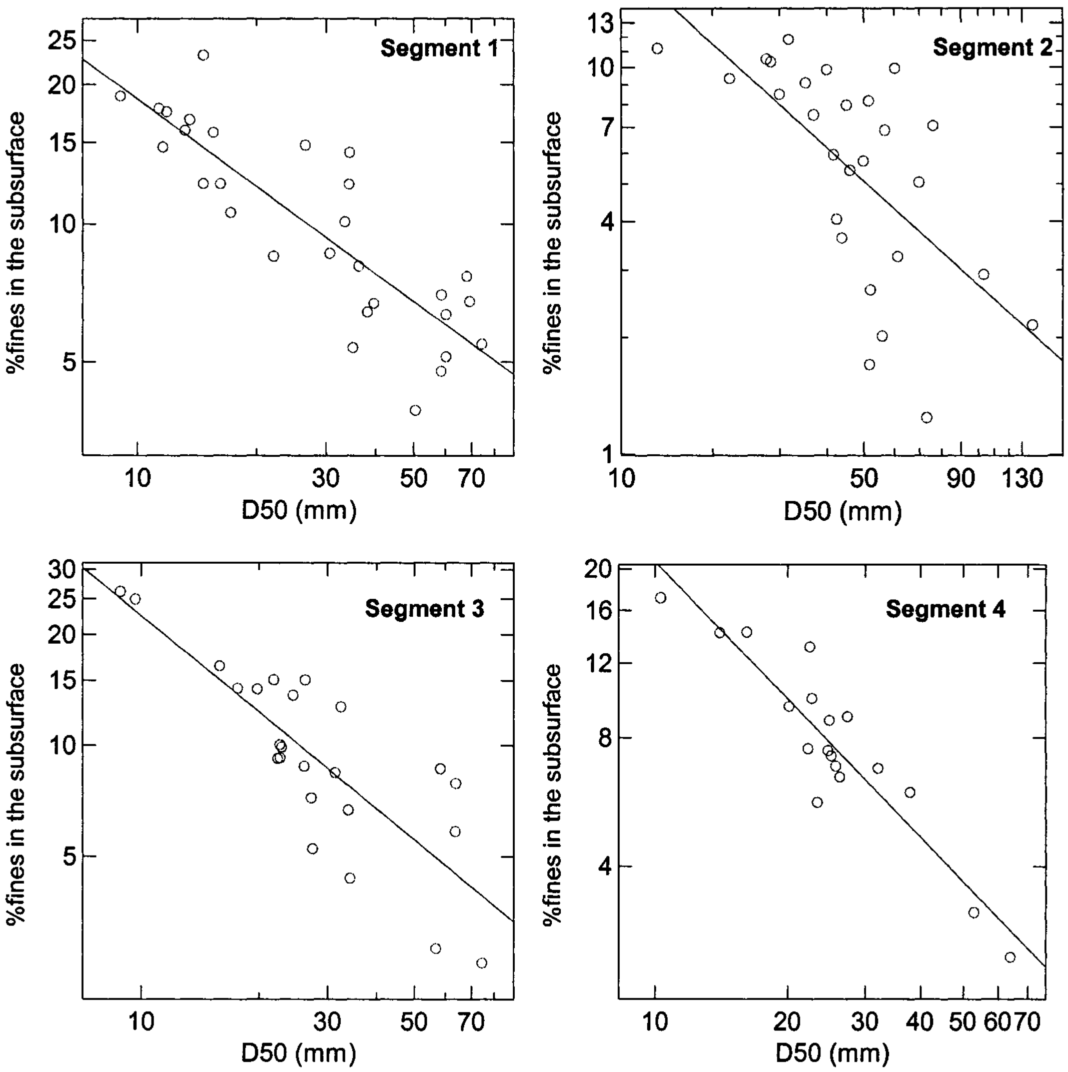


Figure 27. Relation between % fines in the subsurface (%fines$_{sp}$) and subsurface D50 (D50$_{sp}$) for each segment. The linear line of best fit is shown.

The analysis of reach-scale variables begins with the relation between channel slope and %fines. The subsurface fine sediment content should be negatively related to slope because of the relation between slope (S) and flow velocity (V) (equation 3) and slope and shear stress (τ) (equation 4). High velocities and shear stresses are positively related to larger sediment sizes and negatively related to fines (Gordon *et al.,* 1992). A decrease in slope is followed by a decrease in velocity and shear stress, and this can increase the amount of fines that deposit in the substrate. When %fines$_{sp}$ are regressed against slope, a significant, negative relation emerges for segments 1 and 3 (Table 20). Regional slope (LS4) is the strongest model for segment 1. Polynomial slope (PS), which represents the water surface slope at bankfull discharge, when most of the sediment movement occurs (Church, 1996; Sweet and Geratz, 2003), explains 38% of the variance in %$fines_{sp}$ in segment 3. These relations are robust because they do not rely on a few points to make the model significant. Multivariate models of slope and $D50_{sp}$ were not significant in any of the segments. However, while slope is related to the variance in %$fines_{sp}$, $D50_{sp}$ remains the best predictor of %$fines_{sp}$ for all segments.

Table 20. Models relating subsurface fine sediment content (%fines) to bed slope and water surface slope. * indicates a significant relation at the 5% level.

Site	Equation	r^2	P		Equation	r^2	P
%$Fines_{sp}$ vs. Regional slope (LS4)				*%$Fines_{sp}$ vs. Polynomial slope (PS)*			
Segment 1	**$0.18 \cdot LS4^{-0.63}$**	**0.553**	**0.000***	**Segment 1**	**$0.48 \cdot PS^{-0.48}$**	**0.333**	**0.001***
				Segment 2	$0.04 \cdot PS^{-0.87}$	0.080	0.082
				Segment 3	**$0.14 \cdot PS^{-0.60}$**	**0.382**	**0.001***
				Segment 4	$0.05 \cdot PS^{-0.93}$	0.142	0.069

Because shear stress and slope are related (equation 4), significant models were also found between shear stress and the subsurface fine sediment content. Significant models were found for regional and polynomial shear stress estimates in segments 1 and 3 (Table 21). These models are theoretically sound for two reasons. First, the nature of the relations is in line with theory. Second, the relations are not sensitive to outliers or points with high leverage (i.e. they are robust). The remaining reach-scale variables (channel width and point bar width) did not yield any significant relations (Appendix V). Furthermore, while the shear stress models are significant (Table 21), the $D50_{sp}$ models explain a larger portion of the variance for both segments 1 and 3 (r^2 = 0.71 and 0.65, respectively).

Table 21. Models relating %fines in the subsurface to shear stress estimates. * indicates a significant model at the 5% level.

Site	Equation	r^2	P		Equation	r^2	P
Regional shear stress - SS4 (γ d* LS4)*				*Polynomial shear stress - PSS (γ* d* PS)*			
Segment 1	**$25.5 \cdot SS4^{-0.33}$**	**0.329**	**0.001***	**Segment 1**	**$41.2 \cdot PSS^{-0.44}$**	**0.200**	**0.010***
Segment 2	$9.08 \cdot SS4^{-0.13}$	0.000	0.749	**Segment 3**	**$28.5 \cdot PSS^{-0.41}$**	**0.304**	**0.003***

Various multivariate models were also tested. Nonetheless, the strongest models (both statistically and theoretically) remained the $D50_{sp}$ models (Figure 27, Table 19). It is thus the residuals from these models that were saved and are used in the analysis of harvesting metrics discussed in Chapter VIII. Section VII.3.1 also lists the sites along each segment with unusually high %fines (H03, 05, and 17, L05, 16, 18, and 20, and E02, 05, and 12). The residual value assigned to each site by its respective $D50_{sp}$ model is shown in Table 22.

Table 22. Residuals and %deviation from the subsurface D50 ($D50_{sp}$ – the median sediment diameter) model of sites with abnormally high subsurface fine sediment contents (%fines).

Site name	%fines	Residual	%deviation	Site name	%fines	Residual	%deviation
H03	16%	0.007	2%	L05	14%	0.059	15%
H05	16%	0.048	12%	L16	15%	0.189	55%
H17	15%	0.167	47%	L18	14%	0.016	4%
E02	22%	-0.047	-10%	L20	14%	0.121	32%
E05	14%	-0.009	-2%	E12	14%	0.058	14%

VII.4 Discussion

VII.4.1 Reach-scale variables as controls of stream sedimentology

The annotated bed and water surface long profiles (Figure 24) illustrate how the streams adjust their sediment distribution in conjunction with shear stress and slope and tributaries (Figure 25) and how the latter are adjusted to the presence of cliffs, log jams, and cut-off meanders. In all four segments, the bedrock outcrops are located in steeper regions of the channel and are associated with higher shear stresses and armouring ratios (Figure 24, Figure 25). Theoretical models on downstream adjustments to channel form hold true in these four segments of the Cascapédia: $D50_p$ and subsurface fines are negatively related (Figure 25), slope and shear stress are positively related, as are $D50_p$ and shear stress (Figure 25), except at the end of segment 4, perhaps due to the numerous bedrock and large boulder outcrops.

Furthermore, an analysis of the fine sediment content distribution along each segment (Figure 24, Figure 25) identified some riffles with unusually high fine sediment contents. None of the riffles sampled in segment 2 had fine sediment contents above 15%. This is also the only segment which follows the theoretical downstream fining trend. Thus, the quality of the salmon habitat in this segment is classified as good. Half of the 20 sites with high %fines (› 15%) can be explained by changes in $D50_p$, slope, and shear stress.

However, for those riffles with high %fines that cannot be explained by reach-scale variables (H03, H05, H17, L05, L16, L18, L18, E02, E05, and E12), the answer may come in the next chapter when the harvesting metrics are considered. There is no clear reason why these sites have higher fine sediment contents, although some of these have high %fines and are situated downstream of a tributary, which could have a high harvesting intensity. This question will be explored further in the next chapter.

VII.4.2 Landscape and local determinants of variations in pavement D50

The variance in $D50_p$ along each segment is best explained by one of two reach-scale variable models. For segment 1, the variance in $D50_p$ is related to polynomial slope (r^2 = 0.33, Table 16). For segments 2 and 3, the variance in $D50_p$ is related to polynomial shear stress (r^2 = 0.55 and 0.19, respectively) (Table 17). While no model explains the variance in $D50_p$ in all four segments, the two models noted above are similar, given that both use polynomial slope (either directly, as in segment 1, or indirectly through shear stress in segments 2 and 3). Unfortunately, none of the landscape structure or reach-scale variables yielded a significant relation for segment 4. These results highlight some of the complications associated with trying to fit a model that explains $D50_p$ variations to multiple segments, even if these are located within the same watershed. They also illustrate how sites adjust differently to local conditions, making it difficult to create a representative model capable of being used in different watersheds (Brookes, 1996; Church, 1996; FISRWG, 1998). The two general observations that emerge from this analysis are discussed below.

Two broad categories of variables were tested for their relation to the variance in $D50_p$: large-scale landscape structure (basin area and geology) and reach-scale (slope, shear stress, channel width, and average point bas width). Neither of the landscape structure variables yielded a theoretically sound model. For example, in segment 3, while basin area and $D50_p$ were significantly related, the nature of the relation was contrary to theory (where $D50_p$ should decrease as area increases) (Figure 2, Church, 1996). Since no theory explains why this would be the case, this model was rejected, even though it was stronger (r^2) than the polynomial shear stress model (r^2 = 0.31 versus 0.19, respectively. Table 15 and Table 17). A similar problem occurred with geology, where one geology category yielded models that were contradictory from one segment to the next (Appendix V). No significant, theoretically sound models were found (Appendix V). This may have occurred because the numerous geology categories had to be amalgamated into broader categories to increase the number of sites with non-0 values (thus increasing the number of sites included in the analysis). This may have lost some of the information contained in the categories. Therefore, while significant results were found (in terms of significant P values), these models should be validated prior to being applied universally.

The next observation to emerge from this analysis is the weakness of the models to account for the variations in surface D50 (the strongest model has an r^2 of 0.55 for segment 2). Several factors may account for this. First, the bedrock outcrops in each segment may make it difficult for the channel to adjust its shape, size, pattern, and slope (Trenhaile, 1998). These may also affect where fine sediments deposit; thus, the sediment found in the riffle substrate may not reflect the sediment content that would be found in a 'textbook' alluvial channel. Sediments deposited on bedrock cannot become embedded. As a result, the current can transport the sediment further downstream. Once the bed becomes alluvial once again, the sediment can deposit and become embedded, altering the theoretical sediment distribution. Secondly, the presence of LWD increases the heterogeneity of particle size (Faustini and Jones, 2003) and may explain the deviations in sediment patterns seen in segment 4, where LWD abounds. Thirdly, these relations also indicate that other variables may better explain the variations in $D50_p$. These include, but are not limited to, pavement imbrication, mobility ratio, and the shape of the sediment (i.e. the relation between the axes, degree of roundness, etc.).

VII.4.3 Landscape and local determinants of riffle subsurface fine sediment content

The variance in the subsurface fine sediment content of all four segments is best related to the D50 of the subsurface. The other significant models were not used because a) they yielded relations that were contrary to theory (e.g. basin area) or b) there was no theory to justify or support the model (e.g. geology). These issues, along with possible factors that can account for the remaining variations in %fines, and the residual values assigned to the sites with unusually high %fines are discussed below.

To begin, theoretical downstream adjustments in channel form show an expected increase in fines as basin area increases and slope decreases (Figure 2). However, these trends were not found in the Cascapédia dataset. First, the relation between %fines and basin area is contrary to the theory. This may be because the theoretical models are built on the change in %fines over a wide range of area, whereas there was only a 25 km^2 change in segments 1, 2, and 4. However, the 600 km^2 range in segment 3 should have been enough to test for the relation between %fines and area, but it yielded the same negative relation as the other segments. Second, reach-scale slope did not explain any of the variance in %fines, despite its relation to shear stress and the capacity of the channel to move sediment. Therefore, other factors such as large woody debris accumulations, precipitation intensity, and flashiness, among others, could be involved.

While the models of the %fines analysis are stronger than those of the $D50_p$ analysis, a portion of the variance in %fines remains unexplained by the large-scale and reach-scale factors considered in this study. The objective of Chapter VIII is to determine if harvesting metrics can explain any of this remaining variation. As mentioned in section VII.4.2, the bedrock outcrops could alter the riffle fine sediment content. Fines cannot deposit permanently in bedrock, and would thus be transported and deposited further downstream. Secondly, tributaries discharging into the various segments (Figure 24) increase discharge and could wash away the fines in the riffles located below their junction. Thirdly, the accuracy of the bulk sampling technique should also be verified using freeze-core sampling (Zimmermann, 2003) to determine the proportion of fines lost during sampling and to have a more accurate %fines at each riffle. This could be done at a few locations to calibrate the amount sampled from the bulk samples to actual levels, as was done by Wilson (2003).

Furthermore, previous studies have shown that the Cascapédia has a relatively low fine sediment content but a higher silt and clay content (< 63 μm) when compared to other rivers on the Gaspé Peninsula (Zimmermann, 2003). Therefore, perhaps a threshold other than sediments with a diameter less than 2 mm should be considered. For example, the portion of fines smaller than 1 mm or 250 μm may be more important than the portion smaller than 2 mm in the quality of salmon habitat. However, if these thresholds are used, freeze-core sampling methods should be used, since the accuracy of bulk sampling is reduced as the fine sediment class decreases (Zimmermann, 2003).

Finally, the sites identified in section VII.3.1 as having abnormally high fine sediment contents are discussed briefly (Table 22). The residual values assigned to these sites facilitate the task of determining if the %fines of these sites truly are atypically high. The closer a residual value is to 0, the better the observed $\%fines_{sp}$ is predicted by the model. Positive values have a higher %fines than can be expected given the $D50_{sp}$ and negative fines have a lower %fines than predicted by the model. From this, seven of the ten sites are identified as having residuals that are within 15% of the model's predicted fine sediment content value: H03 and 05, L05 and 18, and E02, 05, and 12 (Table 22). Thus, while $D50_p$ did not explain the high %fines, $D50_{sp}$ does, perhaps because of the armouring ratio, which is above two (i.e. $D50_p$ is at least twice the size of $D50_{sp}$) for all these sites except E02. Therefore, the $D50_{sp}$ models explain seven of the high fine sediment contents, leaving only H17, L16, and L20 with abnormally high %fines. These three sites will be monitored in the analysis of Chapter VIII to determine if harvesting explains their unusually high fine sediment contents (see page 113).

