Dynamics of a Transitional River Pattern: A Multi-Scale Investigation of Controls on the Wandering Pattern of Miramichi Rivers, New Brunswick, Canada

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i. Abstract

The wandering river pattern represents one of the last remaining river patterns that are not well understood. Many aspects of these rivers are not well known, particularly the processes of their creation and maintenance. The term wandering describes gravel or cobble bedded rivers, transitional between braided and meandering, with multiple channel sections around semi-permanent islands connected by single channel sections. This dissertation investigates the controls on the characteristics of wandering rivers within the Miramichi region of New Brunswick through time and at three nested spatial scales.

At the scale of rivers, three factors appear to be needed for wandering to occur: (1) wide valleys, (2) channel energy between braiding and meandering, and (3) avulsion triggers, frequent overbank flows caused by icejams in the Miramichi. Principal component analysis showed that larger wandering rivers displayed greater anabranching intensity than smaller rivers, perhaps related to higher stage ice jams within larger rivers.

At the scale of channels, the wandering pattern of the Renous River was found to be in a state of dynamic equilibrium, with channel creation balanced by channel abandonment. The anabranch cycle model was developed to illustrate the temporal dynamics of anabranch creation, maintenance and abandonment within wandering rivers.

Also at the channel scale, principal component analysis of channel reaches within the Renous River displayed differences in grain size and hydraulic efficiency between side-channels and main-channels. Energy and sediment mobility within side-channels was related to their formation, maintenance and abandonment. Energy and sediment mobility within main-channels was related to mega bedforms called bedwaves. The apex of some bedwaves occurred at diffluences.

At the scale of channel elements, diffluences are stable where a large bar is formed and accretes upstream, creating a large reservoir of sediment upstream of anabranch channels to buffer their degradation. Where diffluences are unstable, a large bar forms within one anabranch channel to partially block flow and may cause its abandonment. The dissertation illustrates that within wandering rivers, processes occurring at multiple spatial and temporal scales interact to create and maintain the pattern.

i. Résumé

Les formes de rivière <<wandering>> représentent une des seules forme de rivière toujours mal comprise. Plusieurs aspects des rivières <<wandering>> ne sont pas bien compris, en particulier les processus de création et d`entretien. Le mot <<wandering>> décrit les rivières recouvert d`un lit de gravier en transition entre les formes tresser et méandre et possèdant des sections multiples canaux autour d`îles reliées en quasi-permanence relié par des sections de canal singulier. Cette thèse recherche les éléments régulateurs sur les caractéristiques des rivières de forme <<wandering>> à travers le temps pour trois échelles spatiaux dans la région de Miramichi en Nouveau-Brunswick.

À l`échelle des rivières, trois facteurs sont requis pour l`apparition du comportement <<wandering>>: (1) des vallées larges, (2) une énergie de canal entre celle du tresser et du mèandre et (3) des déclenchements d`avulsions, c`est-à-dire, des fréquent écoulements hors-banc causés par les obstructions de glace dans les rivières du Miramichi. L`analyse composant principal (ACP) démontre que les plus grandes rivières de forme <<wandering>> présentent une tendance d`anachement plus intense en comparaison avec les plus petites rivières. Ceci pourrait ètre relié a une hauteur d`eau plus élevee pour les plus grandes rivières pendant les obstructions de glace.

À l`échelle des canaux, la forme <<wandering>> de la rivière Renous démontre un état d`équilibre dynamique où la création des canaux est contre-balancée par l`abandonment. Le modèle du cycle des canaux a été développé pour illustrer le comportement dynamique temporel de la création, de l`entretien et de l`abandonment des rivières de forme <<wandering>>.

L`analyse ACP des sections de canaux dans la rivière Renous également à l`échelle des canaux, révèle des différences de grosseur de grain et d`efficacité hydraulique entre les canaux principaux et secondaires. L`énergie et la mobilité du sédiment dans les canaux non-principaux ont été relié à la formation, l`entretien et l`abandonment des canaux. L`énergie et la mobilité des sédiment dans les canaux principaux ont été relié aux formes de grande échelle dans le lit du canal, appelées <<bedwaves>>. Le sommet de certain <<bedwaves>> a lieu aux diffluences.

À l`échelle des éléments du canal, les diffluences sont stables là où une grande barre se forme et s`acréte amont, ce qui créé un réservoir de sédiments en haut des canaux anabranches qui agissent comme tampon à leurs dégradation. Là-où les diffluences sont instables un grand bar se forme à l`intérieur d`un canal anabranche ce qui bloque partiellement l`écoulement et peut causer l`abandonment. Cette thèse démontre que les processus qui ont lieu aux échelles multiples temporelles et spatialles interagissent afin de créer et d`entretenir des formes de rivière <<wandering>>.

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I would like to dedicate this dissertation to my future wife Barbara Ramovs without whose support this dissertation would not have come to fruition. I would also like to thank my parents who give their encouragement freely in support of my adventures.

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ii. **Table of contents**

iii. List of tables

iv. List of figures

v. Preface

vi. Contributions of authors

This dissertation was written as a sequence of four chapters (chapters two through five) that will form papers to be submitted for publication in peer-reviewed journals. Leif Burge and Michel Lapointe will coauthor each paper. Burge and Lapointe collaborated in the study design; Burge collected the data, conducted the analysis and wrote the papers; Lapointe conducted detailed editing of each paper and supervised the project.

vii. Contribution to science

The research presented in this dissertation represents original contributions to the areas of river patterns, wandering river processes, channel dynamics, bedwaves, and the dynamics of diffluence zones. The wandering river pattern represents one of the remaining river patterns that are not well understood. Many aspects of these rivers are not well known, particularly the processes that create and maintain this pattern. The dissertation illustrates that within wandering rivers, processes occurring at different spatial and temporal scales interact to create and maintain the wandering pattern. Water and sediment is routed into anabranches at diffluences, the amount of which depends on the diffluence geometry and stability. Processes occurring within the anabranches, spatially and temporally, determine whether anabranches will grow, be stable or become abandoned. The pattern itself may differ among rivers depending on the magnitude and frequency of events that create or abandon anabranches. This creates a complex river pattern that varies across rivers (inter-river) and spatially and temporally within a river (intra-river).

Chapter two provides a unique examination of factors influencing the river pattern characteristics of wandering rivers in New Brunswick. Sections from five wandering rivers, from one region, were analyzed using multivariate statistics to investigate differences in river pattern among rivers across a size gradient. This study design controlled for factors such as climate, vegetation, lithology and sediment production that differ among regions.

The study determined that for a river to become wandering three factors appear to be needed: (1) wide valleys, (2) channel energy levels between braiding and meandering, and (3) avulsion triggers. Principal component analysis showed that larger rivers within the Miramichi displayed greater anabranching intensity than smaller rivers. This appears to be related to higher stages during icejams within the larger rivers than small rivers, creating a greater number of avulsions. This study suggests that river patterns may vary with size.

Chapter three presents a temporal investigation of the wandering Renous River. The frequency of anabranch creation and abandonment was determined to investigate whether the number of anabranches is stable, increasing or decreasing through time. Within the Renous River study area, channel creation and abandonment frequencies were similar over the 50 years of analysis, indicating that the wandering pattern is in a state of dynamic equilibrium.

This study also illustrated these dynamics through the development of a conceptual model called the anabranch cycle. The cycle begins with the creation of an anabranch by avulsion into an abandoned channel, triggered by an icejam, logjam, sediment wave, or large flood. The cycle continues, as anabranches may be short lived or stable over long periods depending on local conditions. Eventually the cycle ends as anabranches are abandoned, recreating a single channel. The anabranch cycle describes how several channel types may occur within a wandering river as individual anabranch channels are constantly changing.

Chapter four presents a multivariate analysis of a large field-based data set to investigate the interrelationship among channel characteristics within one wandering river. To my knowledge, this application of a multivariate approach is unique, even though the interdependent nature of the fluvial variables creating rivers patterns is well established. In the fluvial geomorphology of river patterns, multivariate analyses are rarely conducted due to the difficulty in obtaining large field data sets with a large number of measured variables.

Principal component analysis determined that two types of processes, side-channel dynamics and bedwaves in main-channels, influence the hydraulic energy and sediment mobility characteristics within wandering river channels. Variability in hydraulic energy and sediment mobility within side-channels depended on their formation, maintenance and abandonment. Variability of energy and sediment mobility within main-channels was influenced by the formation of bedwaves within some main-channels. This multivariate approach allowed for the simultaneous analysis of many interrelated variables and highlights the complexity of the geomorphology of wandering river channels.

Chapter five presents the first detailed temporal analysis of diffluence morphology and surface grain size patterns within wandering rivers. Island head diffluences are important because they route sediment and water into downstream anabranches. This study demonstrated, through a chronosequence, that diffluences are dynamic river elements that may remain stable over long periods or may destabilise resulting in the abandonment of one anabranch. Diffluence stabilization or destabilization is related to a large bar located just upstream or downstream of the diffluence apex, respectively. Diffluences are integral in maintaining the wandering river pattern.

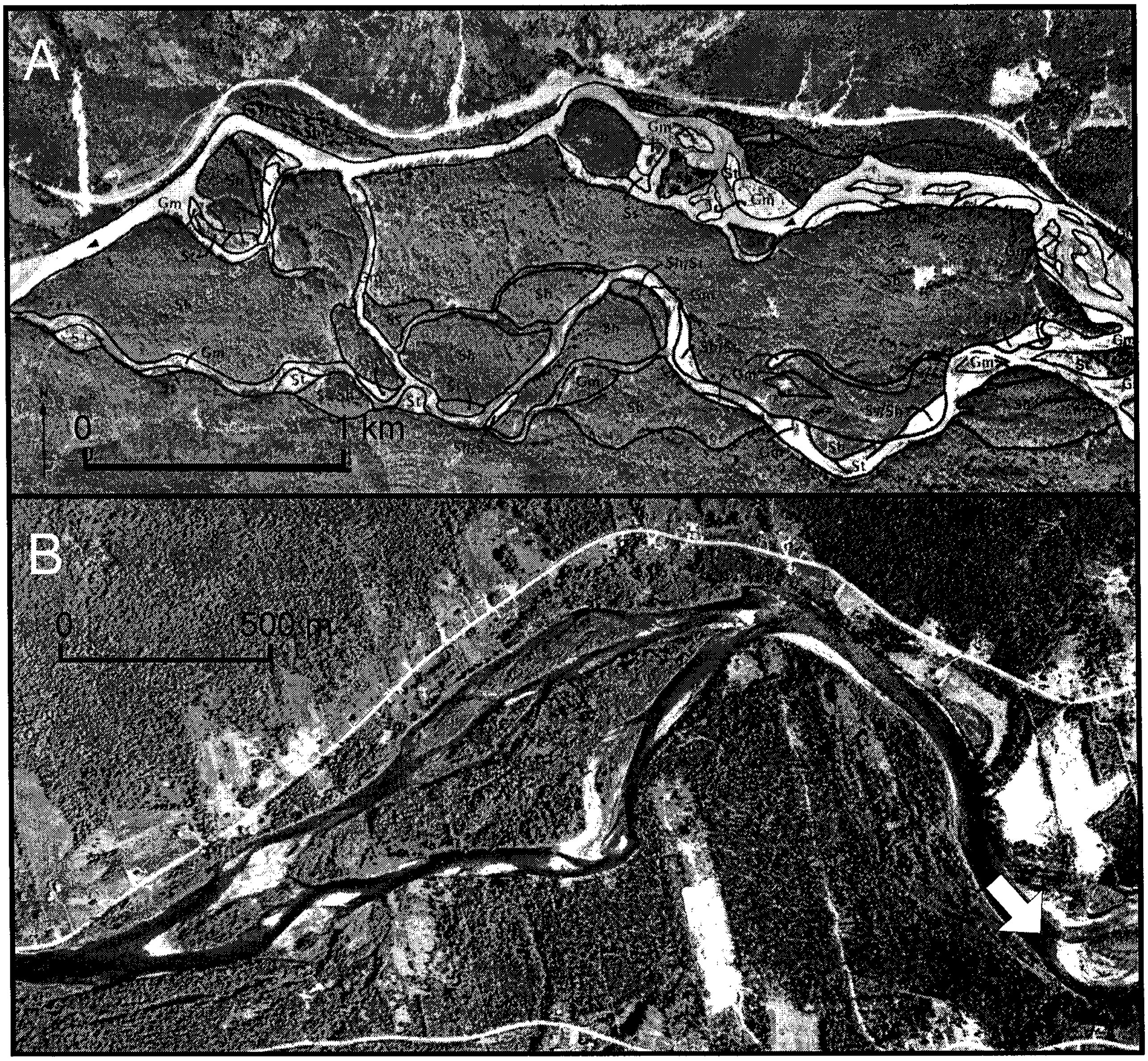
1. Chapter one: Introduction

1.1. Problem statement

Wandering rivers are defined by long sections with multiple channels that surround semi-permanent islands with mature forests (Figure 1-1), connected by neighbouring short single channel sections (Church 1983). Wandering rivers represent one of the remaining river types not well understood. Many aspects of these rivers are not well known, particularly the range of processes that create and maintain this pattern. Factors including hydraulic energy, sediment transport levels, bedwaves and diffluence zones may be important in controlling the wandering pattern, but have not been thoroughly investigated. Wandering rivers also provide diverse and productive habitat for many aquatic organisms, particularly salmonids (Peterson 1982, Tschaplinski and Hartman 1983, Brown and Hartman 1988, Swales and Levings 1989, Nickelson *et al.* 1992, Komadina-Douthwright *et al.* 1997). To manage these rivers effectively, detailed knowledge about the controls on their dynamics is necessary.

Wandering rivers have intermediate energy levels between braided and meandering rivers (Church 1983). However, specific stream power values for wandering rivers have been shown to range from 25 Wm^{-2}, well within the range of single channel gravel bedded meandering rivers, to 115 Wm^{-2}, near the level of braided rivers (Nanson and Knighton 1996). The processes creating and maintaining wandering rivers at energy levels at the lower end of wandering, much below braiding, remain little studied. The creation of wandering rivers has been associated with high sediment input or high sediment transport rates that cause thalweg shoaling and avulsions (Church 1983, Carson

Figure 1-1. Examples of multiple channel wandering sections displaying stable islands and side channels. A) The Bella Coola River, British Columbia (from Desloges and Church 1987). B) The Little Southwest Miramichi River, New Brunswick.


A
0
1 km
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0
500 m

1984b). The abundance of thalweg shoaling under lower energy conditions seems unlikely and literature indicates that wandering rivers may be produced by other processes, including, ice and log jams and frequent large floods, not associated with high sediment input (Hicks 1993, Desloges and Church 1989, Gottesfeld and Johnson-Gottesfeld 1990, Ligon *et al.* 1995). Also, multiple channel sections within wandering rivers have been associated with bedwaves (Church and Jones 1982, Church 1983) but this relationship has not been thoroughly tested.

Studies into the morphology, controlling processes and sedimentology of wandering rivers have been conducted in mountainous areas of western North America (e.g. Church 1983, Brierley and Hickin 1991), Europe (Roberts *et al.* 1997) and New Zealand (Carson 1984a, Carson 1984b), however little research has occurred on rivers that drain low mountains or plateaus in eastern North America. Moreover, previous work investigated only one or two rivers, while the factors that drive differences in the wandering pattern of numerous rivers within a single region have not been studied.

1.2. Multiple channel rivers: background

A number of multiple channel river patterns have been identified (Figure 1-2). Leopold and Wolman (1957) described four river pattern types: meandering, braided, anastomosed, and straight. Wandering was added later as a transitional river type between meandering and braiding (Neill 1973, Church 1983), and anastomosed was redefined, with lower energy than meandering and associated with rapid aggradation (Smith 1973, Smith 1983, Smith 1986). Meandering rivers are well studied, have single sinuous channels, migrate through lateral accretion, and have slopes intermediate between braided and anastomosed (Leopold and Wolman 1957, Smith 1983). Straight channels

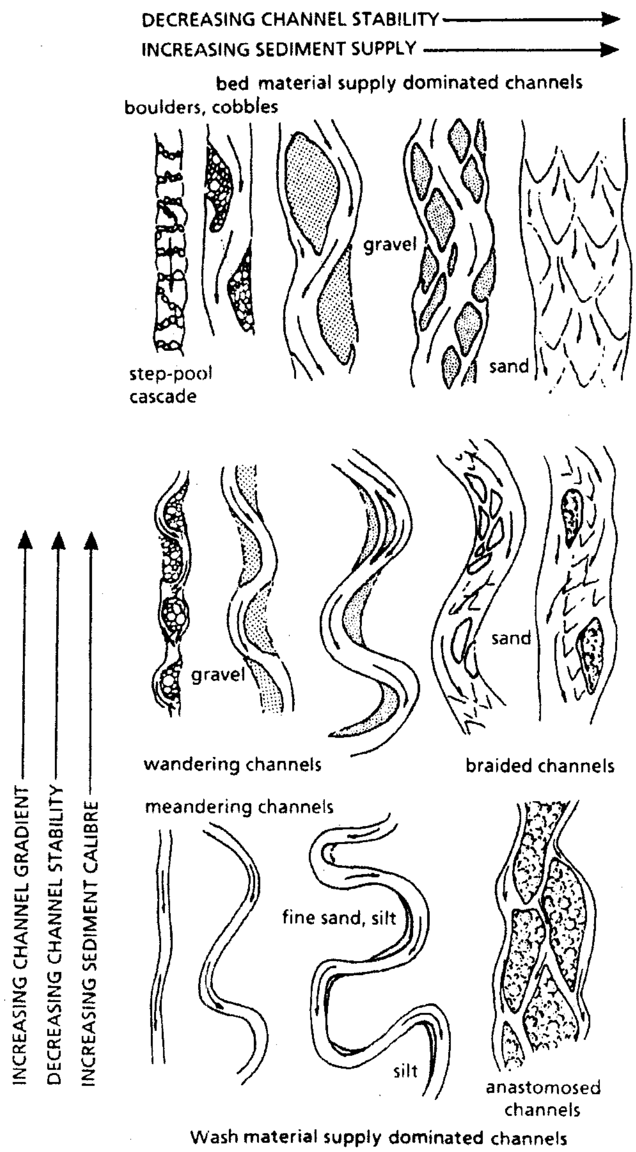

Figure 1-2. Model of channel pattern types in relation to channel gradient, stability and sediment calibre and supply (from Church 1992). Wandering channels have intermediate stability, channel gradient and moderate sediment calibre on the vertical axis and are relatively stable with low sediment supply on the horizontal axis.

are rare, occurring mainly in delta distributaries. Leopold and Wolman (1957), and Lane (1957) recognized a relationship between slope, bankfull discharge, and channel pattern (Figure 1-3). Braided rivers were found to plot above meandering rivers with similar sediment grain size on a scatter plot of slope and bankfull discharge. More recently, anastomosed rivers have been shown to plot below meandering rivers (Figure 1-3) (Locking 1984, Knighton 1998) while wandering rivers plot between braided and meandering (Figure 1-3) (Desloges and Church 1989).

The processes that create and maintain multiple channel river patterns are difficult to understand because multiple channel rivers form a number of morpho-types, which occur under a number of environmental conditions, with variable energy levels and grain size (Figure 1-2). Defining multiple channel river patterns has been a problem for geomorphologists for decades (e.g. Leopold and Wolman 1957). For classifications of river patterns to be useful they must be based on readily interpreted planform characteristics from maps and aerial photographs, and distinguish among rivers with different genesis, hydraulic characteristics or floodplain sedimentology (Makaske 2001). In view of the continuum of channel patterns (anastomosed-meandering-wandering-braiding) generally increasing in energy level this may not be fruitful because transitional patterns may overlap with other patterns. In a recent review paper, Makaske (2001) defined low energy anastomosing rivers as composed of two or more interconnected channels that enclose flood basins (floodplains are enclosed or not enclosed by levees). Unfortunately, this classification includes the wandering river pattern, which displays much higher energy levels than anastomosing rivers (Nanson and Knighton 1996). Simple

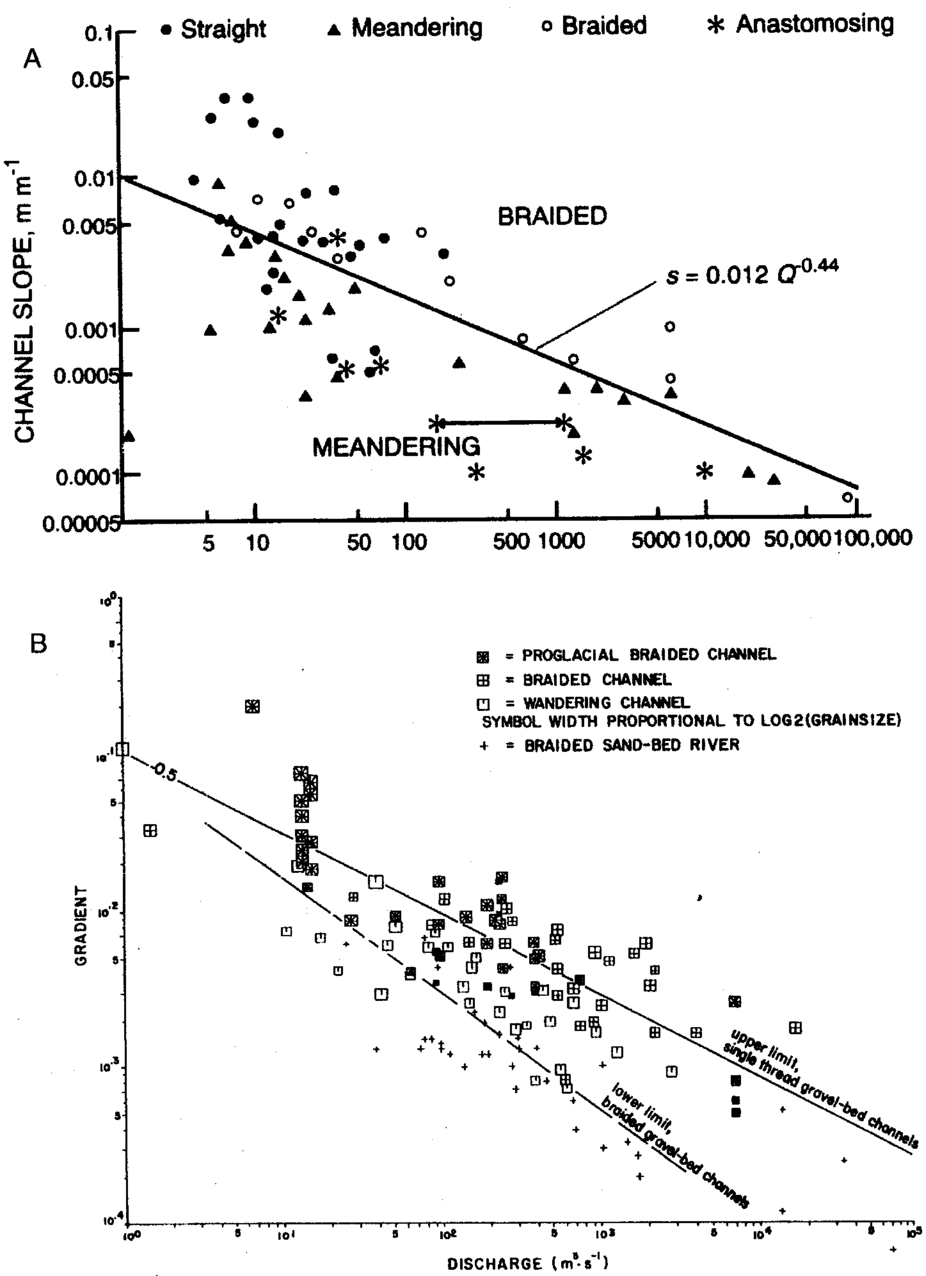

Figure 1-3. A. Discrimination between braided and meandering river patterns based on slope and discharge after Leopold and Wolman (1957). Straight and anastomosed patterns are also included (from Knighton 1998). B. Plot of slope and discharge from braided and wandering channels (from Kellerhals and Church 1989). Wandering rivers plot below braided gravel bedded rivers and above braided sand bedded rivers.

characteristics to differentiate between high energy and low energy multiple channel river patterns with floodplain islands from maps and aerial photographs remain elusive.

Among multiple channel rivers, braided rivers have probably received the greatest scientific study. Braided rivers display higher energy and sediment mobility values than wandering rivers (Desloges and Church 1989). Specific stream power in gravel braided rivers ranges between 120 and 300 Wm^{-2} (Ferguson 1981). At low flows braided rivers are braided in appearance, but may only display a single channel when bars are submerged at high flows. The braided appearance is due to the formation and dissection of large bars within the channel (Smith 1976). The channel bed and location of channels within braided rivers are unstable (Ashmore 1991). They may have gravel or sand beds, have high width-depth ratios, and the highest slope and energy levels (stream power) of all river types (Smith and Smith 1980, Ferguson 1981, Ashmore 1991). Hypotheses for the formation of braided rivers have included high bedload transport rates, high valley slope, aggradation, fluctuating discharge and low bank strength (Knighton 1998). Schumm (1960) found that channels with a bank composition of high silt-clay content (high bank strength) were narrow and deep (meandering) while those with low silt-clay content (low bank strength) were wide and shallow (braided). Local, within-channel aggradation and loss of competence in a zone of lateral flow expansion is the direct sedimentary cause of primary braiding because thalweg shoaling is the fundamental physical mechanism (Ashmore 1991).

Anastomosing rivers have received greater attention in the past decades. Anastomosing describes a network of interconnected channels that split and rejoin (Smith 1983). Anastomosed channels are laterally stable and have the lowest slope and energy levels of all river patterns, except perhaps straight channels (Smith 1973, Smith 1983, Locking 1984, Smith 1986). Nanson and Kinghton (1996) found that specific stream power in anastomosed rivers range between 2 and 40 Wm^{-2}. Anastomosed rivers are usually sand bedded but may also transport gravel (Smith 1973, Nanson and Kinghton 1996). Typical anastomosed channels have deep canal shaped cross sections with cohesive banks, narrow uniform width, and low gradient (Smith and Smith 1980). Channels are often sinuous, but exhibit very little lateral accretion, and despite having very low stream power, tend to form new channels by avulsions. Recently, anastomosed rivers were subdivided into three subtypes: organic, organo-clastic, and mud dominated systems (Nanson and Knighton 1996).