VIII MULTI-SCALE ANALYSIS OF THE EFFECTS OF FORESTRY ON STREAM SEDIMENTOLOGY

VIII.1 Introduction

In Chapter VII, models were created to explain the portion of the variation in riffle pavement median diameter ($D50_p$) and riffle fine sediment content (%$fines_{sp}$) along four segments of the Cascapédia related to reach-scale variables. The variables slope and shear stress explain a portion of the variance in $D50_p$, in three of the four segments:

Segment 1 – $D50_p = 879 \cdot \text{Polynomial slope}^{0.46}$ ($r^2 = 0.193$, $P < 0.018$)
Segment 2 – $D50_p = 0.04 \cdot \text{Polynomial shear stress}^{1.96}$ ($r^2 = 0.553$, $P < 0.0005$)
Segment 3 – $D50_p = 23 \cdot \text{Polynomial shear stress}^{0.29}$ ($r^2 = 0.190$, $P < 0.028$)
Segment 4 – No significant model was found for this segment.

The variance in riffle fine sediment content was best explained by the D50 of the subsurface ($D50_{sp}$). The model used for each segment is shown below:

Segment 1 – $\%Fines_{sp} = 79 \cdot D50_{sp}^{-0.63}$ ($r^2 = 0.714$, $P < 0.0005$)
Segment 2 – $\%Fines_{sp} = 165 \cdot D50_{sp}^{-0.9}$ ($r^2 = 0.393$, $P < 0.0005$)
Segment 3 – $\%Fines_{sp} = 167 \cdot D50_{sp}^{-0.49}$ ($r^2 = 0.646$, $P < 0.0005$)
Segment 4 – $\%Fines_{sp} = 248 \cdot D50_{sp}^{-1.08}$ ($r^2 = 0.848$, $P < 0.0005$)

The purpose of these models was to remove the natural variation in the $D50_p$ and %$fines_{sp}$ explained by reach-scale variables in order to achieve the second objective of this thesis, which is to determine how the residuals (i.e. the remaining variations) are related to the harvesting metrics equivalent cut area and road density at different scales. This question is addressed because forestry-related perturbations in the headwaters of a watershed can have repercussions downstream by increasing riffle subsurface fine sediment contents and decreasing mean pavement diameter if the injected sediment deposits in the riffles.

Two analyses are performed to reach this objective. First, the $D50_p$ and %$fines_{sp}$ residuals of each segment are modelled against the harvesting metrics to determine if these account for any of the remaining anomalies along each segment, given that harvesting and its associated road network inject increased amounts of fine sediment into the river (Wemple *et al.*, 1996; Lopes *et al.*, 2001; Luce and Black, 2001). If the injected sediments deposit on the riffle crests located in mildly sloped reaches, they will change their sedimentology. The second analysis studies how tributaries discharging along the studied segments impact the fine sediment content of the riffles located up to 1 km downstream of the tributary junction with the mainstem. This analysis focuses on a few sites and compares their fine sediment content to three groups of sites. The hypothesis is that tributaries create a local impact when they discharge into the mainstem by increasing the fine sediment content of riffles located immediately downstream of their junction because of the decrease in channel slope arising from the higher discharge. This reduces shear stress and can lead to sediment deposition (FISRWG, 1998).

VIII.2 Methods

VIII.2.1 Estimation of harvesting metrics and zones of influence using a GIS

For the first analysis, two harvesting metrics were estimated in a GIS: equivalent cut area (ECA, where harvested parcels are weighted with a time attenuation factor to account for the hydrological recovery of a basin with time since harvest) and road density. These were calculated at six different scales: 60 m buffer scale, in zones of influence of 500 m, 1 km, 2 km, and 5 km radius, and at the watershed scale. The 60 m buffers are buffer corridors of 60 m following both sides of the stream (i.e. 120 m total width) along its entire length. The zones of influence are centred on the study site and include only the portion of the watershed that is within the specified radius (500 m, 1, 2, or 5 km). These zones are created in a GIS geoprocessing tool and intersected with each site's watershed to delineate the area of the zone of influence (Figure 28).

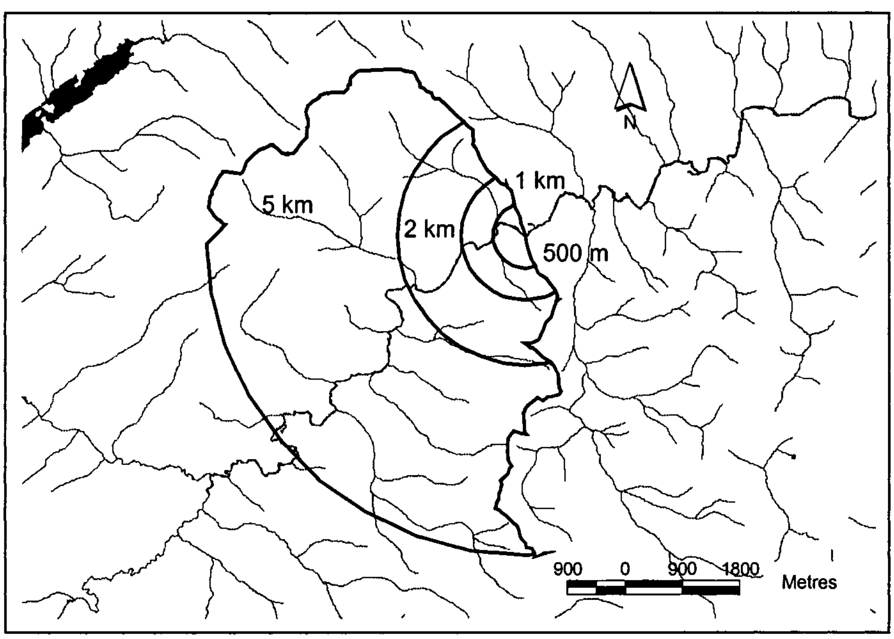


Figure 28. Example of the zones of influence.

A regression analysis was run between the metrics calculated at each scale and the surface D50 ($D50_p$) and subsurface fine sediment content ($\%fines_{sp}$) residuals to explore the relations between these. In this analysis, the focus is on the significance of the relations rather than their strength (i.e. P versus r^2), as the goal is to determine if there is an association between the harvesting metrics and the residuals, and not to predict how harvesting at a particular intensity will affect the $D50_p$ and $\%fines_{sp}$ at a particular riffle.

VIII.2.2 Determining the local effect of tributaries on riffle fine sediment content

For the second analysis, all tributaries discharging into a segment and the riffles located up to 1 km downstream of these were identified from the annotated long profiles of each segment (Figure 24). The number of riffles sampled up to 1 km downstream of the tributaries ranges from one to three. A paired t-test was run between the average fine sediment content of these riffles and the average $\%fines_{sp}$ of three groups of sites: 1) sites located up to 1 km upstream of the tributary junction (this ranges from two to four sites, depending on the tributary), 2) all sites in the segment having a similar $D50_p$ as the sites downstream of the tributary (one to three sites), and 3) all sites in the segment having a similar $D50_{sp}$ (one to five sites). A similar $D50_p$ or $D50_{sp}$ was defined as a D50 +/- 10 mm of the average D50 of the sites located downstream of the tributary. The paired t-test determines if there is a significant difference in the $\%fines_{sp}$ between each group.

VIII.3 Results

VIII.3.1 Relation between residuals and harvesting metrics

The distributions of the equivalent cut area (ECA) and road density harvesting metrics (i.e. maximum, minimum, mean, and standard deviation) by segment are shown in Table 23. At the watershed scale, segment 4 has not been harvested to the intensity of the other segments in the last five years (less than 2% for segment 4 versus up to 25% for segments 1 and 3). Segment 2 has the greatest range in intensity of harvest (ECA), particularly in the 500 m zone of influence (40%). Segment 1 has the highest intensity of harvest, both overall (25%) and in the last five years (13%). The road densities in each segment range from a low of 0 km/km^2 in the 500 m zone of influence in all four segments to a high of 9.6 km/km^2 in the 2 km zone of influence of segment 2. The highest road densities in the zones of influence are in segment 2, even though this segment is not the most intensely harvested (mean of 20%), particularly in the last five years (6.5%). The lowest watershed road densities are in segment 4 because this segment has not been harvested intensely in recent years and would thus not require as many roads as segments 1, 2, and 3.

Table 23. Distribution of the harvesting metrics road density, equivalent cut area (%ECA), and equivalent cut area in the last five years (%ECA(85)) for the four sampled segments.

Segment 1 - Haute Mineurs

	Road density (km/km^2)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	1.8	1.5	1.0	1.0	0.0
Maximum	2.8	3.4	3.6	4.9	6.5
Median	2.1	2.2	2.5	2.2	1.1
Mean	2.1	2.2	2.5	2.4	1.7
Std Dev	0.2	0.6	0.7	1.1	2.0
	Equivalent area Cut (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	24.1	15.0	13.5	11.8	2.1
Maximum	25.3	20.9	24.4	26.9	29.8
Median	24.5	18.3	16.7	16.5	15.0
Mean	24.7	18.1	16.9	17.5	14.7
Std Dev	0.5	1.3	2.7	4.3	6.0
	ECA - in the last 5 years (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	11.8	1.1	0.0	0.0	0.0
Maximum	15.0	4.7	6.9	1.5	0.1
Median	12.6	3.4	2.4	0.0	0.0
Mean	13.2	3.2	2.5	0.3	0.0
Std Dev	1.2	0.9	2.0	0.5	0.0

Segment 2 - Basse Mineurs

	Road density (km/km^2)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	2.2	1.5	1.8	1.7	0.0
Maximum	2.3	4.3	9.6	7.6	7.6
Median	2.3	2.9	3.6	4.4	1.1
Mean	2.3	2.9	4.8	4.5	1.9
Std Dev	0.0	1.0	2.8	1.9	2.1
	Equivalent area Cut (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	19.7	9.2	11.4	7.2	2.3
Maximum	20.4	30.9	30.2	31.8	25.7
Median	20.4	26.2	24.5	17.0	11.5
Mean	20.2	22.2	22.6	18.0	12.8
Std Dev	0.3	8.4	6.3	6.4	6.4
	ECA - in the last 5 years (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	6.4	0.0	0.0	0.0	0.0
Maximum	6.7	0.3	1.1	3.0	1.6
Median	6.4	0.3	0.0	0.0	0.0
Mean	6.5	0.2	0.3	0.5	0.2
Std Dev	0.1	0.1	0.4	1.0	0.4

Segment 3 - Lac

	Road density (km/km^2)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	2.3	1.5	1.7	0.0	0.0
Maximum	2.4	4.1	5.6	4.7	3.3
Median	2.4	3.2	3.3	2.7	0.5
Mean	2.4	2.9	3.5	2.5	1.1
Std Dev	0.0	1.0	1.2	1.3	1.2
	Equivalent area Cut (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	19.7	16.9	10.0	6.1	3.6
Maximum	24.9	37.2	41.4	42.5	36.3
Median	22.5	28.0	23.1	22.6	19.5
Mean	22.8	26.6	25.2	23.6	19.3
Std Dev	1.7	7.2	11.7	13.5	9.0
	ECA - in the last 5 years (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	4.7	2.2	0.1	0.0	0.0
Maximum	5.7	11.0	8.4	15.5	27.4
Median	5.7	5.8	0.9	0.7	0.7
Mean	5.3	6.3	2.1	3.2	4.4
Std Dev	0.5	3.1	2.4	4.9	7.8

Segment 4 - Echouement

	Road density (km/km^2)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	1.8	1.7	1.4	0.5	0.0
Maximum	2.0	2.8	3.1	3.9	4.4
Median	1.9	2.1	2.4	2.2	1.9
Mean	1.9	2.2	2.3	2.0	1.6
Std Dev	0.0	0.4	0.6	1.2	1.4
	Equivalent area Cut (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	8.3	16.9	15.2	9.2	0.1
Maximum	11.9	39.0	39.8	38.4	39.5
Median	10.8	29.3	33.5	23.7	16.1
Mean	10.6	29.8	29.9	25.3	17.4
Std Dev	1.3	8.1	8.6	7.7	10.3
	ECA - in the last 5 years (%)				
	Watershed	5 km	2 km	1 km	500 m
Minimum	1.0	0.0	0.0	0.0	0.0
Maximum	1.9	12.8	15.3	16.7	19.7
Median	1.9	7.6	2.4	1.4	2.7
Mean	1.7	6.9	5.6	5.1	4.3
Std Dev	0.4	4.2	6.2	6.4	5.6

Analysis of the relation between $D50_p$ residuals and harvesting metrics

This section deals with the regression models between the harvesting metrics and the $D50_p$ residuals for segments 1 to 3 and the original data for segment 4. None of the harvesting metrics explain a portion of the remaining variance in $D50_p$ residuals of all four segments. Furthermore, while some metrics are related to the $D50_p$ residuals of one or two segments, the following section will show that these relations are tenuous or unsubstantiated by theory. Segments 2 and 3 are discussed together because both segments used the same model (polynomial shear stress) to obtain the residuals. Segments 1 and 4 are discussed individually. Note the residuals in Figure 29, Figure 30, and Figure 32 are in log units.

Segment 1. Four of the harvesting metrics tested explain a portion of the remaining variance in $D50_p$: %ECA in the 1 km and 5 km zones of influence, %ECA(65) in the 2 km zone of influence (i.e. parcels harvested six to ten years ago), and %ECA(55) (i.e. parcels harvested 16 to 20 years ago) (All models are listed in Appendix VI). While these models are theoretically significant at the 5% level, there remains much variance between the models (i.e. the linear regression line) and the residual values (the circles in Figure 29). Furthermore, the models are also sensitive to the value of one or two points (e.g. the relation in Figure 29 is sensitive to the values of H06, 10, and 25).

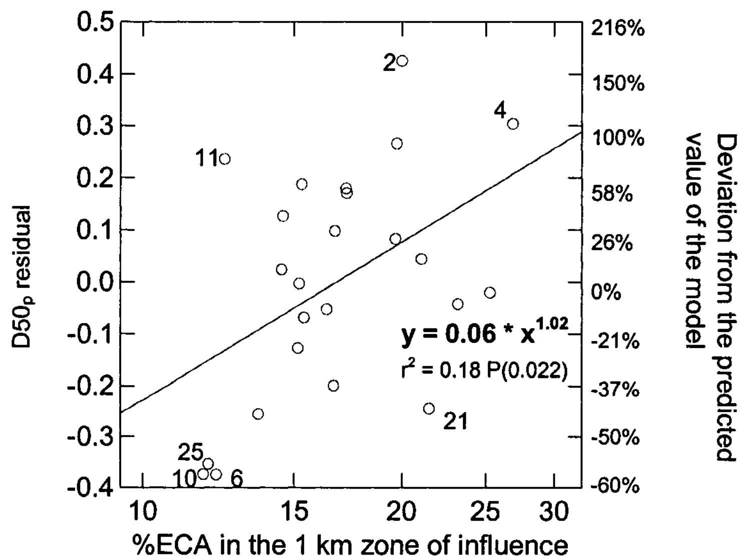


Figure 29. Changes in the surface D50 ($D50_p$) residuals of segment 1 as the % equivalent cut area (%ECA) increases in the 1 km zone of influence. The linear regression line is shown.

Harvesting is also often associated to an increase in subsurface fines (Chamberlain *et al.*, 1991; Andersen, 1998), which should lead to a decrease in $D50_p$ given the relation between these two variables (Table 19). However, the four harvesting metrics and $D50_p$ residuals of segment 1 are positively (%ECA – 1 km and %ECA(55)) and negatively (%ECA – 5 km and %ECA(65) – 2 km) related (Appendix VI). No mechanism could be found to explain why harvesting in certain years would create an increase in $D50_p$ and a decrease in other years. Thus, the combination of these two issues suggests these models may be due to chance and may not be theoretically sound.

Segments 2 and 3. The $D50_p$ residuals of segments 2 and 3 are related to road densities in the 500 m zone of influence (r^2 = 0.23 and 0.27, respectively, Figure 30). However, the relations are sensitive to two sites in segment 2 (B16 and B17) and to sites with a road density less than 1 km/km^2 in segment 3 (Figure 30). While roads can be a large source of sediment to a stream (Campbell and Doeg, 1989; Slaymaker, 2000), they usually inject fine sediment (Reid and Dunne, 1984), which would decrease $D50_p$, given the relation between D50 and %fines (Table 19). However, the relation is positive in segment 2 and negative in segment 3 (Figure 30). This inconsistent model suggests the relation is not actually significant, as no mechanism can explain why the relation would be positive in one segment and negative in the other. The remaining harvesting metrics were not significantly related to the $D50_p$ residuals of segment 2 or 3 (Appendix VI).