Although anastomosed and wandering rivers have similarities, there are several key differences. First, anastomosed rivers are accepted to have much lower specific stream power levels (2 - 40 Wm^{-2}) than wandering rivers (25 - 115 Wm^{-2}, Nanson and Knighton 1996). Second, anastomosed rivers have smaller bed sediment grain size (sand or sand and gravel) than wandering rivers (gravel or cobble) (Nanson and Knighton 1996). Third, anastomosed channels appear to be more interconnected than wandering channels and have fewer single channel sections (personal observation). Finally, anastomosed rivers have high aggradation rates (Smith 1983, Nanson and Knighton 1996, Makaske 2001, Makaske *et al.* 2002), while wandering rivers are thought to be in grade (Church 1983). For example, the anastomosed Columbia River was found to aggrade at a rate of 1.75 mm/yr, while the wandering Bella Coola River shows evidence of being vertically stable for some time (Church 1983).

1.2.1 Environmental controls on wandering rivers

There are many controls on river patterns. These controls are set within the geomorphic context of a river and may be divided into upstream, within reach, and downstream controls. The geomorphic context includes the valley width and slope, general shape of the river long profile, base level and sediment input from tributaries or valley walls. Certain controls may only become important in areas where the slope and grain size are within a critical range. If grain size is too large or the slope too shallow, there may not be enough extra energy to change the channel shape.

Upstream controls have been used as an argument for the formation of multiple channel reaches in braided and wandering rivers. Enhanced sediment input from the erosion of neoglacial moraines can cause the formation of sediment waves that lead to thalweg shoaling and avulsions. On the wandering Bella Coola River, Church (1983) and Desloges and Church (1989) described unstable, multiple channel sedimentation zones (Figure 1-1A) created through high sediment input rates. Carson (1984a, 1984b) determined that erosion of gravel fans and local aggradation controlled the meandering-braided transition (wandering) on the Canterbury plains, New Zealand. However, at larger spatial scales wandering rivers are thought to be in grade (Desloges and Church 1987, Gottesfeld and Johnson-Gottesfeld 1990). Grade is achieved when a river channel is neither aggrading nor degrading its bed, that is, increasing or decreasing its bed elevation over time (Mackin 1948). This is achieved when the amount of bed material load entering a reach balances the amount exiting a reach over a number of years. On the wandering Bella Coola River, Church (1983) described single channel reaches as transportation zones and multiple channel reaches as sedimentation zones. If sediment is being deposited in multiple channel reaches, they must be aggrading. The distinction may be that the whole river system may not be aggrading, only local aggradation may be occurring in sedimentation zones. One study addressed this question by using ground penetrating radar cross-sections to determine alluvial geometry and gravel depth on a wandering section of the Yukon River, Yukon (Froese *et al.* 2000). This data showed that the Yukon River was in grade over long periods despite possessing sedimentation zones in some reaches.

Church and Jones (1982) proposed a model for the long profile of multiple channel gravel bed rivers (Figure 1-4). It showed convex waves of sediment, termed bedwaves, stored in sedimentation zones superimposed on an overall concave long profile. Transportation zones, located between sedimentation zones, rejoined the concave profile. In the model, deposition was located on the upstream ends of the sediment wedge, where slope decreases, and erosion was located at the downstream ends of sediment wedges, where slope increases. If this model is correct, sedimentation zones should migrate upstream, however, this has not been tested. Also, if the multiple channels are located where deposition occurs in the model, then multiple channels have relatively low slopes and transportation reaches have higher slopes. Within the Bella Coola River, British Columbia multiple channel sedimentation zones were observed to have steeper slopes, lower depth and finer grain size than transportation zones (Desloges and Church 1989). This may be inconsistent with the bedwave model of Church and Jones (1983) and requires further inquiry.

Within reach controls act locally. Local decreases in bank strength may cause a river to widen, causing the deposition of mid-channel bars that form islands. Reach scale

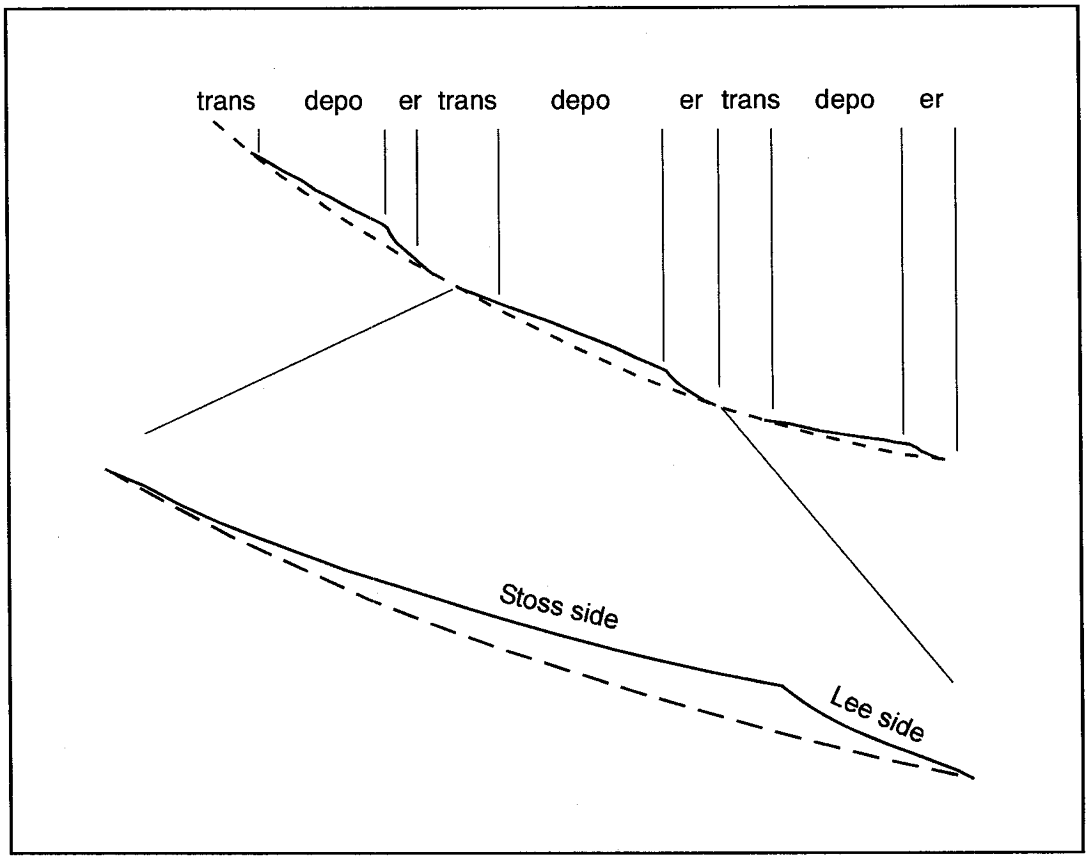

Figure 1-4. Bedwave model of Church and Jones (1982) showing depositional (depo) and erosional (er) sections of bedwaves and sections without bedwaves. Transportation reaches (trans) occur between bedwaves. Bedwaves are superimposed on a general concave profile. Note the long, upstream, low slope stoss side and the short, downstream, lee side of the example bedwave. Deposition occurs on the upstream stoss side, while erosion occurs on the downstream lee side.

processes also cause the abandonment of channels. Morningstar (1988) described a meandering-like process of lateral channel migration in the wandering section of the Fraser River, with islands accreting onto the floodplain and channel abandonment. Icejams or logjams may force water into secondary channels or onto the floodplain creating or maintaining anabranch channels. Gottesfeld and Johnson-Gottesfeld (1990) described a process of channel switching into pre-existing channel segments and observed that new channel development was uncommon on the wandering Morice River, British Columbia. One within-reach trigger for the creation of avulsions is icejams. In certain cold climates, icejams commonly occur at tight bends, shallow cross-sections, the heads of islands, and constrictions (Beltaos *et al.* 1989); all features are common in wandering rivers. Flow restriction from ice accumulation in the main-channel during break-up may force flow into secondary channels or abandoned channels (Smith 1980, Hicks 1993). This constricted flow created during icejams may result in permanent flow redistribution in open water conditions.

There are several channel characteristics formed by ice break-up and ice runs in river channels. These include boulder pavements, ice push buttresses, boulder ridges, ice push bulldozing, grooves on the bed, scour, and, deposition (Collinson 1971, Mackay and Mackay 1977, Smith 1980). Smith (1979) suggested that river ice jams caused major enlargement of channel cross-sections in Alberta rivers. This enlargement increased the bankfull return period to 16 years for open water, from the predicted value of 1.6 years as determined from work on southern rivers without ice. On a boulder rich section of the Little Southwest Miramichi River near Catamaran Brook, New Brunswick a large ice jam in 1994 created a pool approximately 200 m long and 20 m wide (Cunjack pers. com.

1999).

Finally, downstream controls change the energetics of the channel by changing base levels. A base level rise, such as a tributary mouth aggrading in to a valley or rising lake or sea levels, decreases channel slope and may force a river from a meandering to an anastomosed pattern. Base level fall increases slope and may transform a meandering to a wandering pattern, or an anastomosed to a meandering pattern. Base level rise, due to growth of alluvial fans blocking the Bella Coola River valley for example, may decrease the slope of the bed and cause local deposition (Church 1983). Upstream, within reach and downstream controls may all lead to multiple channel river patterns.

1.2.2 Fish habitat in wandering rivers

Multiple channel rivers contain important fish habitat because they offer habitat diversity and substantial habitat variability through the seasons. Understanding of anabranch processes is needed to manage and conserve side-channel habitat that may be threatened by upstream or downstream anthropogenic environmental changes. There are three channel types within wandering rivers. Perennial main-channels are the largest and carry the greatest flow, seasonal side-channels are smaller than main-channels, and abandoned channels are closed from the main-channel upstream but are often open downstream containing backwater from main-channels. Habitat diversity is important as fish utilize habitat differently through different life stages, and through the seasons. Different habitat may be used during times of heat stress, feeding or winter conditions (Dolloff 1987). Also, individual species may need specific habitat different from other species through their life cycle. In this way, biodiversity and biomass is enhanced by habitat diversity.

Radio tracking determined that over-wintering adult Atlantic salmon (*Salmo salar*) use side-channels and abandoned-channels occurring along valley walls within Miramichi wandering rivers in New Brunswick (Komadina-Douthwright *et al.* 1998). Side-channels may also be important habitat for sea run or resident brook trout (*Salvelinus fontinalis*), a species for which there is increasing interest in co-management with Atlantic salmon. Side-channels have been found to be important over-wintering habitat for juvenile salmonids in West Coast rain forests (Peterson 1982, Hartman and Brown 1987). Hydraulic and substrate data, and probability of use models for Atlantic salmonshowed that wandering cobble-bed reaches offered three to five times more rearing habitat for juveniles than meandering or straight reaches on the Nouvelle River, Quebec (Payne and Lapointe 1997). The fish communities within side-channels in Atlantic Canada remain largely undocumented.

On the west coast of North America, off channel habitat (including side-channel habitat) has been found to be major rearing areas for juvenile Coho salmon (*Oncorhynchus kisutch*) (Peterson 1982, Tschaplinski and Hartman 1983, Brown and Hartman 1988, Swales and Levings 1989, Nickelson *et al.* 1992). In the Taku River, Alaska, Sockeye (*Oncorhynchus nerka*) and Coho salmon juveniles were found in off-channel habitat (Murphy *et al.* 1989). Within a small watershed on Vancouver Island in winter, juvenile Coho salmon occupy both main-channel habitats and off-channel habitats that are isolated from the main-channel during winter base flow (Brown and Hartman 1988). Many Coho emigrate from the main-channel to seek shelter in low-velocity tributaries and valley soughs during autumn and early winter (Peterson 1982). The seasonal shift in distribution reverses in the spring when large numbers of Coho re-enter main-channels. Fish overwintering in side-channels have a high apparent survival rate (Tschaplinski and Hartman 1983). Brown and Hartman (1988) found that off-channel habitat contributes up to 23% of the Coho salmon smolt in a watershed in coastal British Columbia. The production of wild Coho salmon smolt in most salmon spawning streams on the Oregon coast is probably limited by the availability of adequate winter habitat (including side-channels) (Nickelson *et al.* 1992).

Steelhead (sea run rainbow trout, *Salmo gairdneri*) also use side-channels for rearing (Hartman and Brown 1987). When steelhead were transplanted into a side-channel on Vancouver Island, smolts were 31 times more abundant, and had 10 times more biomass than smolts raised in the main-channel (Mundie and Traber 1983). Dolloff (1987) determined that all habitats should be managed to meet both summer and winter needs of juvenile Coho salmon because most fish do not move among habitats after the initial population adjustments in the spring. The ability of a stream to produce fish depends not only on the amount and accessibility of habitat, but also on the distribution of habitat types. Wandering rivers provide variable habitat important for aquatic organisms. Therefore, understanding the processes that influence this habitat is important for managing these rivers.