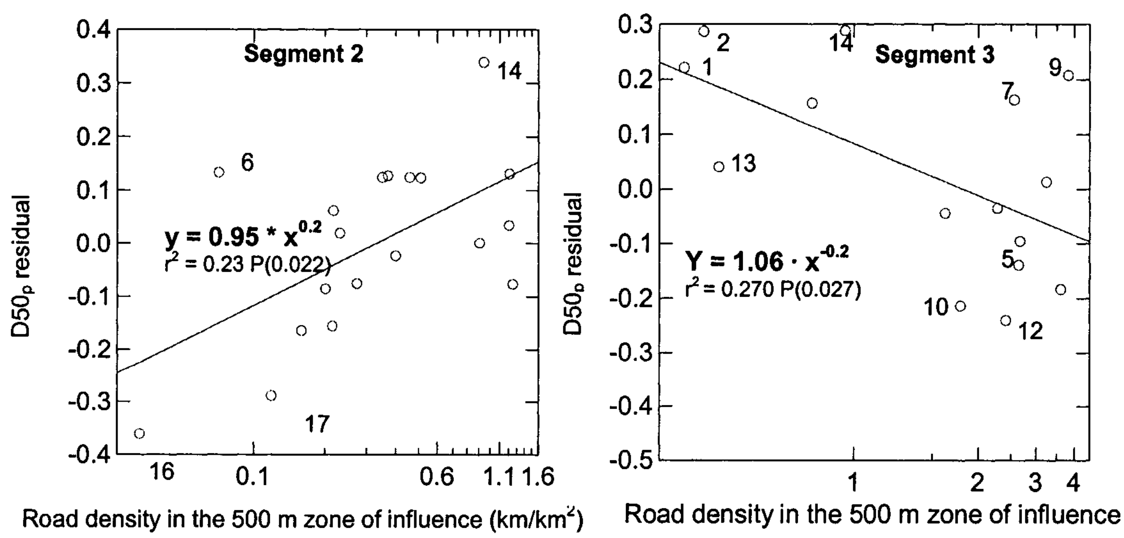


Figure 30. Change in the surface D50 ($D50_p$) residuals of segments 2 and 3 as road density in the 500 m zone of influence increases. The linear regression line is shown.

Segment 4. None of the large-scale or reach-scale variables explained the variance in $D50_p$ for segment 4 (Appendix VI). Therefore, no residuals were calculated and the original $D50_p$ data were modelled with the harvesting metrics. Of these, only %ECA and %ECA(60) in the 1 km zone of influence are positively related to $D50_p$ (Figure 31). An attenuation factor of 60 is associated to pre-commercial thinning activities carried out in the last five years (Langevin *et al.,* 2001). However, as with segments 1 and 2, this relation is contrary to theory and is sensitive to a few sites (E05, E10, and E18). An increase in peak flows could flush out the substrate and create a decrease in the %fines found in the pavement and could explain this positive relation between $D50_p$ and %ECA. However, because these models are sensitive to a few points, they could easily be statistical coincidences and should be employed with caution.

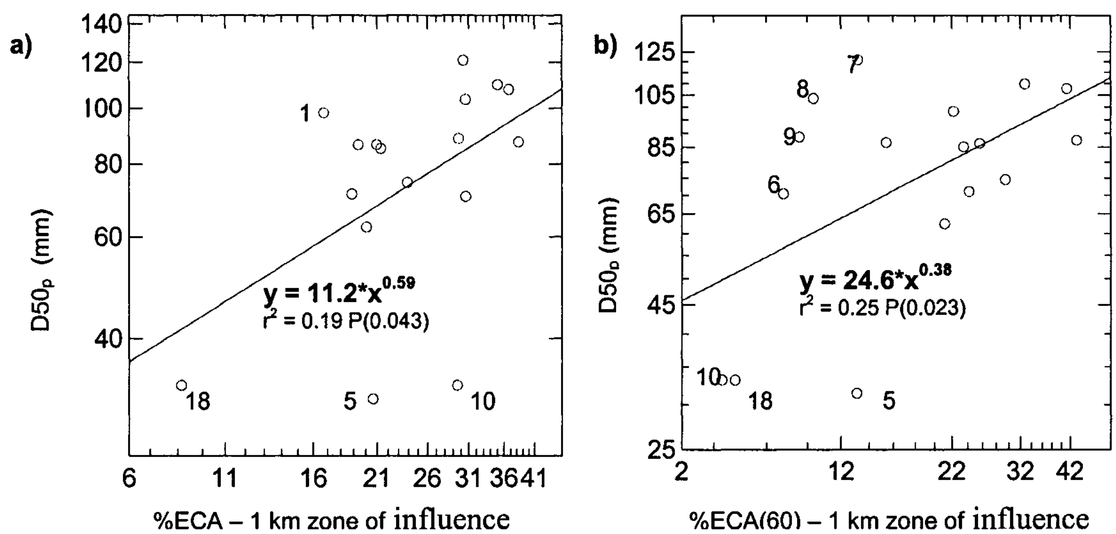


Figure 31. Changes in the pavement D50 ($D50_p$) of segment 4 as a) % equivalent cut area (%ECA) in the 1 km zone of influence and b) % equivalent cut area of thinning activities in the last five years (%ECA(60)) in the 1 km zone of influence increase. The linear regression lines are shown.

Analysis of the relation between $\%fines_{sp}$ residuals and harvesting metrics

A regression analysis was also run on the subsurface fine sediment content because of its importance to salmon habitat quality (Petersen and Metcalfe, 1981; Anderson, 1998) and because of a suspected increase in the Cascapédia's turbidity and flashiness following rain events. However, testing for turbidity and flashiness would require either a control watershed or turbidity and flashiness data prior to the commencement of harvesting activities, neither of which are available. Therefore, the $\%fines_{sp}$ residuals are used to determine if the areas with abnormally high fine sediment contents are related to the harvesting metrics. Given that the $D50_{sp}$ model was the strongest, theoretically reliable predictor of fine sediment content in each segment, their results are discussed together.

Few significant relations emerge from this analysis (Appendix VI). There are two in segment 1, one in segment 2, and none for segments 3 and 4. The three significant relations are sensitive to a few sites and are considered tenuous. For example, in segment 2, a relation exists between the residuals and %ECA(1996) (Figure 32), where ECA(1996) represents parcels harvested six years ago (AF = 65). In addition, the relation is sensitive to the values of B11 and 12 (i.e. the model would not be significant if the value of these points was different). Furthermore, despite the moderately strong relation (r^2 = 0.37), there is still much variance between the residuals and predicted values (e.g. B16 and 18 have negative residuals, despite harvest levels of 15-20%).

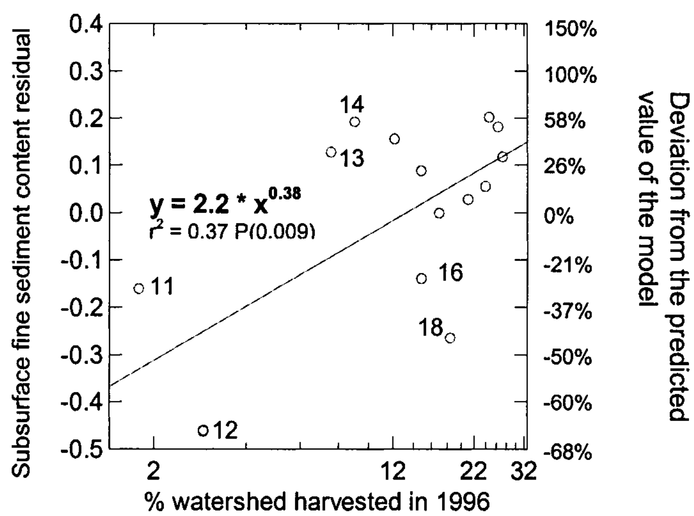


Figure 32. Change in the % of subsurface fine sediment (%fines$_{sp}$) residuals of segment 2 as the % of the watershed harvested in 1996 increases (%ECA(1996)). The linear regression line is shown.

The two other significant relations and the multivariate models do not have a theoretical basis, and are therefore not considered factual or significant. For example, in segment 1, the percentage of recently harvested area in the 5 km zone of influence is negatively related to the fine sediment residuals (Figure 32), which is contrary to theory (Chamberlain *et al.,* 1991; Andersen, 1998). Furthermore, the relation is sensitive to sites H01, 02, and 03. No mechanism explains why the relation would only be significant in segment 1. Consequently, while significant models emerged from this analysis, these were tenuous or contrary to theory. More research is required prior to concluding the relation between variations in $\%fines_{sp}$ and harvesting activities.

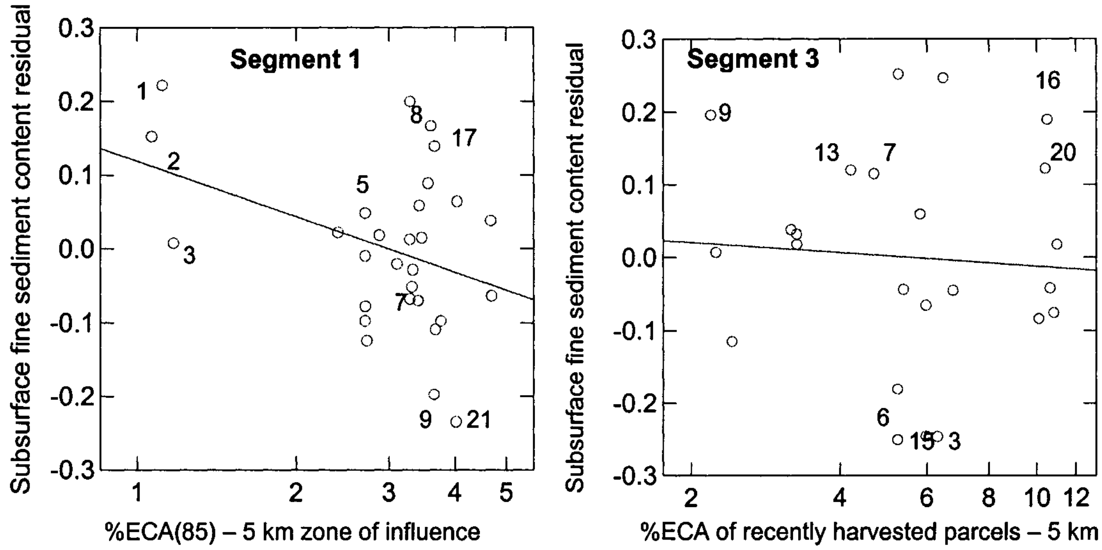


Figure 33. Change in the subsurface fine sediment content residuals ($\%fines_{sp}$) of segments 1 and 3 as the % equivalent cut area (%ECA) of the most recently harvested parcels (parcels harvested in the last five years) in the 5 km zone of influence increases. The linear regression line is shown.

VIII.3.2 Relation between tributaries and riffle fine sediment content

To test if the tributaries discharging into the mainstem segments increase riffle fine sediment content, a comparison was made of the average sediment content of the riffles located up to 1 km downstream of tributary junctions to three groups of sites: 1) sites located up to 1 km upstream of the tributary, 2) sites with a $D50_p$ similar to the study riffles, and 3) sites with a $D50_{sp}$ similar to the study riffles (Table 24). The tributaries discharging into segments 1, 3, and 4 (recall segment 2 has no tributaries, Figure 24b) and their associated riffles were studied together.

The pairwise t-test of the average sediment content of the one to three sites located up to 1 km downstream of a tributary to sites in groups 2 and 3 did not yield a significantly different average fine sediment content between the two groups at $\alpha = 0.05$ (Table 25). This is even despite the presence of some of the sites highlighted in Chapter VII as having high fine sediment contents (e.g. H17, H05, and E05). Therefore, unless the tributaries have altered the sedimentology of the riffles located downstream of their junctions, their

$\%fines_{sp}$ are not significantly different than sites with similar $D50_p$ or $D50_{sp}$. To determine if the tributaries have altered the $D50_p$ and/or $D50_{sp}$ of these sites requires their pre-harvesting values, which were not available.

Table 24. List of sites located downstream of tributary junctions and sites in the comparison groups for the 53 sites visited in 2003.

Tributary name (%Equivalent cut area)		Sites up to 1km downstream of the tributary	Comparison groups: 1 – Sites up to 1 km upstream of the tributary	2 - Sites with a similar surface D50 ($D50_p$)	3 - Sites with a similar subsurface D50 ($D50_{sp}$)
Segment 1 – Haute Mineurs					
Th2	(0%)	04, 05, 24	02, 03	14, 18	10
Th3	(35%)	09, 25, 10	07, 08	07	03, 05
Th4	(18%)	10, 11	07, 08, 25	04, 19	21
Th5	(16%)	15, 16, 17	13, 26, 14	19, 26	11, 14, 21
Segment 4 – Échouement					
Te1	(46%)	05, 06, 07	03, 04	03, 04, 06	01, 04, 17
Te2	(36%)	06, 07, 08	04, 05	01, 08	11, 13, 14, 18
Segment 3 – Lac					
Tl1	(24%)	01, 02, 03	18, 19, 20, 21	07, 09	06
Tl2	(33%)	03, 04, 05	01, 02	05, 13, 19	02, 10, 15, 16, 20
Tl3	(36%)	07, 08, 09	04, 05, 06	01, 11	15
Tl5	(19%)	13, 14, 15	11, 12	11	03, 06, 09
Tl6	(6%)	14, 15	11, 12, 13	01	06
Tl7	(8%)	15	11, 12, 13, 14	06, 11	02, 08, 10, 16

Table 25. Pairwise t-test of the average fine content in the downstream sites versus the average subsurface fine sediment content (%fines) of each of the 3 comparison groups.

Downstream fines = mean of 9%	Average fines of group (%)	P	t-value (2 – tailed)	Confidence interval
1 - Sites up to 1 km upstream of the tributary junction	13.4	0.014*	-2.92	-7.7 to -1.1
2 - Sites with a similar surface D50 ($D50_p$)	10.7	0.125	-1.66	-3.9 to 0.6
3 - Sites with a similar subsurface D50 ($D50_{sp}$)	8.5	0.480	0.73	-1.1 to 2.2

The pairwise t-test between the sites located up to 1 km downstream of the tributary and group 1 yielded a significant difference at $\alpha = 0.05$ (Table 25). Theoretically, the decline in slope at the tributary junctions (Figure 24) should reduce flow velocity and shear stress (Gordon *et al.,* 1992). This could then lead to greater sediment deposition in the riffles immediately downstream of the junction. However, there are significantly fewer fines (α = 0.05) in the sites downstream of the tributary when compared to the sites located upstream (Table 25). These two groups of sites have similar $D50_p$, $D50_{sp}$, and channel slopes. Therefore, the increased discharge at the tributary junction may be sufficient to flush out the fines in these riffles, despite the decrease in slope which usually entails an increase in deposition.

VIII.4 Discussion

VIII.4.1 Relation between residuals and harvesting metrics

Pavement D50 analysis

Three general conclusions emerge from the results of the analysis between $D50_p$ residuals and the harvesting metrics (section VIII.3.1). Each is discussed in turn. Firstly, there does not appear to be a strong relation between the metrics ECA and road density and the variations in surface D50 residuals. All significant relations are tenuous and sensitive to the metric values assigned to a few sites (e.g. the ECA in the 1 km zone of influence for segment 1, Figure 29). However, the tenuous nature of these relations should not invalidate these results, but rather encourage future studies to corroborate the results obtained in this study. A different methodology, such as bulk sampling the point bar heads or freeze-core sampling, should also be used to determine the robustness and consistency of the relations.

Secondly, the relations are often contrary to theory. For instance, harvesting and its associated road network have been shown to increase the amount of fine sediment in the substrate (Reid and Dunne, 1984; Chamberlain *et al.,* 1991; Luce and Black, 2001). It is difficult to imagine that $D50_p$ would increase if harvesting activities increased the amount of fine sediment injected into the channel, as seen in Figure 29 to Figure 31, given the relation between D50 and %fines (Table 19). The increase in $D50_p$ could be due to an increase in peak flow resulting from harvesting activities and a change in the flow routing efficiency associated to roads and their drainage ditches (Chamberlain *et al.,* 1991; Richards and Host, 1994; Beschta *et al.,* 2000; Bowling and Lettenmaier, 2001; Megahan *et al.*, 2001). All but one of the significant models (%ECA(55) for segment 1) were for metrics calculated for the zones of influence. The proximity of the harvested regions could result in a quicker or larger increase in peak flow than if the point of disturbance was further away. Concomitant with the increase in flow would be higher shear stresses (Gordon *et al.,* 1992), which could move smaller-sized sediments and increase the $D50_p$.