1.3. Wandering river sedimentology

Wandering gravel-bed river sedimentology is dominated by basal channel deposits of massive to poorly stratified gravel and cobbles overlain by horizontally stratified sand and silt, and channel fill deposits of sand, silt or clay (Forbes 1983, Desloges and Church 1987, Brierley 1989, Brierley and Hickin 1991). On the wandering section on the Bella Coola River, Desloges and Church (1987) differentiated between the sedimentology of unstable multiple channel reaches with gravel deposited as medial bars that are overlain by thin overbank deposits of sand, and stable single channel reaches with gravel deposited as lateral point bars that are overlain by thick overbank deposits of silt. However, when Brierley (1989) tested, using Markov Chain analysis, for differences between the one dimensional lithofacies models he developed for braided, wandering and meandering sections of the Squamish River, he found that the facies models could not consistently predict the river pattern. This calls into question the applicability of this type of analysis in transitional gravel-bedded rivers. Also on the Squamish River, Brierley and Hickin (1991) found differences among braided, wandering and meandering planform facies within the active channel, but these differences failed to produce contrasts in floodplain deposits. Therefore, other approaches, such as three-dimensional alluvial architecture, are needed to describe and differentiate the sedimentology of braided, wandering and meandering gravel rivers.

Recent studies (Roberts *et al.* 1997 and Wooldridge 1999) have investigated the three-dimensional architecture of wandering river sedimentology using ground penetrating radar (GPR). Based on GPR data from the Squamish and Fraser rivers, wandering rivers displayed a complicated three-dimensional alluvial architecture with characteristics of both braided and meandering rivers, with sub-horizontal downstream, upstream inclined and lateral accretion deposits (Wooldridge 1999). Two dimensional, concave-up basal reflections identified channel and chute elements, signified the multiple channel nature of wandering rivers. The prevalence of steeply inclined reflections, interpreted as slip face accretion, distinguished wandering deposits form gravely meandering or braided successions (Wooldridge 1999). Channel scour elements, that produced three-dimensional scallop-shaped basal reflections whose fill over deepens alluvial successions, were also present. Channel fill deposits in the Rhône River in France were characterized by stacked convex reflections interpreted as the avalanche face of bars that infilled a channel during its abandonment. Although recent strides have been made in understanding wandering river sedimentology through the use of shallow geophysics, future research is still required to determine the influence of river pattern and processes on gravel river sedimentology.

1.4. Research questions

This dissertation examines wandering river dynamics through the investigation of two research questions: 1) what are the characteristics of wandering rivers in the Miramichi drainage? 2) What processes influence these characteristics? To answer these questions the variability of characteristics within wandering rivers was investigated at different spatial scales (Figure 1-5) and through time. Analyses were conducted at three nested spatial scales to investigate how processes occurring at a lower scale affect a higher scale. As shown in Figure 1-6, the four dissertation chapters provide an integrated investigation of the processes controlling the wandering pattern.

At the largest scale, the river pattern, chapter two investigated differences among the channel patterns of wandering rivers within the Miramichi region of New Brunswick (Figure 1-5A, Figure 1-6). Chapter two investigated three questions: (1) what regional factors influence the location of wandering rivers? (2) When factors such as

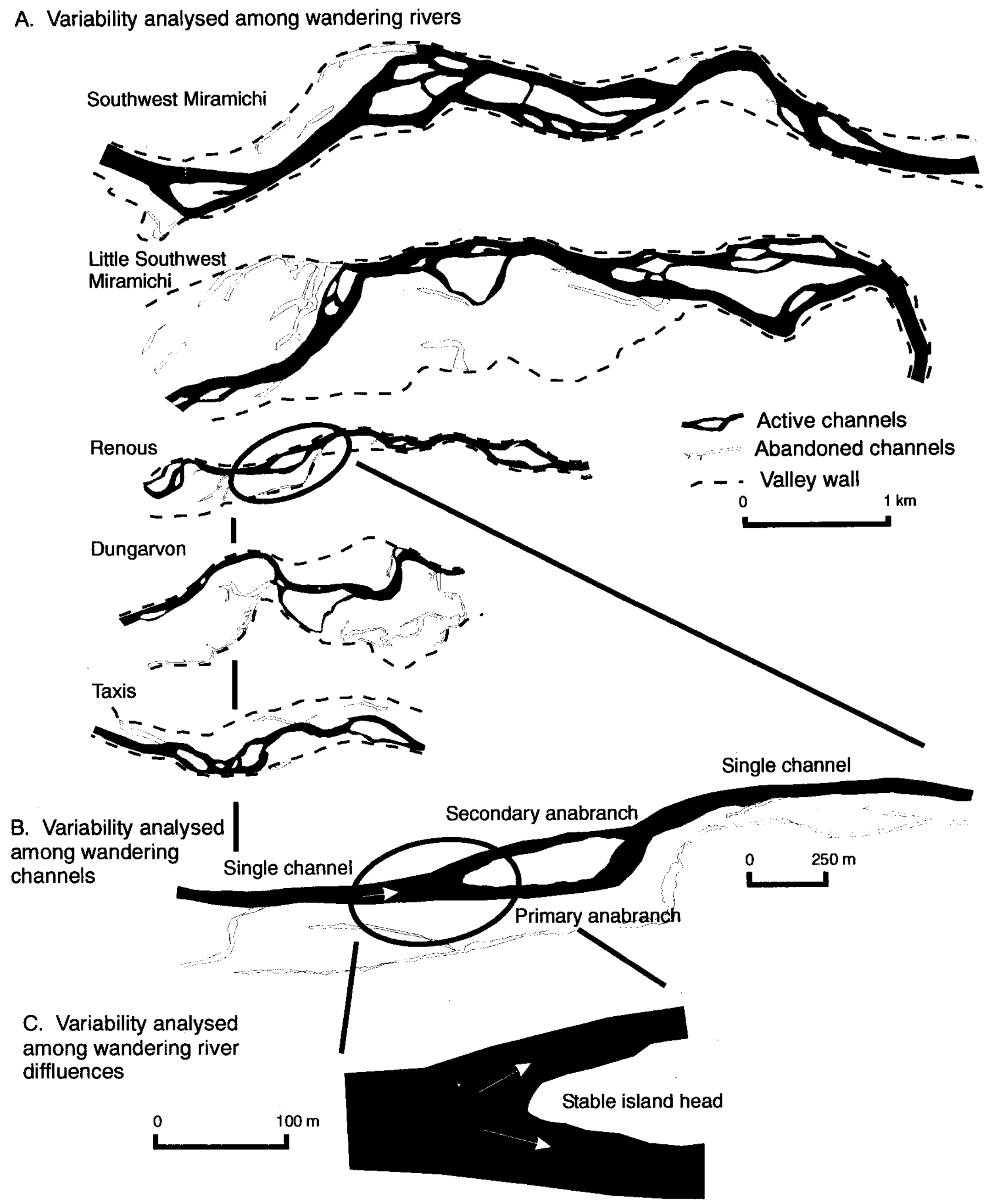

Figure 1-5. Maps displaying the three spatial scales of investigation: (A) at the largest scale, river pattern characteristics analyzed among wandering rivers, (B) at the middle scale, channel dynamics analysed among wandering river channel reaches, (C) at the smallest scale, diffluence dynamics analyzed. Processes occurring at smaller scales are nested within the larger scales.

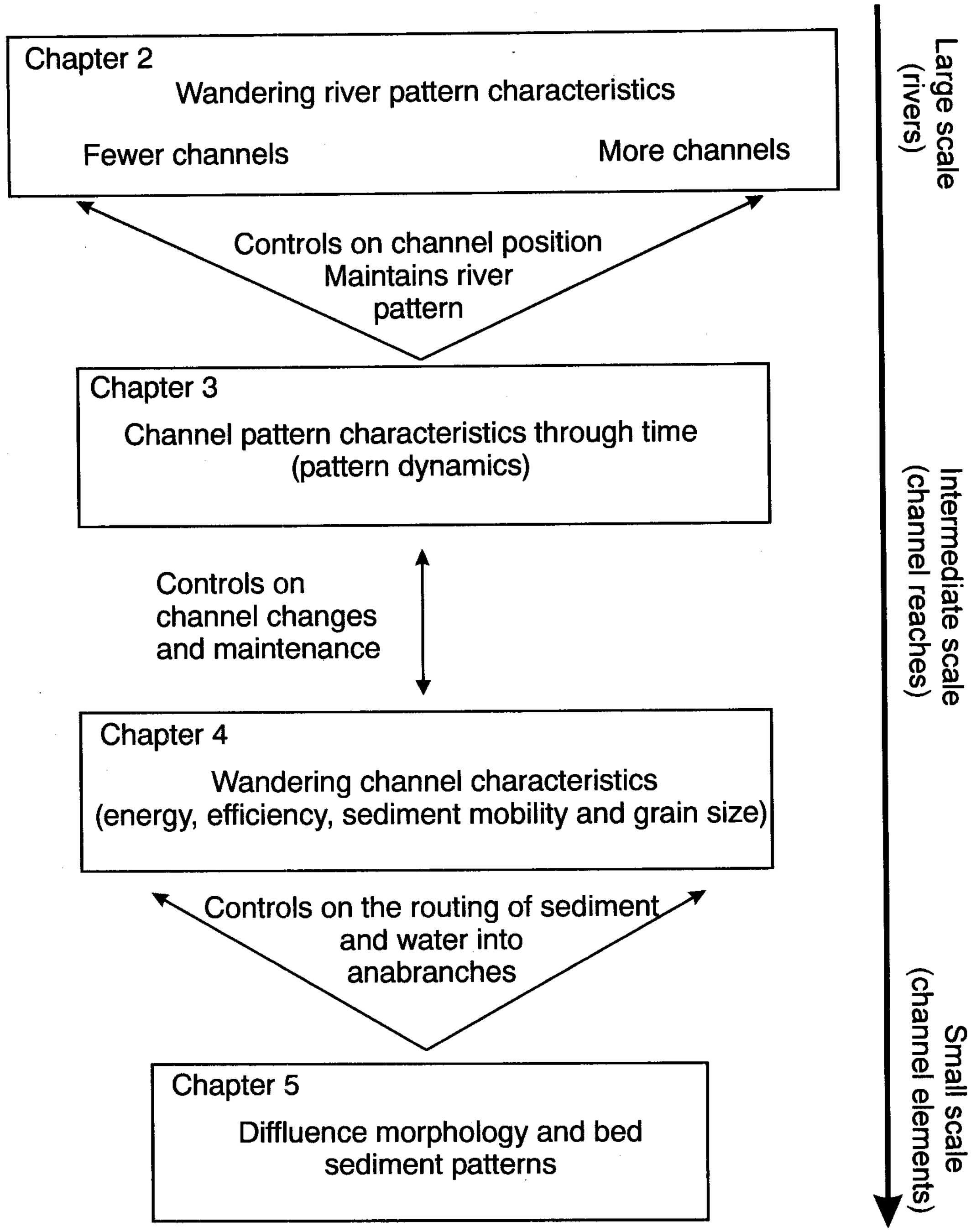

Figure 1-6. Flow chart displaying nesting of analysis scales. Dissertation chapters decrease in scale from the river pattern, to channels within the pattern, to diffluences that divide flow into anabranches.

climate, vegetation, lithology and sediment production are controlled for, what determines differences in pattern characteristics among wandering rivers of different sizes? (3) What are the effects of avulsion triggers, specifically icejams, on the wandering river pattern?

At an intermediate scale, chapter three examined the channels themselves. The changes in individual channels through time within one river were quantified and analyzed (Figure 1-5B, Figure 1-6). Chapter three investigated two research questions: (1) can the pattern characteristics of wandering rivers be in dynamic equilibrium? (2) If so how is dynamic equilibrium maintained?

Also at the intermediate scale, chapter four examined characteristics among all channels within one river (Figure 1-5B, Figure 1-6). Chapter four investigated two questions: (1) how do bedwaves influence the energy and sediment mobility within wandering river channels? (2) How do the processes of the creation, maintenance and abandonment of side-channels influence these characteristics?

At the smallest scale, chapter five investigated individual channel elements called diffluences. The range of island head diffluence morphologies and bed grain size distributions were determined and analyzed using a chronosequence (Figure 1-5C, Figure 1-6). Chapter five answered two questions: (1) how is the stability of diffluences reflected in their morphology and surface grainsize? (2) What are the processes that maintain stable diffluences through time?

Each chapter investigates a suite of processes that are physically nested within the scale analysed within the previous chapter (Figure 1-6) and provide insight into the processes influencing the scale above. In this way the chapters build on one and other to provide a more complete picture of the river pattern as a whole.