Thirdly, no single metric consistently explains the variance in $D50_p$ residuals throughout the dataset. In fact, a different harvesting variable explained a portion of the variance in $D50_p$ residuals for each segment having a significant model. In segment 1, the variable was harvesting, represented as %ECA (Figure 29). In segment 4, precommercial thinning (represented as %ECA(60)) was related to the $D50_p$ residuals (Figure 31). Finally, in segments 2 and 3, road density was related to the residuals (Figure 30). Therefore, a particular activity's impacts are not necessarily felt across the watershed. This suggests that other factors are involved in determining the strength of the impact on a particular segment (e.g. precipitation events, resident vegetation, changes in slope downstream of harvested parcels, etc.).

Subsurface fine sediment analysis

While locals and anglers are concerned about what they perceive to be an increase in the turbidity of the Cascapédia's waters, which could translate into an increase in the fine sediment content of the substrate should deposition occur, only segments 1 and 2 had a significant relation between riffle fine sediment content residuals and harvesting metrics. This is unexpected given that studies have demonstrated how harvesting can increase the fine sediment content in potential spawning habitat (e.g. Tschaplinski, 1998; Beschta *et al.,* 2000). The paucity of significant relations may be due to several reasons, five of which are discussed below.

Firstly, the scarcity of significant models may be due to the choice of metrics used in this study. ECA may not be as representative as it appears. Chapter VI suggested the use of an ECA metric where the recovery rate of the indigenous tree species should be weighted into the metric. Within the Cascapédia watershed, the native tree species include fir, white and black spruce, paper and yellow birch, white pine, trembling aspen, sugar and red maple, and cedar. Each of these has its own recovery rate. Soil characteristics may also need to be considered in the ECA metric because of its role in tree growth. Consider the following. Based on the digital database, segment 4 has the lowest %ECA (mean of 11%). However, field visits along this segment showed vegetation along the river segment has not recolonised from the whole-tree and careful harvest around regeneration clearcut harvesting of the early 1980's, which should be reflected in the segment's ECA.

Another reason for the few significant relations between fine sediment residuals and harvesting metrics may be the greater capacity of larger streams to buffer changes and absorb the effects of harvesting (Chamberlain *et al.*, 1991; Slaymaker, 2000). This, along with some of the problems associated with using bulk sampling (which can lose up to 6% of fines) (Zimmermann, 2003), could translate into few detectable impacts at the mainstem scale. It may also be a question of storage within the system, where sediment injected by harvesting operations deposits elsewhere than in the riffles (e.g. in pools) and re-enters transport later on (Jacobson and Gran, 1999), such as during the 5 to 10 year floods (Hartman *et al.,* 1996). Sediment may also remain in transit for long periods of time, depositing only once the harvesting activity has ceased (Slaymaker, 2000).

Thirdly, large drainage basins have more heterogeneous landscapes and topography, which can mask or buffer any sedimentological changes associated to harvesting (Wei and Davidson, 1998). Harvesting impacts may also be closely related to climatic variability during snowmelt (Whitaker *et al.,* 2001). Wei and Davidson (1998) studied peak flows in watersheds of 3590 km^2 and found these were not altered by harvesting, but suggest they could be in smaller basins. This logic could be applied to riffle fine sediment content, since an empirical relation exists between harvesting metrics and stream width residuals, implying that sediment is injected into the river during stream widening episodes (see Chapter VI). This sediment must then travel downstream and deposit, although it does not appear to be depositing in the riffles of the mainstem segments studied here. Chamberlain *et al.* (1991) suggest that it is deposited preferentially in pools. However, this hypothesis could not be tested with the methodology used in this study (bulk sampling) due to pool depth, which exceeded the 1 m height of the flow isolation cell. Other methods were not used in order to concentrate on the riffles, since these are potential salmonid spawning habitat and are the focus of this study. Systems can also recover from impacts if the source of sediment is removed (Chamberlain *et al.,* 1991). Therefore, the natural revegetation of harvested parcels reduces and eventually removes the source of sediment. This, combined with the fact that the most recent harvesting operations are in the headwaters of the watershed, some distance from the mainstem, may explain why there are only a few significant relations between the residuals and harvesting metrics in these segments.

Fourthly, streams in harvested watersheds generally have higher fine sediment contents when compared to streams in undisturbed watersheds (Jackson *et al.,* 2001). However, none of the Cascapédia's mainstem segments are in undisturbed watersheds. These exist only in the small headwater streams, which are located in the provincial park. Therefore, a comparison of harvested and undisturbed mainstem segments of the Cascapédia was not possible. One could also compare two different river systems: one harvested and one undisturbed. This comparison requires both watersheds to be located in the same climatic environment, with similar drainage basin characteristics (Caissie *et al.,* 2002; Hicks and Hall, 2003). However, the rivers located in the Gaspé Peninsula have all been harvested to some extent and cannot be used in this type of analysis. Thus, there is no means of establishing what the pre-harvesting $\%fines_{sp}$ levels were in the Cascapédia and determining if the current fine sediment content is higher than in the past, even if it comprises less than 15% of the substrate, which is considered to be the threshold of good quality habitat (Petersen and Metcalfe, 1981).

Finally, buffer width is also a factor in determining the degree to which harvesting can impact a stream. Davies and Nelson (1994) found buffer widths to be the dominant factor in determining the degree of impact from logging (in terms of sediment yield changes, superficial silt cover on riffles, length of open water stream, and snag volume), whereas the slope of the logged area and its geology did not play a role. Harvesting impacts can be abated by leaving buffers of 30 m width on either side of the stream (Davies and Nelson, 1994). As with Davies and Nelson (1994), basin geology did not explain any of the variance in riffle fine sediment content of the four study segments of the Cascapédia River (section VII.3.3). As for snag volume, a visual estimate of LWD along each segment shows segment 4 has the largest amount, despite having the lowest %ECA

(11%). The source of the LWD may be blowdowns, which also diminish the effective width of buffers (Hogan *et al.,* 1998). Upstream of its junction with the Cascapédia, a large log jam has formed at the mouth of segment 4, extending over 500 m. Beavers have built a dam around this jam and the tributary has formed three new junctions into Lac branch to adjust to the obstructions. This could affect how the system adjusts to harvesting because beaver dams and log jams modify stream morphology and hydrology by retaining sediment, organic matter, and water, increasing channel widths by up to 200-fold in the years following construction (Scrivener and Macdonald, 1998). Therefore, the 20 m regulation buffer width may need to be reconsidered to include the impact of blowdowns and prevent the formation of large log jams (Gouvernement du Québec, 2003b). A study should be undertaken to determine the average width of forest susceptible to blowdowns. This width could then be added to the 20 m regulation, creating a 20 m effective buffer width (as opposed to a 20 m total width). This width would also approach the 30 m buffer considered necessary to abate harvesting impacts by Davies and Nelson (1994).

Roads

Studies looking at watersheds with 35% harvested basin areas and with road densities averaging 1.5 km/km^2 have found roads to be a significant source of fine sediment (Reid and Dunne, 1984). The average watershed road densities of this study are slightly above these levels (Table 23), although harvesting intensities peak at 25%. Wilson (2003) found that sites in the Cascapédia with slopes $\leq$1%, and %ECA values over 40% and road densities greater than 4 km/km^2 in a 1 km radius upstream of the site were more liable to have higher fine sediment contents. However, no relation was found between road density, %ECA and the riffle fine sediment content residuals for these four segments of the Cascapédia, perhaps because none of our sites had %ECA values over 30%. Therefore, Wilson's (2003) results could not be confirmed.

Reid and Dunne (1984) found a relation between road length in the watershed and the fine sediment content of spawning riffles. Huntington (1998) also concluded that roads were a major source of fine sediments, with habitat located in unroaded areas having a higher quality (i.e. fewer fines). However, a test of this in the Cascapédia segments showed no significant relation for any of the segments. These results do not correspond to published results regarding the impact of roads, given that none of the fine sediment content residuals are related to the road density metrics.

On the other hand, Barrett *et al.* (1998) reported little change in the quality of spawning habitat between harvested and undisturbed channels, despite their 482 km^2 study basin having levels of harvesting up to 57% and road densities of 3.44 km/km^2. The same study found that basins of 670 km^2 with lower levels of harvesting (24%) and road densities (2.56 km/km^2) had poorer quality habitat (fines comprised 26% of the substrate) than the watershed harvested at 57% (16.6% fines) (Barrett *et al.,* 1998). Other factors that impact habitat conditions include stream size, channel type, and the watershed's management history (Barrett *et al.,* 1998; Downs and Priestnall, 1999; Tschaplinski, 2000; Moglen and Beighley, 2002). These should thus be considered in future studies.

Sites with abnormally high %fines

Recall from Chapter VII that there were three sites with abnormally high fine sediment contents: H17, L16, and L20. The fine sediment content analysis discussed above also uncovered some interesting trends concerning these sites. First, the %fines of H17 do not appear to be associated to harvesting operations. While the %ECA of recently harvested parcels is high for this site and may explain the high residual, it is low for H02, which also has a high residual (Figure 33). Unless other factors are involved, harvesting should be associated to the high residuals of H17 and H02, which is not the case. The situation is much the same for L16 and 18. In certain models (e.g. Figure 33), their high residual appears to be explained by a high %ECA, although other sites with the same residual (e.g. L09) have a much lower %ECA. Therefore, it is unlikely that harvesting alone is associated to the high residuals of H17, L16, and L20. Other factors, such as precipitation intensity and soil characteristics, may be involved in determining the amount of fine sediment found in the substrate.

VIII.4.2 Changes in riffle fine sediment content at tributary junctions

The analysis of riffle fine sediment content downstream of tributary junctions is limited to studying segments with tributaries (omitting segment 2 for this dataset). Despite this limitation, a significant result was found between the riffles located downstream of the tributary junction and one of the three comparison groups. Possible explanations for this result are discussed below.

First, the pairwise t-test yielded no significant difference in the fine sediment content of the sites located up to 1 km downstream of the tributary junction and the sites in group 2 (similar $D50_p$) and group 3 (similar $D50_{sp}$) (Table 24). This is encouraging because if harvesting was injecting fine sediments into the river, the amount of fines should be increasing once the sediments deposit. Analysis (section VIII.3.1) has shown that the variations in $D50_p$ are not associated to harvesting activities. Thus, theoretically, a comparison of sites with similar $D50_p$ should determine if riffles located downstream of tributaries have higher sediment contents. Bulk sample analysis did not show a difference between the two groups. However, these results need to be validated, preferably with freeze core sampling, which better captures sediments < 500 µm (Zimmermann, 2003).

Second, the pairwise t-test of the sites located up to 1 km downstream of a tributary and group 1 (sites located up to 1 km upstream of a tributary junction) showed the latter had a higher average $\%fines_{sp}$. Thus, the sediment injected into the mainstem from these tributaries is not deposited, despite the reduction in slope, which is usually followed by a reduction in shear stress and transport capacity (Gordon *et al.,* 1992). The added discharge from the tributaries may flush sediment out of the riffles located immediately downstream of their junction, although some of these tributaries have small basin areas (e.g. 0.4 km^2). The range in tributary size is 0.4 to 19 km^2, with a mean of 5.4 km^2. This suggests these tributaries would have small discharges, which would not increase the Lac branch discharge considerably. The energy regime of the Cascapédia is sufficient to flush fines from the river bed, even if harvesting operations are creating more deposition (which has not been shown with this methodology). Future studies should measure sediment loads following rain events to test the hypothesis that even if a tributary's sediment load is increased, these increases are usually not noticeable in the mainstem segments of the river until a storm occurs (Lewis *et al.,* 2001).

Moreover, when tributaries inject sediment, they also increase discharge, which increases a channel's transport capacity, despite the decrease in slope. Therefore, the sediment may be deposited downstream, in segments with milder slopes. Hartman *et al.* (1996) found sediment deposition 4 km downstream of harvested parcels. This hypothesis could not be tested with this dataset because in segments 2, 3, and 4, the slope does not decrease significantly below the tributary junctions. In segment 1, the bed slope decreases at H10, two kilometres below Th2 (Figure 24a). However, Th3, located upstream of H09 could be washing out any fines settling from Th2. Proper testing of this hypothesis requires a decline in slope downstream of the tributary junction and no tributary junction between the decline in slope and the tributary under study.

IX CONCLUSION

Because watersheds have their own sediment distribution and characteristics, climate, and topography, specific impacts of harvesting on one river can rarely be applied to another (Ward, 1971; Alila and Beckers, 2001; Caissie *et al.,* 2002). Therefore, published forest-fish interaction studies such as those undertaken at Carnation Creek (Tschaplinski, 1998, 2000) cannot be applied directly to the Cascapédia without some field verifications. The purpose of this research was to determine whether the harvesting operations in the Cascapédia watershed are related to a change in the morphology of low-order tributaries and in the sedimentology of four mainstem segments.

Two general conclusions emerge from this research. First, in low-order tributaries, harvesting operations are associated with stream enlargement, although widening does not occur in all streams and a portion of the variation in stream width remains unexplained. While the models relating harvesting metrics to stream width residuals in basins of 1.75 to 25 km^2 are weak ($r^2 < 0.20$), three different models (%ECA(85), %ECA(1997), and road density, all three in the 60 m buffer) predict the widening to be approximately 25%. This enlargement erodes the banks and injects sediment into the river, where it travels through the watershed and deposits when the flow's transport capacity is exceeded. Further studies on the relation between stream morphology and harvesting activities are required to validate and verify the robustness of these relations.

Secondly, the analysis of the relation between harvesting metrics and the sedimentology along four segments of the Cascapédia did not yield the expected results. The bulk sampling methodology only detected a few significant relations, which tends to support published conclusions that harvesting impacts are more severe in low-order tributaries than in mainstem segments (Church, 1996; Slaymaker, 2000; Hudson, 2001). Furthermore, the significant models were either contrary to published theories or sensitive to a few points. Three reasons may explain this. Firstly, it is difficult to design studies that provide unequivocal results of a system's response to disturbance (Hicks and Hall, 2003). Therefore, the methodology may be the reason for the paucity of significant, reliable models. Secondly, the Cascapédia's energy regime may be sufficient to flush out any additional sediment injected into the river by harvesting. Thirdly, any change in habitat quality or pavement D50 cannot be attributed solely to harvesting (Hauer *et al.*, 1999). Oceanic conditions (Hartman *et al.*, 1996), suspended sediment levels (Anderson, 1998), and climate (Beschta *et al.*, 2000) could also play a role, and need to be investigated before final conclusions are made.

A word of caution is also required. While the relations described in the preceding chapters are not strong, they should not be dismissed. Other factors may be contributing to the weakness of the models. First, the methodology may not have been accurate enough for the research objectives outlined in Chapter III and other methodologies should be tested before the issue is laid to rest (e.g. freeze-core sampling, multi-year sampling, or bulk sampling of point bar heads). Second, other variables such as precipitation (Beschta *et al.*, 2000; Caissie *et al.*, 2002), vegetation (Plamondon, 1993), and harvesting technique (Caissie *et al.*, 2002) also affect sedimentology. These were excluded from this study to limit the number of variables in the analysis. Thirdly, the impacts of harvesting in the Cascapédia watershed could be delayed if the sediment is still in transit through the system (Slaymaker, 2000).

Finally, this study is part of a larger group of studies undertaken in the Cascapédia watershed. While the results from this study alone may not seem cause for concern, the project's overall results will produce a clearer signal. Preliminary biology results indicate fish abundance and benthic community diversity decrease as harvesting intensity increases (Deschênes, unpublished; Martel, unpublished). This can have an impact on the health of the salmon population that feeds on these. Therefore, it can only be hoped that the combination of these results will encourage future studies of harvesting impacts on the morphology and sedimentology of the Cascapédia River, considering the economic importance of both harvesting and sport-fishing for the region.