1.5. Study area

The Miramichi region of New Brunswick, Canada was chosen for this research because a cluster of ecologically important wandering rivers occurs here (Figure 1-7). Rivers within the Miramichi drain the Miramichi highlands that reach 600 m above sea level and 250 m of local relief (Rampton *et al.* 1984), a plateau without active glaciers or neoglacial moraines. Long multiple channel sections within Miramichi wandering rivers were not associated with extensive erosion of large terraces or the entrance of large tributaries into valleys as described in previous literature (Carson 1984b, Church 1983).

These rivers show a classic wandering pattern with multiple channels around islands, and abandoned channels within the floodplain (Figure 1-5) and range in size from 37 m to 108 in width (Figure 1-5). During winter, Miramichi rivers form a thick (50 cm) ice cover, that commonly forms ice jams during spring break-up and occasionally during winter melts (Beltaos *et al.* 1989). Within the wandering reach of the larger neighbouring Main Southwest Miramichi, break-up occurs between March 22 and May 2, with the average break-up date on April 14 (Allen and Cudbird 1971).

Wandering rivers have been studied in various areas of the world and the basins of these rivers are usually mountainous with glaciers in their headwaters (Church 1983, Brierley and Hickin 1991). In these locations, the formation of wandering rivers has been associated with high sediment input from neoglacial moraines (Church 1983, Carson 1984b) and deposition caused by decreases in channel slope upstream of alluvial fans of tributary rivers (Church 1983). It is difficult to compare rivers from different regions

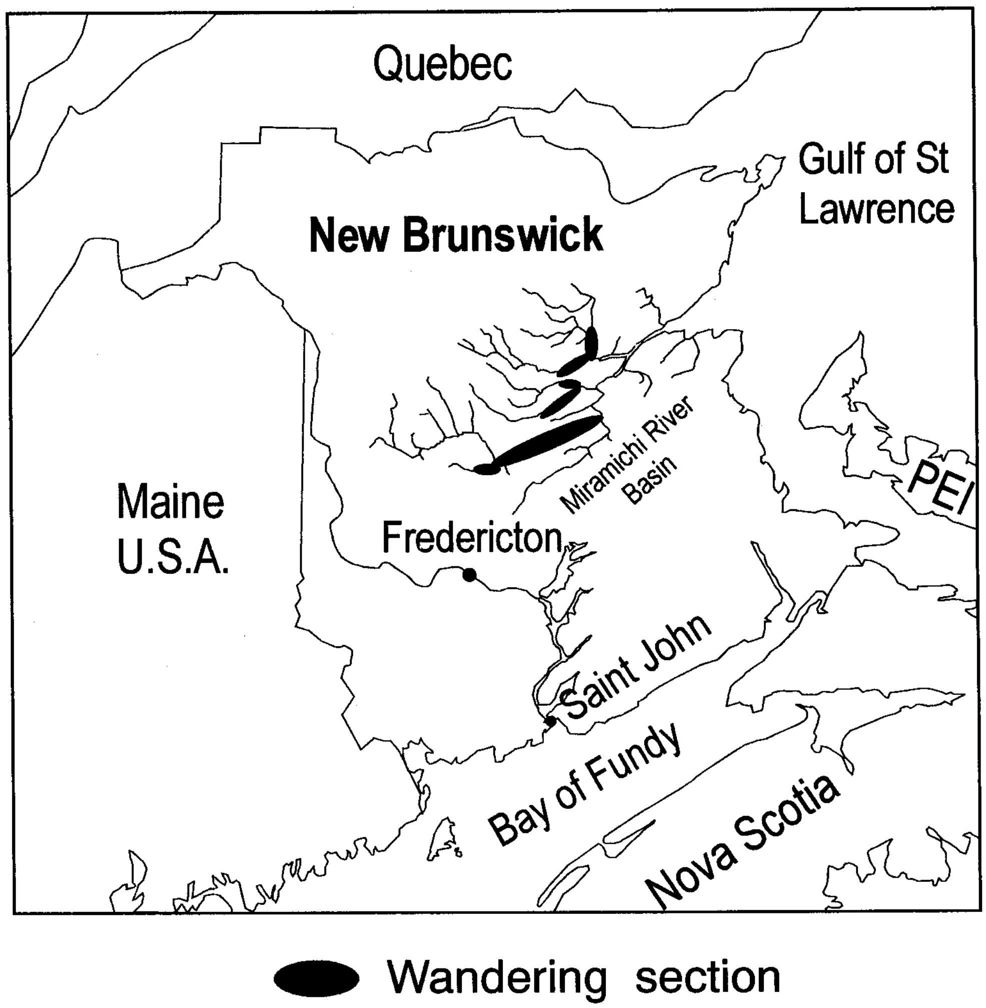

Figure 1-7. Location of the cluster of wandering rivers within the Miramichi basin, New Brunswick.

because factors such as climate, vegetation, lithology and sediment production differ among regions. This study provides an analysis of wandering rivers of different sizes within the same region thereby limiting the effects of these factors. This allowed for the investigation of formative mechanisms other than sediment slugs that may produce the wandering pattern.

1.5.1 Data collection

This dissertation employed a field-based approach. Data was collected during eleven months of fieldwork conducted through 1999 to 2001 in summer and winter. The length of fieldwork allowed for observations of processes occurring within the study rivers through time. It also allowed for an intricate knowledge of the field sites that aided in analysis.

A large, comprehensive data set was collected. Elevations of the channel bed at every riffle and pool and at high water marks were surveyed using a laser level and hip-chain over 28.3 km on the Renous and Taxis rivers. Elevations of the channel bed at every riffle and floodplain were surveyed using differential GPS over 18 km on the main-channel of the larger Little Southwest Miramichi River. Within two rivers, the surface grain size distribution was determined at the head of every riffle present within the study area. Surface grain size distribution was measured on a total of 269 riffles. This data format allowed for a large data set with numerous measured and calculated variables to be compiled and analysed. Finally, channel morphology, surface grain size and lines of imbricated clasts were determined at diffluence zones in the field.

1.5.2 Statistical approach

This dissertation employed a statistical approach to river pattern geomorphology. In the fluvial geomorphology of river patterns, multivariate analyses are rarely conducted due to the difficulty in obtaining large field data sets with a large number of measured variables. To my knowledge, this application of a multivariate approach is unique, even though the interdependent nature of fluvial variables is well established. A recent multivariate analysis on the Mississippi River used multi response permutation procedure to classify channel sections (Orlowski *et al.* 1995), however this analysis did not investigate the processes driving interrelated variables. Figure 1-8 (modified from Knighton 1998) displays the major interrelationships among river variables within the fluvial system. The character and behaviour of the fluvial system in any particular location reflect the integrated effect of a set of upstream controls, notably climate, geology, land use and basin physiology which together determine the hydrologic regime and quantity and type of sediment supplied to influence the river pattern (Knighton 1998).

Two chapters employed multivariate analyses. First, twenty-seven sections within five wandering rivers of different sizes, from one region, were analyzed using principal component analysis to investigate differences among rivers that vary in size. Next, a large field based data set based on channel reaches was used in a principal component analysis to investigate the interrelationship among characteristics of channels within one wandering river. Pearson correlation matrices with Bonferroni probabilities were used to investigate relationships between variables. Analysis of variance was used to test for mean differences between features. Bonferroni post hoc tests were used when more than one feature was compared at once. Two tailed paired-sample t tests ($\alpha = 0.05$) were used

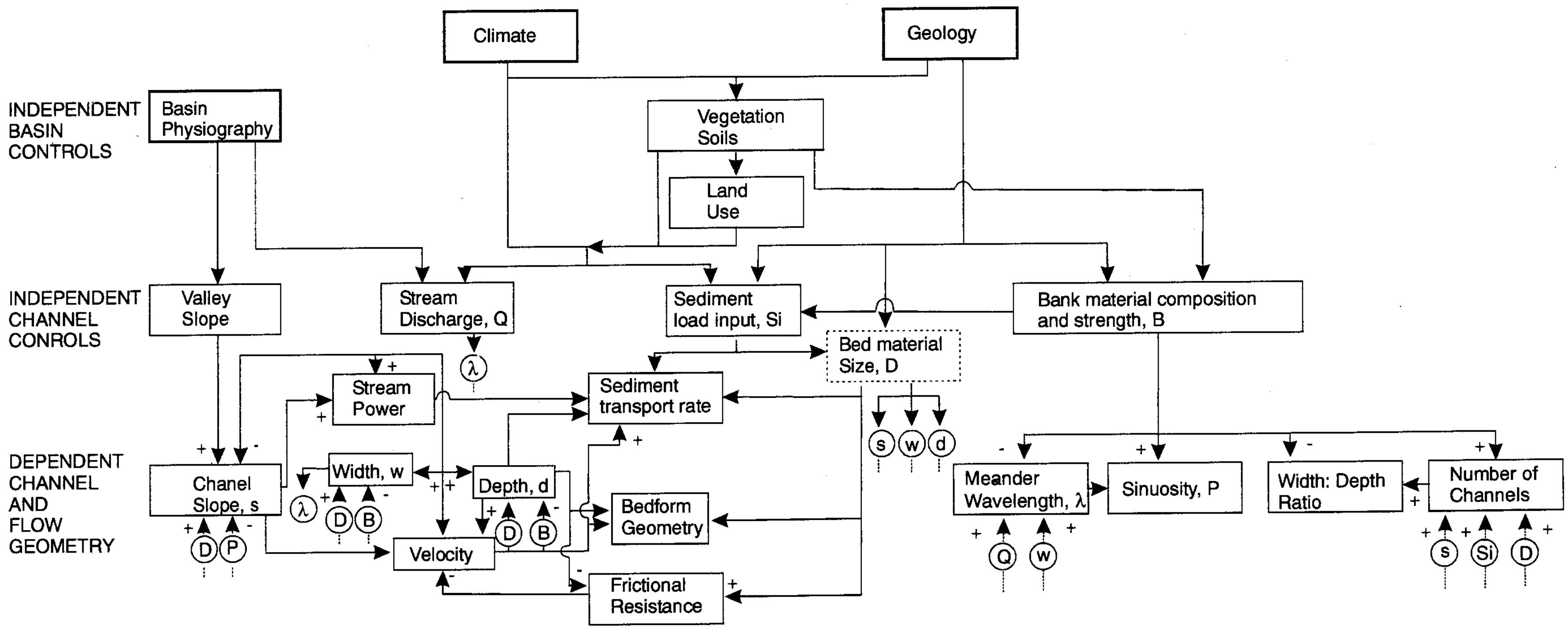

Figure 1-8. Interrelationships in the fluvial system showing the multivariate nature. Relationships are indicated as direct (+) or inverse (-). Arrows indicate the direction of the influence (Modified from Knighton 1998).

to test for differences between paired samples. The statistical analysis allowed for interpretations of relationships among and between variables at each scale to be made with confidence.

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Preface to chapter two

To understand the processes creating the wandering river pattern we first must understand how large-scale regional characteristics influence the location of these rivers and the differences and similarities among the rivers themselves (Figure 1-5A, Figure 1-6). Chapter two investigated three questions: (1) what regional factors influence the location of wandering rivers? (2) When factors such as climate, vegetation, lithology and sediment production are controlled for, what determines differences in pattern characteristics among wandering rivers of different sizes? (3) What are the effects of avulsion triggers, specifically icejams on the wandering river pattern? The location of wandering rivers in relation to regional bedrock trends and valley width, their general energy level and their relationship with icejam frequency and magnitude were determined within the Miramichi region of New Brunswick.

2. Chapter two: Regional setting and controls on pattern characteristics of wandering rivers, Miramichi region, New Brunswick, Canada

2.1. Abstract

Wandering rivers are composed of multiple channel sections containing individual anabranch channels that surround semi-permanent islands, linked by single channel sections. The formation of wandering rivers has been associated with high sediment input from neoglacial moraines, however other formative mechanisms are possible. Three factors are needed to form wandering rivers: (1) wide valleys, (2) channel energy levels between braiding and meandering, and (3) avulsion triggers. Wandering rivers within the Miramichi region occurred within larger valleys located downstream of a regional change in bedrock from hard to soft bedrock lithology. On a slope-discharge plot, Miramichi wandering rivers plotted in the same range as other wandering rivers and displayed similar specific stream power values. Icejams within Miramichi rivers trigger avulsions that create the multiple channel anabranches which define the pattern.

A Pearson correlation matrix and principal component analysis were used to explore relationships among river pattern variables. Five rivers in the Miramichi drainage were divided into homogeneous sections of approximately 100 channel widths in length. For each section, ten pattern characteristics were determined from 1:10 000 orthomaps. Larger rivers within the Miramichi displayed greater anabranching intensity than smaller rivers. Larger rivers appear to produce higher icejams that create more avulsions and maintain channels that may otherwise be abandoned, thereby creating greater anabranching intensity. Wandering rivers appear to be a product of equifinality or

convergence, where different processes, such as high sediment input in some regions or icejams in others, produce similar patterns.

2.2. Introduction

Alluvial rivers exhibit a wide range of channel patterns, which depend on complex interactions of discharge, sediment supply, sediment calibre, channel slope, bank strength, and vegetation (Schumm 1977). Classically, river patterns were thought to vary from meandering to braiding (Leopold and Wolman 1957). The term wandering was added to represent a transitional channel form between braiding and meandering that exhibits characteristics of both (Neill 1973, Church, 1983). Wandering rivers have a complicated channel planform of long sections with multiple channels that surround semi-permanent islands with mature forests, and neighbouring short sections with single channels. Multiple channel sections of wandering rivers have been termed sedimentation or unstable zones, while single channel sections have been described as transportation or stable zones (Church 1983). Wandering rivers have been studied in various areas of the world and the basins of these rivers are usually mountainous with glaciers in their headwaters (Chuch 1983, Brierley 1989, Brierley and Hickin 1991). In these locations, the formation of wandering rivers has been associated with high sediment input from neoglacial moraines (Church 1983, Carson 1984b) and deposition caused by decreases in channel slope upstream of alluvial fans of tributary rivers (Church 1983).

It is difficult to compare rivers from different regions because factors such as climate, vegetation, lithology and sediment production differ among regions. This study provides an analysis of wandering rivers of different sizes within the same region thereby limiting the effects of these factors. The Miramichi region of New Brunswick, Canada was chosen for this research because a cluster of wandering rivers occurs here (Figure 2-1, inset). Rivers within the Miramichi drain the Miramichi highlands that reach 600 m above sea level and 250 m of local relief (Rampton *et al.* 1984), a plateau without active glaciers or neoglacial moraines. Long multiple channel sections within Miramichi wandering rivers were not associated with extensive erosion of large terraces or the entrance of large tributaries into valleys as described in previous literature. This allowed for the investigation of formative mechanisms other than sediment slugs and the possibility of convergence or equifinality, where different processes produce similar patterns.

Understanding wandering rivers is important because they are productive areas for salmonids on the Pacific and Atlantic coasts of Canada. Hydraulic and substrate data, and probability of use models for Atlantic salmon (*Salmo salar*) showed that wandering cobble-bed reaches can offer three to five times more rearing habitat for juveniles than meandering or straight reaches on the Nouvelle River, Quebec (Payne and Lapointe 1997). In addition, biologists found that over-wintering adult Atlantic salmon use side-channels occurring along valley walls within wandering rivers (Komadina-Douthwright *et al.* 1997). Wandering rivers are also ecologically important on the west coast of North America because side-channels within these rivers are significant over-wintering habitat for juvenile pacific salmonids (Peterson 1982, Tschaplinski and Hartman, 1983, Brown and Hartman 1988, Swales and Levings 1989, Nickelson *et al.* 1992). Understanding wandering river processes is important for management of these important fish habitats.

This research investigated two questions: (1) What regional factors influence the location of wandering rivers in the Miramichi basin? (2) What factors influence

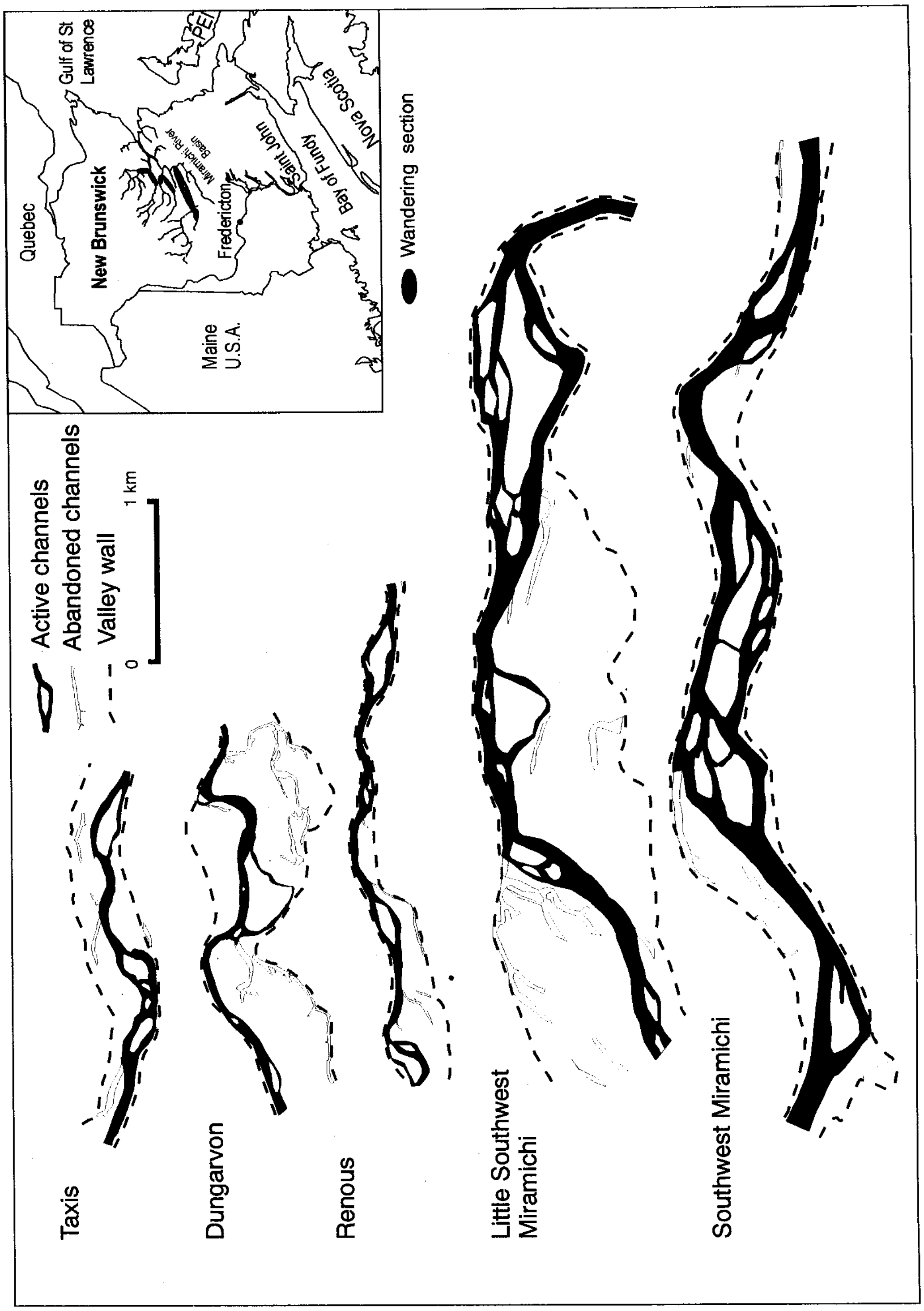


Figure 2-1. Location of wandering rivers within the Miramichi Basin (inset), showing multiple channel sections from the five wandering rivers analyzed.

anabranching intensity, a measure of the number of anabranches, within Miramichi wandering rivers? To investigate the first question I (1) determined the location of wandering sections, (2) determined the width of the valleys in which they occur and (3) compared the valley location of wandering sections and valley width to regional trends in bedrock lithology. To investigate the second question I (1) compared the position of wandering rivers on a slope-discharge plot to other wandering rivers from the literature, (2) quantified wandering river pattern characteristics, and (3) compared these characteristics to specific stream power and the potential height of icejams for each river.

2.3. Methods

To quantify the wandering river pattern in the Miramichi region of New Brunswick, five rivers were investigated. Wandering rivers varied in size from the largest, Southwest Miramichi River (108 m), to the mid-sized Little Southwest Miramichi (80 m), Renous (44 m), and Dungarvon rivers (41 m), to the smallest Taxis River (37 m) (Figure 2-1). Each river was divided into relatively homogeneous single channel and multiple channel sections of approximately 100 channel widths in length. For each section, main-channel width and valley width were measured at every five channel widths downstream (approx. twenty times per section) and averaged for each section. Few low terraces occur within Miramichi valleys; therefore valley width represents floodplain width. To allow for comparison among rivers and floodplains of different sizes, valley width was then normalized by main-channel width.

Channel pattern characteristics were measured from 1:10 000 orthomaps compiled in 1978 and 1979 from aerial photographs flown in 1973, 1974 and 1975 (New Brunswick 1980). Active channels were identified as being connected upstream to another active channel and contained active bar surfaces that were light and water that was dark on the orthomaps. Identification and measurement of channels may be sensitive to river stage on some rivers. In this case, however the visibility of active channels did not depend on river stage because islands and banks generally have mature forest that is not flooded. The orthomaps allowed for the identification of channels greater than 5 m in width (0.5 mm map distance). Some small seasonal channels (< 5 m) may not be evident on the orthomaps, but these channels are systematically excluded from all rivers. Extensive field reconnaissance on three of the study rivers identified few channels less than 5 m wide within the floodplains, however, the occurrence of small channels was greater in the larger Little Southwest Miramichi than the smaller Taxis and Renous rivers.

2.3.1 River pattern variables

Six variables were used to describe the river pattern in each river section. I will use the term **anabranching intensity** to refer to the average overall multiple channelness within a section as an integration of all pattern variables. **Channel sinuosity** (main-channel length / valley length) is the most commonly used river pattern variable and quantifies channel meandering (Knighton 1998). To further investigate channel migration, **migration rates** were determined for 26 km of the Southwest Miramichi using 1:12 000 aerial photographs from 1945 and 1983 compared using a Zoom Transfer Scope (Bausch and Lomb TM). **Braid index** (total length of all active channels / main-channel length) describes anabranching intensity by emphasizing the length of all side-channels for a given river length (Mosley 1981). Main-channels were large perennial channels that included the thalweg, while side-channels were seasonal channels that did not contain the thalweg.

Braid wavelength [main channel length / total number of channel nodes (confluences or diffluences)] describes anabranching intensity by emphasizing the number of channel divisions for a given river length (Ashmore 2001). Braid wavelength was normalized by main-channel width to allow for comparison between rivers of different sizes. The **average number of channels** per valley cross-section was measured twenty times per section and averaged. **Channel order** increases as channels divide downstream (Bristow 1987). Highest order represents the greatest number of divisions downstream within a channel and quantifies the hierarchy of channel divisions within a river channel. Second order channels occur downstream from single channel divisions and third order channels occur downstream from second order channel divisions. Abandoned channels contain stagnant water and are not connected to active river channels upstream, however they may be connected to an active channel downstream. **Abandoned channel index** (abandoned channel length / main channel length) was created to quantify the length of abandoned channels within each section but is sensitive to the visibility of abandoned channels on the orthomaps and therefore may be sensitive to river stage. For comparisons among rivers valley width was normalized by main-channel width. Sections with few divided channels were excluded from the analysis.

2.3.2 Statistical analysis

A Pearson correlation matrix with Bonferroni probabilities was used to investigate relationships among sinuosity, braid index, normalized braid wavelength, average number of channels across floodplain, diffluence order, abandoned channel index and normalized valley width among channel sections, using SYSTAT (SPSS 1998). To investigate the relationships among pattern variables, principal component analysis (PCA) was conducted using all variables except normalized valley width using CANOCO (ter Braak and Ŝmilaur 1999). All unconfined multiple channel sections occurring in wide valleys that occur above a discriminant function (presented in Figure 2-2) were used in the analyses. There were 27 sections in the data set and one section was excluded as an outlier. Braid index, main-channel sinuosity, average number of channels per cross section, and normalized braid wavelength showed high skewness and/or kurtosis and were log transformed to produce normal distributions for statistical tests. Analysis of variance (ANOVA) tested univariate mean differences among the five wandering rivers and Bonferroni post hoc tests were conducted when more than two groups were compared at once. Main-channel width and normalized valley width were used as independent variables to investigate the influence of river and valley size on the channel pattern characteristics using correlations with the PCA axis loadings for all sections using SYSTAT (SPSS, 1998). Main-channel width and normalized valley width were excluded from the PCA input because the preliminary analysis showed that they drove PCA axis one.