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XI APPENDIX I

Calculated Site variables for low-order streams of the Cascapédia

Site	2002	Coordinates		Area	C. Width (m)		Slope (%)		D50 (mm)		Stream
	Site	Easting	Northing	(km²)	US	DS	US	DS	US	DS	order
T1		693719	5399617	3.20	2.5		3.2		50		2
T2		692804	5399012	0.64	1.2		7.7		31		2
T3		691819	5398236	0.56	1.1		20.4		41		1
T4		693293	5390790	2.55	1.9		3.5		42		2
T5		693814	5391221	1.67	2.7		0.1		25		2
T6		695880	5391999	3.46	1.4		0.0		10		2
T7		696073	5391922	0.29	2.9		5.4		22		1
T8		696741	5392505	1.71	1.6		4.5		28		3
T9		698660	5393705	4.49	3.1		1.5		21		3
T10		701462	5393210	1.42	1.6		2.8		2		2
T11		702224	5393909	4.60	3.0		0.0		12		3
T12		702652	5394248	7.25	3.3		3.6		32		3
T13		704394	5394628	5.11	2.5		3.9		32		3
T14		692636	5389527	3.56	2.7		4.5		18		3
T15		710908	5398646	6.70	3.7		3.9		22		2
T16		710979	5397551	2.04	2.0		3.6		40		2
T17		711472	5397669	0.80	1.0		4.7		12		1
T18		712547	5396952	10.75	4.7		3.1		36		3
T19		713020	5397275	0.35	1.0		8.2		55		1
T20		711071	5397456	1.02	1.0		7.3		2		1
T21		709819	5392314	4.88	3.1		3.1		32		4
T22		711725	5392616	4.01	2.1		2.8		15		3
T23		711841	5393357	0.09	2.9		8.3		22		1
T24		712795	5393466	1.40	1.2		3.1		2		2
T25		714250	5393189	5.83	3.5		4.2		38		2
T26		714905	5394305	2.94	3.5		3.2		42		2
T27		675340	5394798	6.58	3.8		1.2		13		3
T28		679480	5401491	0.61	1.2		1.9		10		1
T29		680170	5403776	5.38	2.8		2.8		16		2
T30		683502	5405653	0.43	2.1		5.4		20		2
T31		688367	5406576	0.74	2.0		7.1		2		1
T32		689856	5406268	1.18	2.5		2.3		20		2
T33		687571	5407502	0.38	1.3		3.5		5		1
T34		686872	5407642	1.68	1.7		48.4		18		2
T35		708857	5406407	0.39	2.3		30.0		68		1
T36		708801	5406408	0.40	1.2		35.2		24		1
T37		708048	5407646	0.85	2.3		6.1		20		2
T38		708004	5408198	1.56	2.2		7.9		38		3
T39		707604	5411835	1.59	2.2		6.4		44		2
T40		707591	5411846	0.63	2.6		7.3		74		1
T41		707527	5411920	0.05	2.0		8.8		60		0
T42		708799	5390006	4.83	3.5		8.0		74		2
T43		279031	5357518	0.50	3.4		20.8		30		1
T44		278258	5359588	1.08	3.8		37.3		136		1
T45		721642	5365977	2.39	4.8		24.6		70		2
T46		702458	5395170	1.72	1.5		2.6		2		1
T47		704998	5396569	2.21	3.3		4.8		22		2
T48		707464	5394022	4.94	2.5		1.3		32		2
T49		710478	5385135	21.48	7.5		5.0		120		4
T50		711641	5380170	0.09	1.7		48.5		142		0
T51		711637	5380700	0.93	3.1		18.2		118		2
T52		713805	5378235	9.90	6.6		9.3		120		3
T53		720098	5369108	13.28	6.5		4.2		120		4
T54		690508	5388137	21.97	6.2		2.3		36		
T55		691164	5387120	0.04	1.0		20.2		2		0
T56		691331	5386834	2.32	2.5		5.5		30		2
T57		690308	5380341	1.83	3.2		0.3		20		1
T58		691851	5380525	1.43	1.9		4.2		2		2
T59		693803	5381462	0.09	0.8		8.5		2		0
T60		689602	5382106	0.05	1.4		3.2				1

Site	2002 Site	Coordinates Easting	Coordinates Northing	Area (km²)	C. Width (m) US	C. Width (m) DS	Slope (%) US	Slope (%) DS	D50 (mm) US	D50 (mm) DS	Stream order
T61		686005	5384261	2.07	3.6		8.0		124		2
T62		686490	5388028	1.60	3.5		3.6		41		1
T63		690743	5390077	0.29	1.8		8.6		45		1
T64		703145	5397913	0.48	1.5		2.9		2		1
T67		698743	5403672	0.21	3.5		5.1		22		0
T68		698388	5405527	0.70	0.9		24.0		2		2
T69		698213	5405592	0.04	1.9		6.0		44		0
T70		697585	5405694	4.02	3.4		7.4		36		2
T71		696457	5408973	7.46	5.8		1.3		84		3
T72		694333	5409232	6.38	2.4		2.5		2		2
T73		701884	5413864	0.03	2.0		7.9		10		1
T74		697890	5413198	3.59	3.6		6.9		32		3
T75		697904	5413290	0.40	1.8		20.1		20		1
T76		699483	5414574	0.40	2.1		7.4		12		1
T77		699600	5414625	0.06	2.4		10.5		6		0
T78		699768	5414745	1.79	2.1		5.4		5		2
T79		702113	5414810	0.18	0.7		24.9		22		0
T80		702000	5414800	0.74	0.8		8.3		10		1
T101	T5	693807	5391221	1.67	2.5	2.4	6.7	6.4	22	27	2
T102		694838	5391647	0.47	0.7	0.9	4.2	9.2	2	2	1
T103	T6	695883	5392000	3.46	1.4	1.5	4.8	3.1	8	6	2
T104	T7	696084	5391922	0.29	2.2	2.5	7.7	2.6	24	17	1
T105	T8	696764	5392509	1.71	1.6	2.0	5.0	2.9	22	34	3
T106	T9	698624	5393487	4.49	2.0	2.5	0.4	5.5	12	36	3
T107	T11	702183	5393693	4.60	2.7	1.8	4.2	3.8	2	4	3
T108	T12	702597	5394035	7.25	2.7	2.7	2.8	2.8	44	39	3
T109	T13	704350	5394412	5.11	2.1		4.4		34		3
T110	T56	691333	5386854	2.32	2.2	2.9	5.4	2.8	45	37	2
T111		697873	5384465	6.00	3.5	4.4	4.6	0.4	47	4	2
T112a		699590	5384991	13.22	4.5	3.9	2.9	1.3	18	32	3
T112b		699590	5384991	7.41	3.3	3.0	3.3	4.7	60	8	3
T113		701997	5384945	5.93	4.5	3.8	4.2	3.3	24	85	2
T114		697818	5383991	9.67	3.7		1.8		12		3
T115	T4	693389	5390337	2.55	1.8	1.7	7.1	2.8	17	2	2
T116		710486	5398119	21.23	5.3	5.4	1.6	1.6	108	74	3
T117	T18	712509	5396739	10.69	4.4	4.4	1.0	3.5	8	16	3
T118	T25	714201	5392976	5.83	3.6	3.6	4.2	2.2	35	40	2
T119	T24	712746	5393252	1.40	1.3	1.1	3.6	3.1	2	2	2
T120	T22	711678	5392389	4.01	2.4	1.9	4.2	1.9	12	22	3
T121	T21	709797	5392145	4.88	2.6	3.3	12.1	3.5	44	51	4
T122	T26	714867	5394073	2.94	2.8		2.0		41		2
T124		665352	5381431	7.38	3.1	3.8	4.9	2.8	76	15	2
T125		664572	5386044	1.31	2.3	2.6	6.0	1.3	16	21	2
T126		669572	5390606	0.76	2.3	2.3	5.1	7.6	6	18	1
T127		670079	5390956	0.63	2.1	1.7	5.1	5.0	2	14	1
T128		671366	5392539	0.41	0.9	1.9	4.8	2.0	2	10	1
T129		672639	5393484	18.73	7.5	7.2	2.2	3.4	78	86	3
T130		676873	5387750	0.87	2.4	1.4	3.1	1.0	2	4	1
T131		668559	5387646	12.17	4.9	4.1	0.7	0.9	16	6	4
T132		664673	5386307	0.85	1.8	2.5	5.1	7.4	14	16	1
T133		664411	5385830	0.30	1.6	1.4	3.8	8.8	10	24	0
T136	T68	698220	5405603	0.70	1.6	2.3	11.0	9.2	49	50	2
T137	T70	697592	5405679	4.02	2.8	2.7	6.6	5.0	34	22	2
T138		720850	5354501	22.67	10.3	9.5	3.2	2.2	75	70	
T139		672918	5393586	0.72	1.9	1.9	3.8	0.7	11	7	2
T140		674448	5394113	0.12	1.2	1.9	6.0	9.1	7	25	1
T143	T30	683431	5405419	0.43	1.8	1.5	5.2	3.1	43	35	2
T144	T31	688350	5406340	0.59	1.8	2.0	1.3	3.8	24	26	1
T145		695877	5399781	15.82	5.0	6.5	0.7	1.8	24	17	3
T146		679065	5381510	17.18	7.4	5.6	1.5	1.6	53	37	3
T147	T58	691878	5380536	1.43	1.8	2.9	2.3	4.8	11	26	2
T148		719353	5370244	97.70	17.0		1.8		138		
T149		279292	5351567	3.17	4.7	4.1	3.5	1.2	69	57	3
T150		279022	5353660	0.74	2.6	2.8	4.7	5.5	22	30	2
T151		278998	5354223	2.53	3.1		2.8		41		3
T152		698971	5400411	9.11	4.1	4.8	1.3	2.8	68	78	4
T153	T1	693670	5399383	3.23	3.0	2.4	5.8	4.1	56	60	2

XII APPENDIX II

Table XII.1. Models relating composite stream width to various landscape variables. * indicates a significant relation at the 5% level.

Variable	Equation	R^2 (P)
Composite width versus:		
Basin area	**$1.7 \cdot Area^{0.40}$**	**0.549 (0.000)***
Channel length	**$1.4 \cdot Length^{0.38}$**	**0.501 (0.000)***
Basin slope (%)	$2.1 \cdot Basin\ Slope^{0.156}$	0.008 (0.178)
Stream density (km/km^2)	$3.1 \cdot Density^{-0.06}$	0.000 (0.663)
Channel slope (%)	$3.2 \cdot Channel\ slope^{-0.04}$	0.000 (0.406)
Riparian zone side slope (%)	$3.0 \cdot Riparian\ zone\ side\ slope^{0.03}$	0.000 (0.739)
Stream order	**$0.84 + 0.93 \cdot Order$**	**0.319 (0.000)***
Link-magnitude	**$1.84 + 0.16 \cdot Magnitude$**	**0.477 (0.000)***
Geology – alluvial deposits (%)	**$3.4 \cdot AD^{-0.06}$**	**0.063 (0.012)***
Geology – weathered deposits (%)	**$1.3 \cdot WD^{0.22}$**	**0.121 (0.000)***
Basin area and D50	**$1.02 \cdot Area^{0.42} \cdot D50^{0.14}$**	**0.657 (0.000)***

Table XII.2. Models relating bankfull width to various large-scale landscape structure variables for streams in basins < 1.75 km^2. * indicates a significant relation at the 5% level.

Variable	Equation	R^2 (P)
Bankfull width versus:		
Basin area	**$1.5 \cdot Area^{0.14}$**	**0.050 (0.022)***
Stream length	**$1.3 \cdot Length^{0.15}$**	**0.047 (0.035)***
Basin slope (%)	**$0.78 \cdot Basin\ Slope^{0.25}$**	**0.039 (0.043)***
Stream density (km/km^2)	$1.3 \cdot Density^{0.07}$	0.000 (0.587)
Channel slope (%)	$1.65 \cdot Channel\ slope^{-0.13}$	0.023 (0.066)
Riparian zone side slope (%)	$1.36 \cdot RZ\ side\ slope^{0.05}$	0.000 (0.613)
Geology – till (%)	$1.38 \cdot Till^{-0.02}$	0.000 (0.741)
Geology – weathered deposits (%)	$1.36 \cdot WD^{0.02}$	0.000 (0.803)
Basin area and D50	**$0.8 \cdot Area^{0.15} \cdot D50^{0.23}$**	**0.242 (0.000)***
Stream length and D50	**$0.79 \cdot Length^{0.13} \cdot D50^{0.20}$**	**0.200 (0.000)***

XIII APPENDIX III

Table XIII.1. Models relating width residuals to harvesting metrics for streams in medium-sized basins. * denotes a significant relation at the 5% level.

Variable	Equation	r^2	P
Residual width versus:			
Basin-scale metrics:			
Road density (km/km^2)	$0.96 \cdot \text{road density}^{0.05}$	0.007	0.240
%ECA	$0.92 \cdot \text{ECA}^{0.02}$	0.000	0.523
%ECA(85)	$0.86 \cdot \text{ECA(85)}^{0.06}$	0.046	0.072
%ECA(65)	$0.91 \cdot \text{ECA(65)}^{0.03}$	0.000	0.348
%ECA(60)	$0.84 \cdot \text{ECA(60)}^{0.06}$	0.038	0.186
%ECA(55)	$0.92 \cdot \text{ECA(55)}^{-0.03}$	0.002	0.331
Slope of ECA(85) parcels (in %)	$1.1 \cdot \text{Slope}^{-0.07}$	0.000	0.539
Distance to ECA(85) parcel (m)	$1.08 \cdot \text{Distance}^{-0.02}$	0.018	0.174
%ECA(85) + Slope ECA(85) parcels (%)	$1.25 \cdot \text{ECA(85)}^{0.06} \cdot \text{Slope}^{-0.09}$	0.040	0.062
60 m corridor buffer metrics:			
Road density (km/km^2)	$\mathbf{0.99 \cdot road\ density^{0.09}}$	**0.106**	**0.011***
%ECA	$0.92 \cdot \text{ECA}^{0.02}$	0.000	0.582
%ECA(85)	$\mathbf{0.86 \cdot ECA(85)^{0.09}}$	**0.141**	**0.006***
%ECA(65)	$0.95 \cdot \text{ECA(65)}^{-0.01}$	0.000	0.961
%ECA(60)	$\text{ECA(60)}^{-0.04}$	0.000	0.536
%ECA(55)	$0.89 \cdot \text{ECA(55)}^{-0.01}$	0.000	0.779
Slope of ECA(85) parcels (in %)	$0.92 \cdot \text{Slope}^{0.02}$	0.000	0.847
%ECA(85) + slope ECA(85)(%)	$0.85 \cdot \text{ECA(85)}^{0.09} \cdot \text{Slope}^{0.01}$	0.121	0.023

Table XIII.2. Models relating width residuals to individual Attenuation Factor (AF) classes at the 60 m and watershed scales. * denotes a significant relationship.

Variable	Equation	r^2	P	n
Width residual versus:				
%ECA(02) – 60 m	$1.01 \cdot \text{ECA(02)}^{0.01}$	0.000	0.648	25
%ECA(01) – 60 m	$0.98 \cdot \text{ECA(01)}^{0.03}$	0.092	0.076	25
%ECA(00) – 60 m	$2 \cdot \text{ECA(00)}^{0.1}$	0.269	0.059	11
%ECA(99) – 60 m	$0.94 \cdot \text{ECA(99)}^{-0.04}$	0.266	0.135	7
%ECA(98) – 60 m	$\text{ECA(98)}^{-0.01}$	0.000	0.888	19
%ECA(97) – 60 m	$\mathbf{0.81 \cdot ECA(97)^{0.1}}$	**0.195**	**0.012**	**27**
%ECA(02)	$\mathbf{1.01 \cdot ECA(02)^{0.04}}$	**0.236**	**0.001***	**42**
%ECA(01)	$0.98 \cdot \text{ECA(01)}^{-0.01}$	0.000	0.752	32
%ECA(00)	$1.08 \cdot \text{ECA(00)}^{0.04}$	0.061	0.159*	19
%ECA(99)	$0.95 \cdot \text{ECA(99)}^{-0.02}$	0.080	0.235	9
%ECA(98)	$1.01 \cdot \text{ECA(98)}^{0.01}$	0.000	0.850	25
%ECA(97)	$0.92 \cdot \text{ECA(97)}^{0.01}$	0.000	0.722	31

Table XIII.3. Models relating bankfull width to the harvesting metrics at the 60 m and watershed scales for streams in small basins. * indicates a significant result.

Variable	Equation	r^2	P
Residual width versus:			
Watershed metrics:			
Road density (km/km^2)	$0.99 \cdot \text{road density}^{-0.03}$	0.000	0.516
%ECA	$1.1 \cdot \text{ECA}^{-0.05}$	0.000	0.422
%ECA(85)	$1.07 \cdot \text{ECA(85)}^{-0.07}$	0.009	0.265
%ECA(65)	$0.96 \cdot \text{ECA(65)}^{0.04}$	0.000	0.792
%ECA(60)	$1.08 \cdot \text{ECA(60)}^{-0.02}$	0.000	0.850
%ECA(55)	$0.70 \cdot \text{ECA(55)}^{0.14}$	0.279	0.067
%ECA(50)	$0.75 \cdot \text{ECA(50)}^{0.80}$	0.017	0.265
%ECA(45)	$3.52 \cdot \text{ECA(45)}^{-0.46}$	0.000	0.480
%Slope of ECA(85) parcels	$\mathbf{0.30 \cdot Slope^{0.54}}$	**0.185**	**0.008***
Distance to ECA(85) parcel (m)	$0.74 \cdot \text{Distance}^{0.05}$	0.075	0.070
%ECA(85) + Slope ECA(85) parcels (%)	$0.35 \cdot \text{ECA(85)}^{-0.04} \cdot \text{Slope}^{0.52}$	0.171	0.484
60 m buffer metrics:			
Road density (km/km^2)	$1.03 \cdot \text{road density}^{-0.05}$	0.043	0.072
%ECA	$1.19 \cdot \text{ECA}^{-0.07}$	0.025	0.149
%ECA(85)	$0.93 \cdot \text{ECA(85)}^{-0.03}$	0.025	0.097
%ECA(65)	$1.1 \cdot \text{ECA(65)}^{0.03}$	0.003	0.272
%ECA(60)	$0.79 \cdot \text{ECA(60)}^{-0.05}$	0.013	0.170
%ECA(55)	$1.02 \cdot \text{ECA(55)}^{0.01}$	0.000	0.688
%ECA(50)	$0.94 \cdot \text{ECA(50)}^{-0.02}$	0.000	0.460
%Slope of ECA(85) parcels	$0.69 \cdot \text{Slope}^{0.12}$	0.000	0.424
%ECA(85) + slope ECA(85) (%)	$0.74 \cdot \text{ECA(85)}^{-0.05} \cdot \text{Slope}^{0.12}$	0.000	0.533

XIV APPENDIX IV

Observed data for the four mainstem segments along the Cascapédia

Site	LS2	LS4	Surface D50	Surface % fines	Subsurface D50	Subsurface % fines
Segment 1: Haute Mineurs						
H01	0.00039	0.00089	90.8	0.4	34.6	14.2
H02	0.00100	0.00106	94.1	6.3	34.4	12.2
H03	0.00076	0.00120			13.2	15.9
H04	0.00048	0.00104	77.2	1.3	17.3	10.6
H05	0.00030	0.00137	52.0	1.7	14.7	12.2
H06	0.00097	0.00158	14.0	11.8	11.9	17.4
H07	0.00112	0.00122	20.7	3.9	9.1	18.8
H08	0.00056	0.00090	38.3	5.6	11.4	17.7
H09	0.00066	0.00081	36.4	3.2	13.6	16.8
H10	0.00121	0.00131	22.9	9.0	16.3	12.2
H11	0.00086	0.00217	99.6	0.5	60.5	5.1
H12	0.00444	0.00398	95.3	2.2	74.5	5.5
H13	0.00239	0.00332	85.3	2.1	39.7	6.7
H14	0.00285	0.00298	55.6	1.4	58.9	7.0
H15	0.00379	0.00359	41.8	4.6	69.5	6.8
H16	0.00261	0.00343	96.9	3.4	68.2	7.7
H17	0.00349	0.00226	69.7	1.5	26.7	14.8
H18	0.00244	0.00250	54.2	5.0	58.9	4.8
H19	0.00258	0.00426	71.1	1.4	35.2	5.4
H20	0.00293	0.00266	107.9	0.2	38.3	6.4
H21	0.00511	0.00390	36.9	4.6	50.6	3.9
H22	0.00335	0.00383	83.9	1.7	33.6	10.1
H23	0.00288	0.00304	87.7	0.8	60.5	6.3
H24	0.00126	0.00095	33.2	4.4	22.2	8.5
H25	0.00111	0.00087	22.8	3.1	11.6	14.6
H26	0.00254	0.00279	68.3	0.7	30.8	8.6
Segment 2: Basse Mineurs						
B01	0.00592	0.00491	101.2	0.3	56.1	2.0
B02	0.00443	0.00497	157.2	0.1	28.6	108.0
B03	0.00507	0.00452	105.0	0.7	138.9	2.2
B04	0.00500	0.00423	78.8	0.5	46.0	5.4
B05	0.00156	0.00358	76.4	0.8	22.2	9.3
B06	0.00259	0.00373	130.0	0.2	43.9	3.6
B07	0.00480	0.00349	104.3	0.3	61.5	3.2
B08	0.00393	0.00371	105.7	0.7	103.3	2.9
B09	0.00397	0.00349	81.6	1.8	51.6	8.1
B10	0.00315	0.00334	121.8	0.4	60.5	9.9
B11	0.00290	0.00376			42.5	4.0
B12	0.00298	0.00287	73.9	0.5	51.9	1.7
B13	0.00280	0.00254	83.8		69.9	5.0
B14	0.00281	0.00288	118.6	3.0	31.8	11.8
B15	0.00274	0.00293	64.3	2.2	45.1	7.9
B16	0.00353	0.00304	18.8	8.3	14.4	11.2
B17	0.00396	0.00363	21.1	5.3	41.6	5.9
B18	0.00361	0.00311	34.4	10.9	52.1	2.7
B19	0.00376	0.00303	54.5	1.6	30.1	8.5
B20	0.00244	0.00277	49.8	0.7	36.9	7.5
B21	0.00204	0.00336	45.0	4.2	40.1	9.8
B22	0.00329	0.00286	71.7	0.3	56.9	6.9
B23	0.00700	0.00329	53.8	0.5	35.2	9.1

Site	LS2	LS4	Surface D50	Surface % fines	Subsurface D50	Subsurface % fines
Segment 3: Lac						
L01	0.00164	0.00153	88.0	0.6	64.0	7.9
L02	0.00117	0.00148	108.5	0.4	26.2	8.8
L03	0.00127	0.00149	55.2	1.8	34.3	4.4
L04	0.00121	0.00143	43.5	2.6	22.9	9.9
L05	0.00175	0.00138	48.9	3.0	19.9	14.2
L06	0.00159	0.00169	62.2	0.9	34.0	6.7
L07	0.00143	0.00140	97.0	0.9	63.8	5.8
L08	0.00146	0.00128	49.7	2.9	31.4	8.4
L09	0.00111	0.00114	97.0	2.5	32.5	12.6
L10	0.00113	0.00106	34.5	3.6	27.3	7.2
L11	0.00093	0.00074	66.9	1.7	15.9	16.4
L12	0.00093	0.00078	24.9	11.8	9.7	24.9
L13	0.00071	0.00078	50.7	7.1	21.9	15.0
L14	0.00070	0.00078	103.8	0.9	58.5	8.6
L15	0.00049	0.00074	65.3	1.1	27.5	5.2
L16	0.00208	0.00255	35.9	3.0	26.3	15.0
L17	0.00219	0.00213	27.3	7.3	22.7	9.2
L18	0.00255	0.00201	42.1	2.7	17.7	14.3
L19	0.00222	0.00209	51.2	1.0	22.4	9.2
L20	0.00199	0.00192	33.6	5.4	24.6	13.6
L21	0.00206	0.00143	16.0	9.9	22.7	10.0
Segment 4: Échouement						
E01	0.00422	0.00462	97.9	1.6	22.5	13.1
E02	0.00502	0.00406	86.2	0.2	53.0	22.4
E03	0.00250	0.00413	74.2	1.3	22.3	7.5
E04	0.00636	0.00474	70.8	0.4	20.2	9.4
E05	0.00397	0.00391	31.3	8.1	14.1	14.1
E06	0.00292	0.11336	70.2	0.4	25.7	6.9
E07	0.00415	0.00364	120.7	0.2	22.8	9.9
E08	0.00368	0.00416	103.3	0.2	27.4	8.9
E09	0.00418	0.00069	88.3	0.4	32.2	6.8
E10	0.00500	0.00497	33.1	3.0	10.3	17.1
E11	0.00389	0.00400	107.4	0.1	24.9	8.8
E12	0.00547	0.00509	87.1	0.3	16.2	14.2
E13	0.00637	0.00615	109.4	0.8	24.7	7.5
E14	0.00567	0.00505			26.3	6.5
E15	0.00506	0.00498	86.3	0.1	64.1	2.4
E16	0.00536	0.00429	62.2	1.1	38.0	6.0
E17	0.00522	0.00514	84.9	0.1	23.4	5.6
E18	0.00401	0.00424	33.1	1.7	25.1	7.3

XV APPENDIX V

Models relating variations in $D50_p$ to large-scale landscape structure and reach-scale variables

Table XIV.1. Relation between pavement D50 and geology deposits, slope, and shear stress by segment. * indicates a significant relation.

Site	Geology type	Equation	R^2	P
Segment 1	Glacial deposits	$457 \cdot GD^{1.01}$	0.000	0.810
	Organic deposits	$148252 \cdot OD^{-4.83}$	0.069	0.110
	Weathered deposits	$11721 \cdot WD^{-1.73}$	0.179	0.020*
	Alluvial deposits	$18.8 \cdot AD^{-1.96}$	0.082	0.090
Segment 2	Glacial deposits	$0.001 \cdot GD^{-7.62}$	0.228	0.014
	Organic deposits	$0.00001 \cdot OD^{15.15}$	0.262	0.009*
	Weathered deposits	$0.0000001 \cdot WD^{9.87}$	0.266	0.008*
	Alluvial deposits	$203 \cdot AD^{3.45}$	0.382	0.001*
Segment 3	Glacial deposits	$50 \cdot GD^{0.13}$	0.000	0.590
	Organic deposits	$48 \cdot OD^{0.40}$	0.325	0.004*
	Weathered deposits	$100000 \cdot WD^{-1.21}$	0.318	0.005*
	Alluvial deposits	$312 \cdot AD^{-1.80}$	0.316	0.005*
	Fluvioglacial deposits	$15.5 \cdot FGD^{-0.77}$	0.172	0.035*
Segment 4	Glacial deposits	$21.8 \cdot GD^{-1.35}$	0.000	0.811
	Organic deposits	$166 \cdot OD^{-0.48}$	0.000	0.817
	Weathered deposits	$0.66 \cdot WD^{0.79}$	0.000	0.689
	Alluvial deposits	$112 \cdot AD^{-0.59}$	0.000	0.590

Site	Equation	r^2	P	Equation	r^2	P
	$D50_p$ versus LS2			*LS2 and area*		
Segment 1	$153 \cdot LS2^{0.16}$	0.010	0.278	$0.000001 \cdot Area^{3.25} \cdot LS2^{-0.18}$	0.065	0.184
Segment 2	$131 \cdot LS2^{0.11}$	0.000	0.756	$10^{39} \cdot Area^{-15.3} \cdot LS2^{-0.16}$	0.243	0.027
Segment 3	$2.4 \cdot LS2^{-0.46}$	0.113	0.075	$1.53 \cdot Area^{0.98} \cdot LS2^{0.39}$	0.312	0.013
Segment 4	$142 \cdot LS2^{0.12}$	0.000	0.787	$2500 \cdot Area^{-0.52} \cdot LS2^{0.15}$	0.000	0.761
	$D50_p$ versus LS4			*LS4 and area*		
Segment 1	$765 \cdot LS4^{0.42}$	0.148	0.033*	$20000 \cdot Area^{-0.57} \cdot LS4^{0.51}$	0.112	0.104
Segment 2	$39810 \cdot LS4^{1.12}$	0.093	0.091	$6 \cdot 10^{57} \cdot Area^{-23.4} \cdot LS4^{-1.19}$ 0	.279	0.017
Segment 3	$6.15 \cdot LS4^{-0.32}$	0.006	0.303	$6.2 \cdot Area^{1.19} \cdot LS4^{0.8}$	0.425	0.003*
Segment 4	$63 \cdot LS4^{-0.03}$	0.000	0.808	$362 \cdot Area^{-0.33} \cdot LS4^{-0.03}$	0.000	0.962
	$D50_p$ versus LSS			*LSS and area*		
Segment 1	$2371 \cdot LSS^{0.63}$	0.189	0.017*	$1 \cdot 10^{12} \cdot Area^{-3.13} \cdot LSS^{1.3}$	0.210	0.032
Segment 2	$29309 \cdot LSS^{1.07}$	0.121	0.063	$2 \cdot 10^{38} \cdot Area^{-14.44} \cdot LSS^{0.01}$ 0.233	0.031	
Segment 3	$814 \cdot LSS^{-0.14}$	0.000	0.556	$0.3 \cdot Area^{0.67} \cdot LSS^{-0.15}$	0.299	0.016
Segment 4	$88 \cdot LSS^{0.03}$	0.000	0.909	$411 \cdot Area^{-0.32} \cdot LSS^{0.01}$	0.000	0.987
	$D50_p$ versus PS			*PS and area*		
Segment 1	$879 \cdot PS^{0.46}$	0.193	0.018*	$39.6 \cdot Area^{0.52} \cdot PS^{0.38}$	0.156	0.065
Segment 2	$1.39^{6} \cdot PS^{1.72}$		0.421	0.001* $2 \cdot 1025 \cdot Area^{-8.72} \cdot PS^{0.62}$	0.280	0.017
Segment 3	$815 \cdot PS^{0.39}$	0.184	0.030*	$2.9 \cdot Area^{0.57} \cdot PS^{0.1}$	0.283	0.019
Segment 4	$40 \cdot PS^{-0.11}$	0.000	0.817	$66 \cdot Area^{-0.08} \cdot PS^{-0.1}$	0.000	0.974
	SS4			*SS4 and area*		
Segment 1	$18.5 \cdot SS4^{0.33}$	0.073	0.102	$0.12 \cdot Area^{1.14} \cdot SS4^{0.12}$	0.007	0.358
Segment 2	$0.29 \cdot SS4^{1.43}$	0.238	0.012*	$4 \cdot 10^{28} \cdot Area^{-10.66} \cdot SS4^{0.09}$	0.179	0.099
Segment 3	$55 \cdot SS4^{-0.02}$	0.000	0.945	$0.87 \cdot Area^{0.65} \cdot SS4^{0.01}$	0.267	0.028

Site	Equation	r^2	P	Equation	r^2	P
Segment 4	$116 \cdot SS4^{-0.12}$	0.000	0.691	$1.16 \cdot Area^{0.98} \cdot SS4^{-0.28}$	0.000	0.697
LSSS				*LSSS and area*		
Segment 1	$6.7 \cdot LSSS^{0.60}$	0.134	0.041*	$172 \cdot Area^{-0.76} \cdot LSSS^{0.78}$	0.098	0.124
Segment 2	$1.2 \cdot LSSS^{1.07}$	0.107	0.075	$2 \cdot 10^{38} \cdot Area^{-12.44} \cdot LSSS^{0.54}$	0.268	0.020
Segment 3	$43 \cdot LSSS^{0.06}$	0.000	0.788	$0.89 \cdot Area^{0.73} \cdot LSSS^{-0.16}$	0.301	0.015
Segment 4	$107 \cdot LSSS^{-0.1}$	0.000	0.772	$2985 \cdot Area^{-0.61} \cdot LSSS^{-0.12}$	0.000	0.929
PSS				*PSS and area*		
Segment 1	$12 \cdot PSS^{0.43}$	0.111	0.062	$0.00002 \cdot Area^{3} \cdot PSS^{-0.06}$	0.130	0.089
Segment 2	$0.04 \cdot PSS^{1.96}$	0.553	0.000*	$0.0000001 \cdot Area^{-2.17} \cdot PSS^{2.12}$	0.532	0.001
Segment 3	$23 \cdot PSS^{0.29}$	0.190	0.028*	$1.17 \cdot Area^{0.59} \cdot PSS^{0.06}$	0.280	0.020
Segment 4	$65 \cdot PSS^{0.03}$	0.000	0.922	$1862 \cdot Area^{-0.67} \cdot PSS^{0.08}$	0.000	0.965
	Riffle width (m)			*Point bar width (m)*		
Segment 1	$1.3 \cdot RiffleW^{1.3}$	0.053	0.144	$55 \cdot Pt\ Bar\ W^{-0.08}$	0.155	0.030*
Segment 2	$11.6 \cdot RiffleW^{0.55}$	0.000	0.330	$79 \cdot Pt\ Bar\ W^{-0.08}$	0.122	0.062
Segment 3	$77 \cdot RiffleW^{-0.12}$	0.000	0.823	$51 \cdot Pt\ Bar\ W^{-0.01}$	0.000	0.909
Segment 4	$46 \cdot RiffleW^{0.15}$	0.000	0.865	$76 \cdot Pt\ Bar\ W^{-0.02}$	0.000	0.661

Table XIV.2. Models of the relation between subpavement fine sediment content and geology, slope, and shear stress. * denotes a significant relationship at the 5% level.