2.3.3 Channel energy and icejam height

To investigate icejams as avulsion triggers, maximum daily ice influenced stage and discharge values were extracted from an Environment Canada gauge in the neighbouring Little Southwest Miramichi River for the years 1995 to 2001. The available record for analysis is short because stage data is not published and difficult to obtain. The peak annual ice influenced stage was then compared to the highest annual open water flow. Next, the stage-frequency of annual peak stage events influenced by ice was determined using $T = (n + 1) / N$, where T is the return period (in years), n is the number

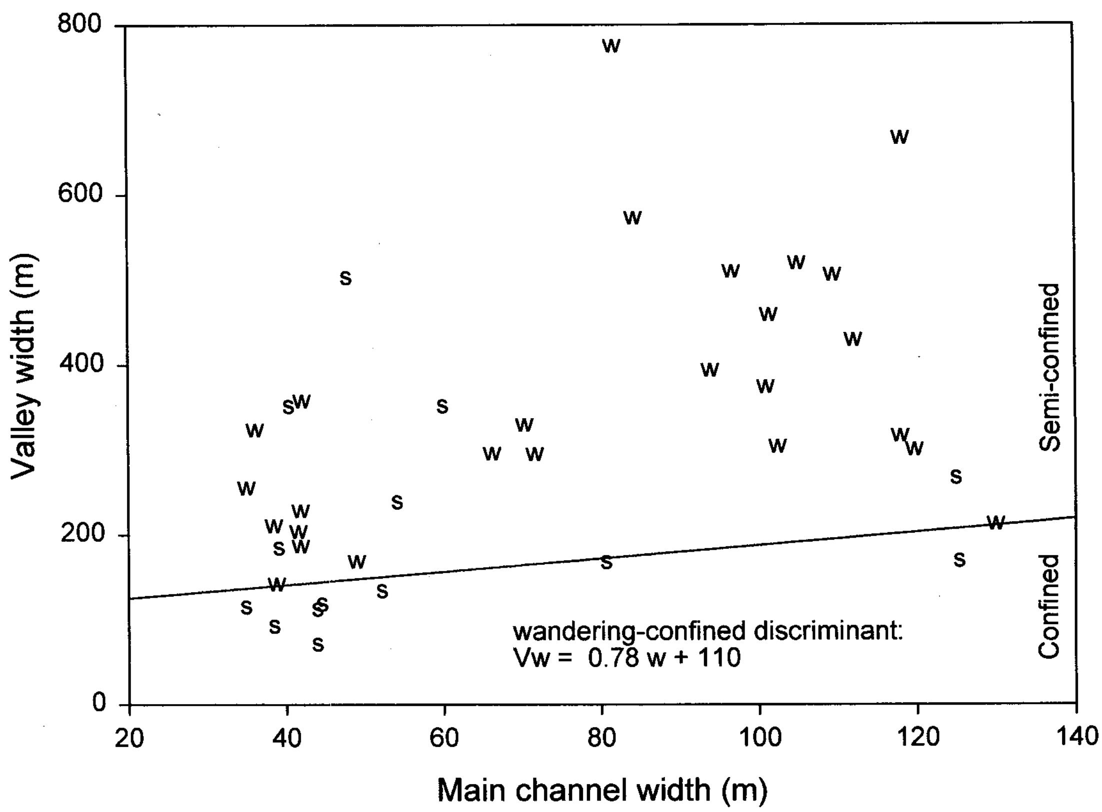


Figure 2-2. Scatter plot of main-channel width and valley width showing wandering sections above a discriminant function between confined and semi-confined sections. Channels are semi-confined and not unconfined because they commonly encounter their valley walls. Note, s denotes single and w denotes multiple channel wandering sections.

of years of record and N is the rank of a particular event (Knighton 1998), and compared to the frequency of annual peak stages under open water.

For each river, specific stream power at bankfull discharge under open water conditions and potential water depth during icejams were calculated. Total stream power ($\Omega = \gamma Q_{bf} S$, where Q_{bf} is bankfull discharge, and S is channel slope) is the rate of energy supply at the channel bed for overcoming friction and transporting sediment per unit length (Knighton 1998). Specific stream power ($\omega = \Omega / w$, where w is channel width) is the energy availability per unit area of the bed (Knighton 1998). Slope values for the Southwest Miramichi, Little Southwest Miramichi, Renous and Taxis rivers were determined using bed elevations surveyed using a level or differential GPS and distances measured using a hip chain over multiple kilometres in the field or measured using maps. The slope of the Dungarvon River was calculated from 1 : 50 000 maps with a 10 m contour interval over multiple kilometres. Bankfull discharge was estimated as the mean annual maximum daily discharge from gauges on the Southwest Miramichi, Little Southwest Miramichi, and Renous Rivers (Environment Canada 1997). Mean annual maximum daily discharge for the unguaged Dungarvon and Taxis rivers were determined using a regional relationship developed for the mean annual maximum daily discharge and drainage area for six rivers within the Miramichi drainage.

Water depth during icejams is a measure of the potential for the creation of avulsions and the slowing of the abandonment of channels by forcing flow into these channels during icejam floods. Unfortunately, only the Little Southwest Miramichi River had a record of stage within the study area. This prevented the determination of differences in icejam caused flooding frequency and magnitude among rivers. Therefore, the potential maximum water depth (H) during icejams was estimated using $H = 1.32 (Q n_c / 1.49 B \sqrt{S})^{3/5} + \rho_i t_i / \rho_w$, where Q is discharge, n_c is the composite Manning roughness coefficient, B is the width of the ice cover accumulation in metres, S is water surface slope, ρ_i is the density of ice, t_i is the ice-cover thickness and ρ_w is the density of water (Prowse and Beltaos 2002). Discharge (Q) was estimated using mean annual maximum daily discharge for each river. The width of the ice cover accumulation (B) was estimated as the channel width. Water surface slope (S) was approximated using the slope of the channel bed. Ice-cover thickness (t_i) was estimated using the average regional ice thickness of 0.5 m (Baltaos *et al.* 1989). The density of ice was estimated using the ice-to-water ratio of 0.92 typical for freshwater ice (Prowse and Beltaos 2002). The composite Manning roughness coefficient (n_c) was estimated using $n_c = [(n_i^{3/2} + n_b^{3/2}) / 2]^{2/3}$, where n_i and n_b are the Manning roughness coefficient of the ice and bed, respectively (Prowse and Beltaos 2002). Manning roughness coefficients for the ice and bed were assumed to be equal and estimated as a typical value of 0.04 for gravel bedded rivers.

To investigate the influence of specific stream power and potential icejam height on channel characteristics, average specific stream power and potential icejam height were correlated with the PCA axis loadings and pattern characteristics. For this analysis PCA axes loadings and pattern characteristics for each river section were averaged for each river and correlated. Unfortunately, this resulted in only five sample points for this analysis.

2.4. Results and discussion

Multiple channel sections of rivers within the Miramichi basin show a classic wandering pattern with multiple channels around semi-permanent islands, and abandoned channels within the floodplain (Figure 2-1). Single channel sections confined by narrow valleys occur upstream and occasionally downstream of wandering sections. Sediment grain size of the beds of these rivers is commonly cobbles. The D_{50} of riffles within the Renous River is 67 mm.

2.4.1 Regional setting of wandering Miramichi rivers

Wandering rivers were located in the lower section of the Miramichi basin, upstream of confluences with larger rivers or near the Miramichi estuary. Wandering sections of the Southwest Miramichi and Little Southwest Miramichi rivers end near the Miramichi River estuary. The wandering sections of the Renous and Dungarvon rivers end near their confluence with one and other, and the wandering section of the Taxis ends near its confluence with the Southwest Miramichi.

Wide valleys provide space for multiple channels to develop. A line was identified that discriminates between the valley width at which multiple channels occurred or were absent. Wandering is not likely to occur below the line $Vw = 0.78\ w + 110$, where Vw is valley width (m) and w is main-channel width (m), on a plot of main-channel width and valley width (Figure 2-2). Normalized valley width was statistically higher (ANOVA, $p = 0.02$) in multiple channel sections (5.04 ± 0.42) than single channel sections (3.07 ± 4.59). Main-channel width was correlated with valley width ($r = 0.42$, $p = 0.02$) in wandering rivers. Other studies have shown valley confinement to influence floodplain morphology (Ferguson and Brierley 1999, Burge and Smith 1999). Six, single channel sections occurred above the discriminant line. In these sections wandering did not occur even though valleys were wide enough for the formation of multiple channels, indicating that large valley width alone does not create multiple channel rivers.

The distribution of wandering rivers within the Miramichi appears to be related to a change in bedrock lithology downstream, from hard volcanic and plutonic to soft sedimentary bedrock that has allowed valleys to widen and accommodate multiple channels (Figure 2-3). A regional contact from late Ordovician-early Devonian volcanic and plutonic belts to late Devonian-Permian sedimentary bedrock runs in a northeast direction through central New Brunswick (New Brunswick Department of Natural Resources and Energy 2000). Within the Miramichi, valleys are sinuous and narrow when occurring in volcanic and plutonic and older marine sedimentary bedrock and wider where younger terrestrial sedimentary bedrock occurs. Geological controls on river behaviour were also found on the Klip River, South Africa which is straight when flowing through a valley composed of hard dolomite, and meanders where the valley bedrock changes to softer sandstone downstream (Tooth *et al.* 2002). The age of Miramichi valleys is not known, however valley locations may have been reorganized during Pleistocene glaciations.

Wider rivers also wander for a greater distance. The length of the wandering pattern on each river was related to the main-channel width ($r = 0.78$, $n = 5$). The Dungarvon River wandered for a longer distance than predicted by its width (Table 2-1). As shown in Figure 2-3, the Dungarvon flows over sedimentary rock a greater distance than other rivers of similar size, allowing the growth of a larger valley for a greater distance.

2.4.2 Channel energy and stability

Plots of channel bed slope against bankfull discharge or mean annual flood have been used to discriminate between river patterns since Leopold and Wolman (1957).

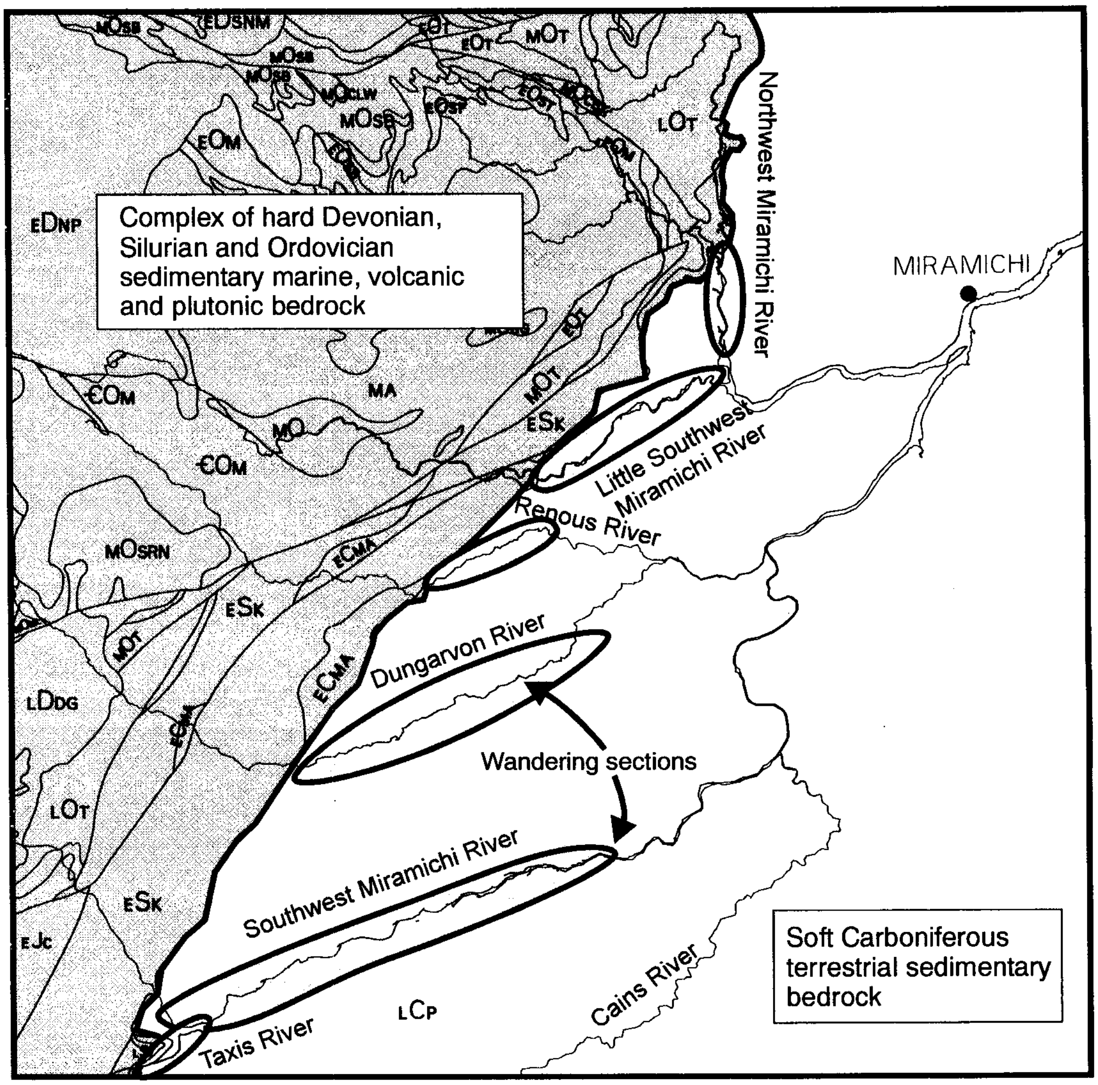


Figure 2-3. Bedrock map of New Brunswick showing the location of wandering rivers within the Miramichi basin located with sedimentary bedrock downstream of volcanic and plutonic bedrock (Department of Natural Resources and Energy New Brunswick 2000).

Wandering rivers within the Miramichi, with the exception of the Southwest Miramichi, plot much lower than the discriminant function between braided and wandering suggested by Desloges and Church (1989) while other wandering rivers plot closer to the line (Figure 2-4). Smaller Miramichi wandering rivers extended the plots into smaller discharge values than were previously reported. Specific stream power values for Miramichi wandering rivers had an average of 86 Wm^2 and ranged from 63 to 147 Wm^2 (Table 2-1), within the low range of other wandering rivers (from Nanson and Knighton 1996, Carson 1984a). When compared to meandering gravel bedded with similar grain size rivers in Quebec (Table 2-1), Miramichi rivers plot within or below these rivers suggesting that they are closer to the transition between meandering and wandering than wandering and braiding.