Site	Geology Deposit	Equation	R^2	P
Segment 1	Glacial deposits	$0.0008 \cdot GD^{-8.19}$	0.212	0.007*
	Alluvial deposits	$54.2 \cdot AD^{3.27}$	0.483	0.000*
	Organic deposits	$0.000008 \cdot OD^{8.54}$	0.489	0.000*
	Weathered deposits	$12 \cdot WD^{-0.07}$	0.000	0.900
Segment 2	Glacial deposits	$488 \cdot GD^{3.14}$	0.000	0.357
	Alluvial deposits	$2.94 \cdot AD^{2.03}$	0.065	0.106
	Organic deposits	$13335 \cdot OD^{-7.56}$	0.017	0.239
	Weathered deposits	$1x10^{12} \cdot WD^{-4.39}$	0.006	0.292
Segment 3	Glacial deposits	$10.2 \cdot GD^{-0.41}$	0.153	0.033*
	Alluvial deposits	$3.65 \cdot AD^{0.94}$	0.022	0.106
	Organic deposits	$9.75 \cdot OD^{0.22}$	0.035	0.239
	Weathered deposits	$0.13 \cdot WD^{0.65}$	0.029	0.207
Segment 4	Glacial deposits	$0.00002 \cdot GD^{-14.55}$	0.300	0.011*
	Alluvial deposits	$64.7 \cdot AD^{-2.82}$	0.284	0.013*
	Organic deposits	$310 \cdot OD^{-2.14}$	0.000	0.374
	Weathered deposits	$1x10^{-13} \cdot WD^{5.40}$	0.341	0.000*

Site	Equation	r^2	P	Equation	r^2	P
%Fines$_{sp}$ vs area				*Area and D50$_{sp}$*		
Segment 1	$2 \cdot 10^{8} \cdot Area^{-3.33}$	0.489	0.000*	$2 \cdot 10^{5} \cdot Area^{-1.17} \cdot D50^{-0.5}$	0.739	0.000*
Segment 2	$1 \cdot 10^{-5} \cdot Area^{6.86}$	0.013	0.256	$0.001 \cdot Area^{2.05} \cdot D50^{-0.87}$	0.372	0.001
Segment 3	$95 \cdot Area^{-0.37}$	0.036	0.186	$252 \cdot Area^{-0.08} \cdot D50^{-0.85}$	0.633	0.000
Segment 4	$9 \cdot 10^{13} \cdot Area^{-5.7}$	0.278	0.014*	$3x10^{13} \cdot Area^{-5.12} \cdot D50^{-0.53}$	0.454	0.004*
%Fines$_{sp}$ vs LS2				*LS2 and area*		
Segment 1	$0.88 \cdot LS2^{-0.36}$	0.396	0.000*	$9 \cdot 10^{7} \cdot Area^{-2.81} \cdot LS2^{-0.07}$	0.475	0.000
Segment 2	$0.63 \cdot LS2^{-0.39}$	0.000	0.335	$8 \cdot 10^{-15} \cdot Area^{5.62} \cdot LS2^{-0.27}$	0.000	0.425
Segment 3	$43 \cdot LS2^{0.23}$	0.000	0.396	$75 \cdot Area^{-0.54} \cdot LS2^{-0.19}$	0.000	0.392

Site	Equation	r^2	P	Equation	r^2	P
Segment 4	$9.5 \cdot LS2^{0.02}$	0.000	0.973	$6 \cdot 10^{15} \cdot Area^{-6.11} \cdot LS2^{0.34}$ 0.261	0.040	
%Fines$_{sp}$ vs LS4				*LS4 and area*		
Segment 1	$0.18 \cdot LS4^{-0.63}$	0.553	0.000*	$81 \cdot Area^{-1} \cdot LS4^{-0.47}$	0.547	0.000
Segment 2	$0.55 \cdot LS4^{-0.41}$	0.000	0.560	$3 \cdot 10^{-34} \cdot Area^{14.61} \cdot LS4^{1.03}$	0.000	0.396
Segment 3	$4.5 \cdot LS4^{-0.11}$	0.000	0.735	$7.83 \cdot Area^{-1.1} \cdot LS4^{-1.05}$	0.212	0.032*
Segment 4	$6.97 \cdot LS4^{-0.04}$	0.000	0.771	$2 \cdot 10^{14} \cdot Area^{-5.69} \cdot LS4^{0.09}$	0.239	0.051
%Fines$_{sp}$ vs LSS				*LSS and area*		
Segment 1	$0.1 \cdot LSS^{-0.75}$	0.461	0.000*	$2 \cdot 10^{6} \cdot Area^{-2.31} \cdot LSS^{-0.26}$	0.479	0.000
Segment 2	$0.1 \cdot LSS^{-0.70}$	0.016	0.244	$1.6 \cdot 10^{-10} \cdot Area^{3.75} \cdot LSS^{-0.44}$	0.000	0.468
Segment 3	$5.6 \cdot LSS^{-0.08}$	0.000	0.647	$60 \cdot Area^{-0.34} \cdot LSS^{-0.06}$	0.000	0.397
Segment 4	$34.1 \cdot LSS^{-0.26}$	0.000	0.454	$5 \cdot 10^{15} \cdot Area^{-6.69} \cdot LSS^{-0.26}$	0.257	0.042
%Fines$_{sp}$ vs PS				*PS and area*		
Segment 1	$0.48 \cdot PS^{-0.48}$	0.333	0.001*	$1 \cdot 10^{11} \cdot Area^{-4.37} \cdot PS^{0.18}$	0.180	0.469
Segment 2	$0.04 \cdot PS^{-0.87}$	0.080	0.082	$40 \cdot Area^{-1.28} \cdot PS^{-0.95}$	0.043	0.226
Segment 3	$0.14 \cdot PS^{-0.60}$	0.382	0.001*	$0.003 \cdot Area^{0.41} \cdot PS^{-0.08}$	0.406	0.002
Segment 4	$0.05 \cdot PS^{-0.93}$	0.142	0.069	$9162 \cdot Area^{-2.02} \cdot PS^{-0.67}$	0.070	0.226
SS2 (calculated as γ* d* LS2)				*SS2 and basin area*		
Segment 1	$57.1 \cdot SS2^{-0.55}$	0.432	0.000*	$2 \cdot 10^{7} \cdot Area^{-2.86} \cdot SS2^{-0.02}$	0.434	0.001*
Segment 2	$1.47 \cdot SS2^{0.34}$	0.000	0.597	$3 \cdot 10^{-27} \cdot Area^{10.24} \cdot SS2^{0.83}$	0.162	0.079
Segment 3	$26.4 \cdot SS2^{-0.34}$	0.000	0.328	$151 \cdot Area^{-0.41} \cdot SS2^{-0.08}$	0.000	0.433
Segment 4	$4.32 \cdot SS2^{0.18}$	0.000	0.589	$2.5 \cdot 10^{12} \cdot Area^{-5.14} \cdot SS2^{0.21}$	0.112	0.429
SS4 (calculated as γ* d* LS4)				*SS4 and basin area*		
Segment 1	$25.5 \cdot SS4^{-0.33}$	0.329	0.001*	$2.2 \cdot 10^{7} \cdot Area^{-2.35} \cdot SS4^{-0.15}$	0.451	0.000
Segment 2	$9.08 \cdot SS4^{-0.13}$	0.000	0.749	$1.5 \cdot 10^{-39} \cdot Area^{14.86} \cdot SS4^{1.26}$	0.312	0.013*
Segment 3	$6.43 \cdot SS4^{0.12}$	0.000	0.684	$568 \cdot Area^{-0.47} \cdot SS4^{-0.39}$	0.071	0.184
Segment 4	$3.26 \cdot SS4^{0.25}$	0.000	0.444	$5.5 \cdot 10^{11} \cdot Area^{-4.83} \cdot SS4^{-0.18}$	0.092	0.211
LSSS (calculated as γ* d* LSS)				*LSSS and basin area*		
Segment 1	$170 \cdot LSSS^{-0.85}$	0.464	0.000*	$2 \cdot 10^{6} \cdot Area^{-2.18} \cdot LSSS^{-0.33}$	0.484	0.000
Segment 2	$26 \cdot LSSS^{-0.41}$	0.000	0.527	$6 \cdot 10^{-16} \cdot Area^{6.4} \cdot LSSS^{-0.11}$	0.000	0.525
Segment 3	$14.6 \cdot LSSS^{-0.16}$	0.000	0.523	$98 \cdot Area^{-0.35} \cdot LSSS^{-0.06}$	0.000	0.415
Segment 4	$8.34 \cdot LSSS^{0.01}$	0.000	0.980	$5 \cdot 10^{15} \cdot Area^{-6.2} \cdot LSSS^{-0.27}$	0.264	0.039
PSS (calculated as γ* d* PS)				*PSS and basin area*		
Segment 1	$41.2 \cdot PSS^{-0.44}$	0.200	0.010*	$8 \cdot 10^{11} \cdot Area^{-5.24} \cdot PSS^{0.41}$	0.518	0.000
Segment 2	$80.7 \cdot PSS^{-0.72}$	0.052	0.131	$0.33 \cdot Area^{0.92} \cdot PSS^{-0.67}$	0.013	0.326
Segment 3	$28.5 \cdot PSS^{-0.41}$	0.304	0.003*	$3.82 \cdot Area^{0.39} \cdot PSS^{-0.56}$	0.315	0.007
Segment 4	$25.5 \cdot PSS^{-0.27}$	0.000	0.461	$3.6 \cdot 10^{15} \cdot Area^{-6.53} \cdot PSS^{0.24}$	0.252	0.044
Riffle width (m)				*Point bar width (m)*		
Segment 1	$162 \cdot RiffleW^{-0.97}$	0.071	0.096	$10 \cdot Pt\ Bar\ W^{0.01}$	0.000	0.844
Segment 2	$4.8 \cdot RiffleW^{0.04}$	0.000	0.951	$5.2 \cdot Pt\ Bar\ W^{0.03}$	0.000	0.430
Segment 3	$0.23 \cdot RiffleW^{1.03}$	0.114	0.064	$8.9 \cdot Pt\ Bar\ W^{-0.03}$	0.001	0.321
Segment 4	$514 \cdot RiffleW^{-1.25}$	0.064	0.168	$5.7 \cdot Pt\ Bar\ W^{0.25}$	0.128	0.087

XVI APPENDIX VI

Models relating harvesting metrics to $D50_p$ and fine sediment content residuals

Table XV.1. Models relating harvesting metrics to $D50_p$ residuals and fine sediment content residuals for the 4 sampled segments. * denotes a significant relation.

Variable	Equation	r^2	P	Equation	r^2	P
Segment 1 – $D50_p$ residuals versus				$Fines_{sp}$ residuals versus		
Road Density (RD)	$1.69 \cdot RD^{-0.71}$	0.000	0.496	$1.72 \cdot RD^{-0.75}$	0.048	0.131
RD – 500 m	$1.19 \cdot RD^{-0.2}$	0.103	0.097	$1.05 \cdot RD^{-0.05}$	0.000	0.426
RD – 1 km	$0.91 \cdot RD^{0.11}$	0.000	0.643	$1.12 \cdot RD^{-0.16}$	0.057	0.113
RD – 2 km	$1.08 \cdot RD^{-0.08}$	0.000	0.843	$1.26 \cdot RD^{-0.27}$	0.075	0.082
RD – 5 km	$1.13 \cdot RD^{-0.15}$	0.000	0.734	$1.18 \cdot RD^{-0.22}$	0.015	0.245
%ECA	$3206 \cdot ECA^{-2.52}$	0.000	0.651	$0.001 \cdot ECA^{2.07}$	0.000	0.402
%ECA – 500 m	$0.26 \cdot ECA^{0.4}$	0.148	0.036	$0.85 \cdot ECA^{0.07}$	0.000	0.484
%ECA – 1 km	$0.06 \cdot ECA^{1.02}$	0.180	0.022*	$1.25 \cdot ECA^{-0.08}$	0.000	0.702
%ECA – 2 km	$1.47 \cdot ECA^{-0.14}$	0.000	0.855	$2.9 \cdot ECA^{-0.38}$	0.023	0.208
%ECA – 5 km	$92600 \cdot ECA^{-3.93}$	0.152	0.034*	$37.5 \cdot ECA^{-1.25}$	0.078	0.078
%ECA – 60 m	$678 \cdot ECA^{-2.35}$	0.000	0.444	$0.1 \cdot ECA^{0.81}$	0.000	0.570
%ECA(85)	$2.12 \cdot ECA^{-0.29}$	0.000	0.818	$0.18 \cdot ECA^{0.67}$	0.021	0.218
%ECA(85) – 500m	$0.68 \cdot ECA^{-0.04}$	0.000	0.566	$1.12 \cdot ECA^{0.01}$	0.000	0.732
%ECA(85) – 1km	$0.99 \cdot ECA^{-0.01}$	0.000	0.931	$0.93 \cdot ECA^{-0.01}$	0.006	0.291
%ECA(85) – 2km	$0.99 \cdot ECA^{-0.01}$	0.000	0.711	$1.01 \cdot ECA^{0.02}$	0.034	0.169
%ECA(85) – 5km	$2.49 \cdot ECA^{-0.78}$	0.156	0.032	$1.32 \cdot ECA^{-0.25}$	0.104	0.049*
%ECA(85) – 60m	$4.62 \cdot ECA^{-0.67}$	0.000	0.562	$0.29 \cdot ECA^{0.54}$	0.005	0.294
%ECA(65)	$0.04 \cdot ECA^{2.71}$	0.027	0.212	$1.09 \cdot ECA^{-0.07}$	0.000	0.944
%ECA(65) – 2km	$3.5 \cdot ECA^{0.14}$	0.129	0.047*	N/A		
%ECA(65) – 5km	$0.98 \cdot ECA^{-0.01}$	0.000	0.751	$1.03 \cdot ECA^{0.02}$	0.052	0.122
%ECA(65) – 60m	$0.29 \cdot ECA^{4.3}$	0.043	0.167	$0.74 \cdot ECA^{1.02}$	0.000	0.500
%ECA(60)	$0.72 \cdot ECA^{0.28}$	0.000	0.784	$2.07 \cdot ECA^{-0.62}$	0.042	0.147
%ECA(60) – 500m	$0.96 \cdot ECA^{-0.01}$	0.000	0.925	$1.05 \cdot ECA^{0.01}$	0.000	0.843
%ECA(60) – 1km	$1.04 \cdot ECA^{0.01}$	0.000	0.816	$0.63 \cdot ECA^{0.18}$	0.000	0.389
%ECA(60) – 2km	$0.98 \cdot ECA^{-0.01}$	0.000	0.767	$0.9 \cdot ECA^{-0.03}$	0.234	0.005
%ECA(60) – 5km	$0.99 \cdot ECA^{0.01}$	0.000	0.939	$1.05 \cdot ECA^{-0.05}$	0.006	0.289
%ECA(60) – 60m	$0.62 \cdot ECA^{0.67}$	0.000	0.547	$1.69 \cdot ECA^{-0.75}$	0.050	0.128
%ECA(55)	$54 \cdot ECA^{-3.35}$	0.159	0.030*	$4.2 \cdot ECA^{-1.22}$	0.158	0.019
%ECA(55) – 500m	$0.38 \cdot ECA^{0.35}$	0.089	0.085	$0.9 \cdot ECA^{0.04}$	0.000	0.697
%ECA(55) – 1km	$0.18 \cdot ECA^{0.57}$	0.053	0.144	$1.21 \cdot ECA^{-0.06}$	0.000	0.692
%ECA(55) – 2km	$1.68 \cdot ECA^{-0.19}$	0.000	0.607	$1.56 \cdot ECA^{-0.16}$	0.006	0.287
%ECA(55) – 5km	$1.45 \cdot ECA^{-0.16}$	0.000	0.653	$0.62 \cdot ECA^{0.2}$	0.035	0.169
%ECA(55) – 60m	$1.71 \cdot ECA^{-1.03}$	0.000	0.351	$1.92 \cdot ECA^{-1.29}$	0.229	0.005*
Segment 2 – $D50_p$ residuals versus				$Fines_{sp}$ residuals versus		
Road Density (RD)	$0.86 \cdot RD^{0.19}$	0.000	0.960	$0.04 \cdot RD^{4}$	0.000	0.400
RD – 500 m	$0.95 \cdot RD^{0.2}$	0.230	0.022*	$0.96 \cdot RD^{-0.04}$	0.000	0.696
RD – 1 km	$1.01 \cdot RD^{-0.01}$	0.000	0.963	$1.35 \cdot RD^{-0.22}$	0.006	0.295
RD – 2 km	$0.99 \cdot RD^{0.01}$	0.000	0.971	$0.85 \cdot RD^{0.12}$	0.000	0.481
RD – 5 km	$0.97 \cdot RD^{0.03}$	0.000	0.908	$0.86 \cdot RD^{0.16}$	0.000	0.542
%ECA	$0.05 \cdot ECA^{1.01}$	0.000	0.860	$1.5 \cdot 10^{-6} \cdot ECA^{4.45}$	0.000	0.522
%ECA – 500 m	$0.74 \cdot ECA^{0.13}$	0.000	0.381	$1.16 \cdot ECA^{-0.06}$	0.000	0.715
%ECA – 1 km	$0.86 \cdot ECA^{0.05}$	0.000	0.801	$1.32 \cdot ECA^{-0.1}$	0.000	0.698
%ECA – 2 km	$0.60 \cdot ECA^{0.17}$	0.000	0.511	$1.02 \cdot ECA^{-0.01}$	0.000	0.982
%ECA – 5 km	$0.91 \cdot ECA^{0.03}$	0.000	0.857	$0.74 \cdot ECA^{0.1}$	0.000	0.615
%ECA – 60 m	$0.32 \cdot ECA^{0.45}$	0.000	0.845	$0.03 \cdot ECA^{1.38}$	0.000	0.617
%ECA(85)	$5.32 \cdot ECA^{-0.9}$	0.000	0.826	$56 \cdot ECA^{-2.11}$	0.000	0.667
%ECA(85) – 500m	$1.09 \cdot ECA^{0.01}$	0.000	0.632	$1.13 \cdot ECA^{0.02}$	0.000	0.541

Variable	Equation	r^2	P	Equation	r^2	P
%ECA(85) – 1km	$1.03 \cdot ECA^{0.004}$	0.000	0.820	$0.99 \cdot ECA^{-0.001}$	0.000	0.966
%ECA(85) – 2km	$1.03 \cdot ECA^{0.01}$	0.000	0.767	$0.94 \cdot ECA^{-0.01}$	0.000	0.567
%ECA(85) – 5km	$1.05 \cdot ECA^{0.02}$	0.000	0.572	$1.07 \cdot ECA^{0.03}$	0.000	0.531
%ECA(85) – 60m	$2.68 \cdot ECA^{-0.65}$	0.000	0.837	$10 \cdot ECA^{-1.52}$	0.000	0.689
%ECA(65)	$4.6 \cdot ECA^{-1.7}$	0.000	0.726	$0.15 \cdot ECA^{2.1}$	0.000	0.713
%ECA(65) – 500m	$1.01 \cdot ECA^{0.01}$	0.000	0.736	$0.97 \cdot ECA^{-0.01}$	0.000	0.612
%ECA(65) – 1km	$1.01 \cdot ECA^{0.01}$	0.000	0.869	$0.98 \cdot ECA^{-0.01}$	0.000	0.756
%ECA(65) – 2km	$1.01 \cdot ECA^{0.01}$	0.000	0.876	$0.99 \cdot ECA^{-0.01}$	0.000	0.895
%ECA(65) – 5km	$1.01 \cdot ECA^{0.01}$	0.000	0.870	$ECA^{-0.001}$	0.000	0.999
%ECA(65) – 60m	$1.01 \cdot ECA^{-0.9}$	0.000	0.836	$0.97 \cdot ECA^{2.95}$	0.000	0.560
%ECA(60)	$0.71 \cdot ECA^{0.17}$	0.000	0.832	$0.37 \cdot ECA^{0.5}$	0.000	0.606
%ECA(60) – 500m	$0.97 \cdot ECA^{-0.01}$	0.000	0.703	$1.04 \cdot ECA^{0.01}$	0.000	0.699
%ECA(60) – 1km	$0.97 \cdot ECA^{0.05}$	0.233	0.013*	$ECA^{0.01}$	0.000	0.690
%ECA(60) – 2km	$0.5 \cdot ECA^{0.21}$	0.000	0.396	$1.4 \cdot ECA^{-0.1}$	0.000	0.732
%ECA(60) – 5km	$1.21 \cdot ECA^{-0.06}$	0.000	0.708	$0.99 \cdot ECA^{0.01}$	0.000	0.991
%ECA(60) – 60m	$0.88 \cdot ECA^{0.09}$	0.000	0.837	$0.71 \cdot ECA^{0.23}$	0.000	0.648
%ECA(55)	$2.79 \cdot ECA^{-0.87}$	0.000	0.823	$9.64 \cdot ECA^{-1.92}$	0.000	0.681
%ECA(55) – 2km	$0.95 \cdot ECA^{-0.01}$	0.000	0.710	$0.98 \cdot ECA^{-0.01}$	0.000	0.889
%ECA(55) – 5km	$1.01 \cdot ECA^{-0.03}$	0.000	0.726	$1.07 \cdot ECA^{-0.14}$	0.029	0.194
%ECA(55) – 60m	$1.52 \cdot ECA^{-0.62}$	0.000	0.836	$2.47 \cdot ECA^{-1.34}$	0.000	0.710
Segment 3 – $D50_p$ residuals versus				$Fines_{sp}$ residuals versus		
Road Density (RD)	$255 \cdot RD^{-6.43}$	0.000	0.441	$0.17 \cdot RD^{2.03}$	0.000	0.716
RD – 500 m	$1.06 \cdot RD^{-0.2}$	0.270	0.027*	$0.995 \cdot RD^{-0.13}$	0.102	0.106
RD – 1 km	$1.08 \cdot RD^{-0.02}$	0.000	0.886	$1.13 \cdot RD^{-0.14}$	0.000	0.349
RD – 2 km	$0.72 \cdot RD^{0.28}$	0.007	0.298	$1.12 \cdot RD^{-0.1}$	0.000	0.638
RD – 5 km	$0.84 \cdot RD^{0.18}$	0.000	0.488	$1.02 \cdot RD^{-0.02}$	0.000	0.904
%ECA	$357 \cdot ECA^{-1.88}$	0.050	0.167	$0.29 \cdot ECA^{0.4}$	0.000	0.686
%ECA – 500 m	$1.8 \cdot ECA^{-0.21}$	0.029	0.222	$1.27 \cdot ECA^{-0.08}$	0.000	0.494
%ECA – 1 km	$1.3 \cdot ECA^{-0.08}$	0.000	0.580	$1.14 \cdot ECA^{-0.04}$	0.000	0.690
%ECA – 2 km	$1.2 \cdot ECA^{-0.05}$	0.000	0.796	$0.83 \cdot ECA^{0.06}$	0.000	0.669
%ECA – 5 km	$0.56 \cdot ECA^{0.18}$	0.000	0.609	$1.03 \cdot ECA^{-0.01}$	0.000	0.972
%ECA – 60 m	$6 \cdot ECA^{-0.73}$	0.000	0.686	$1.38 \cdot ECA^{-0.13}$	0.000	0.917
%ECA(85)	$0.89 \cdot ECA^{0.07}$	0.000	0.951	$1.14 \cdot ECA^{-0.08}$	0.000	0.926
%ECA(85) – 500m	$1.02 \cdot ECA^{0.01}$	0.000	0.720	$0.97 \cdot ECA^{-0.01}$	0.000	0.381
%ECA(85) – 1km	$ECA^{-0.01}$	0.000	0.946	$ECA^{-0.02}$	0.000	0.648
%ECA(85) – 2km	$1.01 \cdot ECA^{-0.08}$	0.000	0.416	$0.99 \cdot ECA^{0.06}$	0.000	0.343
%ECA(85) – 5km	$1.1 \cdot ECA^{-0.05}$	0.000	0.783	$1.08 \cdot ECA^{-0.05}$	0.000	0.747
%ECA(85) – 60m	$0.62 \cdot ECA^{0.41}$	0.000	0.565	$1.15 \cdot ECA^{-0.12}$	0.000	0.823
%ECA(65)	$2.18 \cdot ECA^{-0.42}$	0.013	0.276	$0.82 \cdot ECA^{0.11}$	0.000	0.704
%ECA(65) – 500m	$1.15 \cdot ECA^{0.03}$	0.068	0.133	$0.91 \cdot ECA^{-0.02}$	0.065	0.121
%ECA(65) – 1km	$1.04 \cdot ECA^{0.02}$	0.004	0.312	$0.97 \cdot ECA^{-0.02}$	0.013	0.264
%ECA(65) – 2km	$1.001 \cdot ECA^{-0.01}$	0.000	0.913	$1.02 \cdot ECA^{-0.03}$	0.000	0.333
%ECA(65) – 5km	$1.54 \cdot ECA^{-0.26}$	0.000	0.535	$0.61 \cdot ECA^{0.31}$	0.003	0.312
%ECA(65) – 60m	$1.62 \cdot ECA^{-0.46}$	0.028	0.223	$0.91 \cdot ECA^{0.09}$	0.000	0.742
%ECA(60)	$24.5 \cdot ECA^{-1.48}$	0.033	0.209	$0.58 \cdot ECA^{0.35}$	0.000	0.676
%ECA(60) – 500m	$0.92 \cdot ECA^{-0.01}$	0.000	0.740	$0.87 \cdot ECA^{-0.02}$	0.000	0.408
%ECA(60) – 1km	$1.02 \cdot ECA^{0.01}$	0.000	0.733	$0.99 \cdot ECA^{-0.01}$	0.000	0.863
%ECA(60) – 2km	$1.02 \cdot ECA^{0.02}$	0.000	0.388	$ECA^{-0.01}$	0.000	0.741
%ECA(60) – 5km	$ECA^{0.02}$	0.000	0.330	$ECA^{-0.01}$	0.000	0.729
%ECA(60) – 60m	$0.54 \cdot ECA^{0.47}$	0.000	0.444	$1.17 \cdot ECA^{-0.12}$	0.000	0.791
%ECA(55)	$33 \cdot ECA^{-2.4}$	0.082	0.112	$0.49 \cdot ECA^{0.49}$	0.000	0.674
%ECA(55) – 500m	$0.95 \cdot ECA^{-0.02}$	0.000	0.355	$0.98 \cdot ECA^{-0.01}$	0.000	0.546
%ECA(55) – 1km	$0.98 \cdot ECA^{-0.01}$	0.000	0.619	$ECA^{0.001}$	0.000	0.971
%ECA(55) – 2km	$1.09 \cdot ECA^{-0.05}$	0.000	0.469	$1.02 \cdot ECA^{-0.01}$	0.000	0.806
%ECA(55) – 5km	$1.03 \cdot ECA^{-0.02}$	0.000	0.804	$1.04 \cdot ECA^{-0.02}$	0.000	0.717
%ECA(55) – 60m	$0.97 \cdot ECA^{0.05}$	0.000	0.933	$1.13 \cdot ECA^{-0.17}$	0.000	0.680

Variable	Equation	r^2	P	Equation	r^2	P
Segment 4 – $D50_p$ versus				$Fines_{sp}$ residuals versus		
Road Density (RD)	$140 \cdot RD^{-1}$	0.000	0.822	$2.79 \cdot RD^{-1.61}$	0.000	0.389
RD – 500 m	$57 \cdot RD^{0.37}$	0.003	0.340	$0.98 \cdot RD^{0.01}$	0.000	0.981
RD – 1 km	$70 \cdot RD^{0.12}$	0.000	0.402	$1.01 \cdot RD^{-0.03}$	0.000	0.617
RD – 2 km	$72 \cdot RD^{0.02}$	0.000	0.961	$1.12 \cdot RD^{-0.15}$	0.000	0.399
RD – 5 km	$76 \cdot RD^{-0.04}$	0.000	0.952	$1.2 \cdot RD^{-0.23}$	0.000	0.395
%ECA	$84 \cdot ECA^{-0.05}$	0.000	0.948	$1.7 \cdot ECA^{-0.22}$	0.000	0.530
%ECA – 500 m	$64 \cdot ECA^{0.06}$	0.000	0.478	$0.96 \cdot ECA^{0.02}$	0.000	0.608
%ECA – 1 km	$11 \cdot ECA^{0.6}$	0.196	0.043*	$0.81 \cdot ECA^{0.07}$	0.000	0.616
%ECA – 2 km	$44 \cdot ECA^{0.15}$	0.000	0.634	$1.01 \cdot ECA^{-0.003}$	0.000	0.984
%ECA – 5 km	$81 \cdot ECA^{-0.03}$	0.000	0.937	$1.41 \cdot ECA^{-0.1}$	0.000	0.507
%ECA – 60 m	$84 \cdot ECA^{-0.09}$	0.000	0.818	$1.18 \cdot ECA^{-0.11}$	0.000	0.503
%ECA(85)	$74 \cdot ECA^{-0.02}$	0.000	0.965	$1.02 \cdot ECA^{-0.04}$	0.000	0.794
%ECA(85) – 500m	$73 \cdot ECA^{-0.001}$	0.000	0.970	$ECA^{0.001}$	0.000	0.899
%ECA(85) – 1km	$73 \cdot ECA^{-0.01}$	0.000	0.749	$ECA^{-0.001}$	0.000	0.952
%ECA(85) – 2km	$73 \cdot ECA^{-0.01}$	0.000	0.600	$ECA^{-0.001}$	0.000	0.952
%ECA(85) – 5km	$73 \cdot ECA^{-0.01}$	0.000	0.610	$ECA^{-0.003}$	0.000	0.721
%ECA(85) – 60m	$73 \cdot ECA^{-0.04}$	0.000	0.752	$ECA^{-0.02}$	0.000	0.747
%ECA(65)	$0.003 \cdot ECA^{6.8}$	0.046	0.202	$0.02 \cdot ECA^{2.6}$	0.020	0.262
%ECA(65) – 2km	$86 \cdot ECA^{0.02}$	0.000	0.518	$1.05 \cdot ECA^{0.01}$	0.000	0.651
%ECA(65) – 5km	$73 \cdot ECA^{0.03}$	0.023	0.258	$ECA^{0.01}$	0.000	0.365
%ECA(65) – 60m	$35 \cdot ECA^{3}$	0.000	0.488	$0.59 \cdot ECA^{2.1}$	0.030	0.234
%ECA(60)	$77 \cdot ECA^{-0.06}$	0.000	0.703	$1.04 \cdot ECA^{-0.05}$	0.000	0.460
%ECA(60) – 500m	$78 \cdot ECA^{0.03}$	0.126	0.089	$1.02 \cdot ECA^{0.01}$	0.006	0.308
%ECA(60) – 1km	$25 \cdot ECA^{0.38}$	0.253	0.023*	$0.95 \cdot ECA^{0.02}$	0.000	0.807
%ECA(60) – 2km	$41 \cdot ECA^{0.19}$	0.000	0.578	$1.36 \cdot ECA^{-0.1}$	0.000	0.506
%ECA(60) – 5km	$94 \cdot ECA^{-0.08}$	0.000	0.646	$1.16 \cdot ECA^{-0.05}$	0.000	0.516
%ECA(60) – 60m	$72 \cdot ECA^{-0.02}$	0.000	0.560	$0.99 \cdot ECA^{-0.01}$	0.000	0.569
%ECA(55)	$51 \cdot ECA^{0.3}$	0.000	0.898	$0.41 \cdot ECA^{0.72}$	0.000	0.461
%ECA(55) – 500m	$84 \cdot ECA^{0.02}$	0.000	0.520	$1.05 \cdot ECA^{0.01}$	0.000	0.614
%ECA(55) – 1km	$80 \cdot ECA^{0.01}$	0.000	0.610	$1.02 \cdot ECA^{0.003}$	0.000	0.804
%ECA(55) – 2km	$73 \cdot ECA^{0.004}$	0.000	0.870	$1.04 \cdot ECA^{0.01}$	0.000	0.352
%ECA(55) – 5km	$71 \cdot ECA^{0.06}$	0.124	0.090	$0.99 \cdot ECA^{0.02}$	0.000	0.335
%ECA(55) – 60m	$67 \cdot ECA^{0.26}$	0.000	0.911	$0.77 \cdot ECA^{0.76}$	0.000	0.438