Many wandering rivers are located in or near mountain valleys with glaciers within their headwaters, like the Bella Coola (Church 1983) and Squamish (Brierly and Hickin 1991) in British Columbia, and may also have large terraces like those on the Canterbury Plains, New Zealand (Carson 1984a). In these systems, neoglacial events produced large amounts of gravel that now form large easily erodable terraces (Church and Slaymaker 1989). Sediment input from these terraces overloads channels, causing the formation of large mid-channel bars and triggering avulsions. Avulsions are associated with passages of sediment lobes that cause channel shoaling (Ashmore 1991), leading to multiple channels.

Emergence of mid-channel bars to form islands is less common within the Miramichi than other wandering rivers occurring in high relief areas that erode neoglacial moraines. Figure 2-5 displays six examples of wandering Miramichi channels where

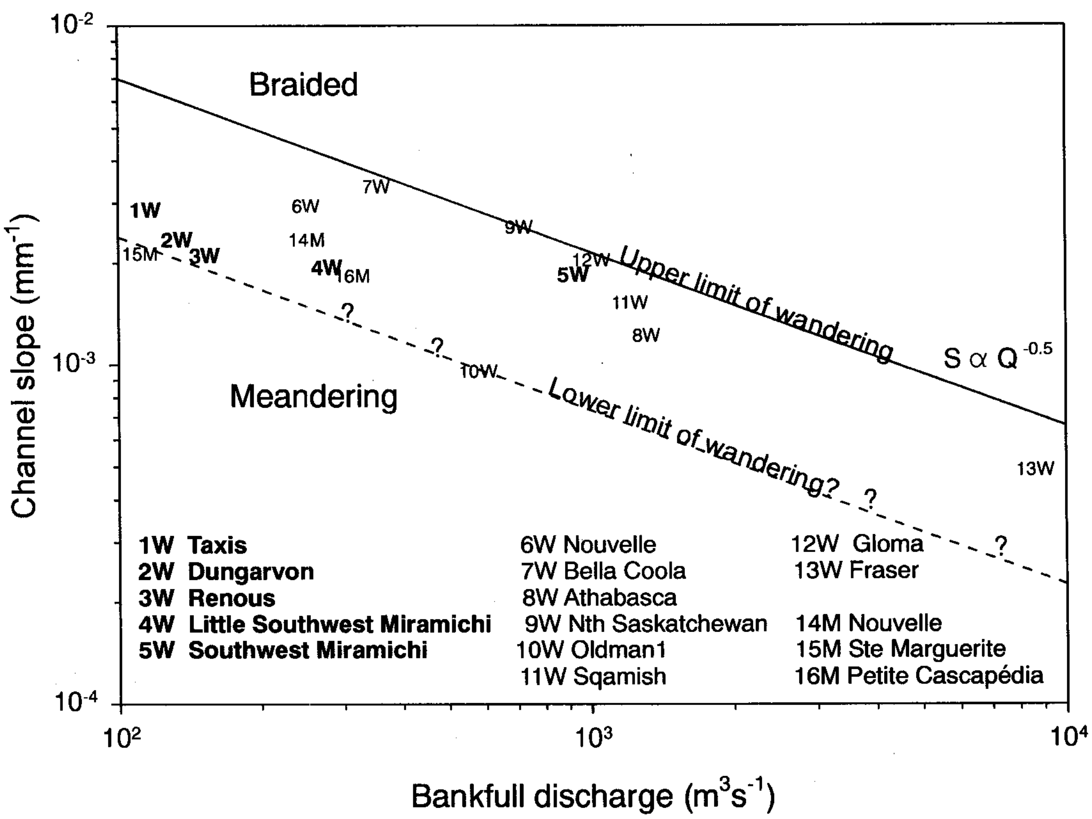
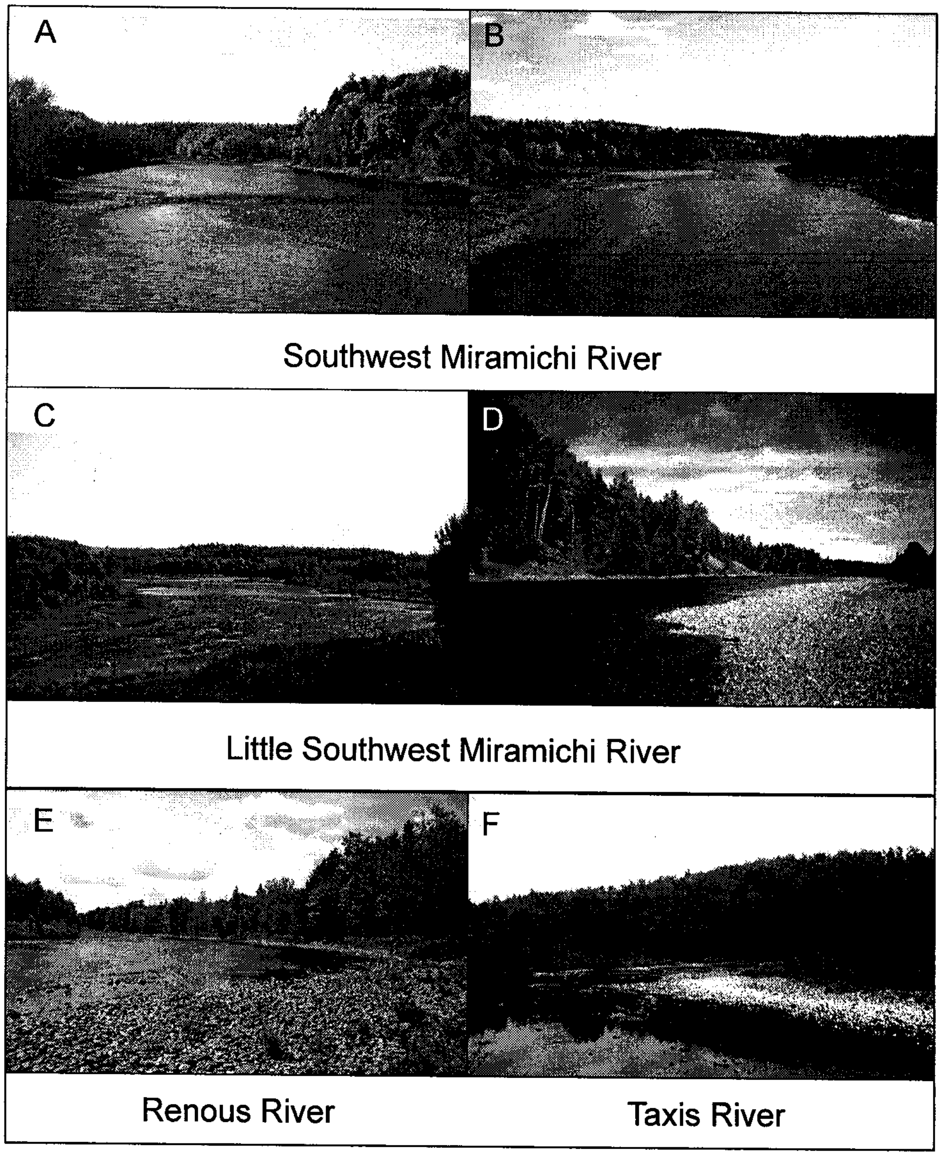


Figure 2-4. Slope-discharge plot for the Miramichi gravel-cobble bedded study rivers and eight other gravel-cobble wandering systems (from Nanson and Knighton 1996, Desloges and Church 1989 and Payne 1995) and three gravel bedded meandering rivers (from Payne 1995, Eaton 1998 and Coulombe Pontbriand 2001). W denotes a wandering pattern while M denotes a meandering pattern. The discriminant function between braiding and wandering is from Desloges and Church (1989). Slope values are for the channel bed and mean annual flood was used to estimate bankfull discharge for the Taxis, Dungarvon, Renous, Little Southwest Miramichi and Southwest Miramichi rivers. Discharge values from Nanson and Knighton 1996, Payne 1995, Eaton 1998 and Coulombe Pontbriand 2001 are mean annual flood or bankfull discharge.

Table 2-1. Specific stream power values for five wandering Miramichi rivers (bold) and one wandering and three meandering gravel bedded rivers within Quebec. Grain size for riffles on three Miramichi wandering rivers and rivers in Quebec are also quoted. Wandering rivers within the Miramichi have larger grain size and similar, often lower stream power values than meandering rivers, indicating Miramichi rivers are closer to meandering than braiding.

River	*Reference*	*Channel pattern*	*Sp. stream power (Wm^{-2})*	*D_{50} (mm)*	*Grain size sample*
Taxis		Wandering	81	55	Pebble count
Dungarvon		Wandering	72		
Renous		Wandering	69	70	Pebble count
Little Southwest Miramichi		Wandering	63	67	Visual estimations
Southwest Miramichi		Wandering	147		
Nouvelle	Payne 1995	Wandering	108	40	Pebble count
Nouvelle	Payne 1995	Meandering	89	47	Pebble count
Petite Cascapédia	Coulombe-Pontbriand 2001	Meandering	83	67	Pebble count
Ste Marguerite	Eaton 1998	Meandering	55	28	Bulk

Figure 2-5. Photographs of channels within the wandering sections of four wandering rivers. Mid-channel bars within these river channels are rare. A and B show riffles on the largest Southwest Miramichi. C displays the uppermost section of wandering within the Little Southwest Miramichi where the greatest number of mid-channel bars occurs. D displays the downstream end of an eroded valley wall terrace on the Little Southwest Miramichi. E displays a meander on the Renous River. F displays an anabranch channel within the Taxis River.


A
B
Southwest Miramichi River
C
D
Little Southwest Miramichi River
E
F
Renous River
Taxis River

point bars and riffles are evident but mid-channel bars are uncommon. Miramichi rivers drain the relatively flat Miramichi plateau which is not glacierized and produces less gravel than higher relief regions. Much of the region is overlain by a thin blanket of late Wisconsinan till deposited prior to the glaciation that ended around 13 ka (Lamothe 1992). Glaciofluvial deposits are scattered throughout New Brunswick, (Rampton *et al.* 1984) and extensive field reconnaissance to Miramichi rivers discovered important local erosion of relatively small (3 – 10 m in height) terraces where channels contact valley walls (Figure 2-5D). Sediment input from terraces was seen to cause local (hundreds of m downstream) deposition of bars but not braiding.

The average width-depth ratio of wandering channels within the Miramichi was lower than those cited for the Bella Coola River (Church 1983). The average width-depth ratio of single channel sections of the Renous River was 35, while the average bankfull width-depth ratio of anabranches that contained the thalweg was 32. These values are considerably lower than those quoted for stable, single channel sections of the Bella Coola River (50), unstable, multiple channel sections of the Bella Coola River (122) and for the wandering section of the Fraser River (78) (Desloges and Church 1989). This may indicate the presence of fewer mid-channel bars in wandering Miramichi rivers because high width-depth ratios are related to braiding processes associated with mid-channel bars (Richardson and Thorne 2001, Knighton 1998). The relative absence of mid-channel bars within Miramichi wandering rivers suggests they have lower energy and sediment mobility regime than wandering rivers associated with high rates of sediment input.

Wandering Miramichi rivers are also relatively stable laterally. The average maximum lateral migration rate at the outside of bends was only 0.9 ± 0.1 m yr^{-1} or $1.0 \pm$

0.2 % of the channel width per year for 26 km on the Southwest Miramichi between 1945 and 1983. These rates are lower than lateral migration rates based on dendrochronology for the Bella Coola River of 3.0 to 3.5 m yr^{-1} or 2 % of the average channel width per year, (Desloges and Church 1987). Migration rates for the Miramichi were also lower than those documented on a wandering section of the Feshie River, Scotland, (7 m yr^{-1} or 18 % of the channel width per year) (Ferguson and Werritty 1983) or a wandering section of the Nouvelle river in Quebec (5 m yr^{-1} or 8 % of the channel width per year) (Payne 1995). Lower rates of channel migration within the Miramichi also suggest a lower energy and sediment mobility regime on Miramichi rivers than other wandering rivers.

2.4.3 Presence of icejams

Within the Miramichi, hydrographs begin to rise in late March and peak at the beginning of May, and then fall into June. At McGraw Brook, in the centre of the Miramichi basin, the mean monthly air temperature varies between -11.8°C in January and 18.8°C in July, where April to October is above freezing (Caissie and El-Jabi 1995). During winter, Miramichi rivers form a thick (50 cm) ice cover, that commonly forms icejams during spring break-up and occasionally during winter melts (Beltaos *et al.* 1989). On the wandering Southwest Miramichi, break-up occurs between March 22 and May 2, with the average break-up on April 14 (Allen and Cudbird 1971).

In New Brunswick, approximately 70 % of recorded flood damages are caused by ice related floods (Beltaos *et al.* 1989). The Miramichi region seldom experiences mid-winter thaws that result in ice break-up, but moderate to severe icejams are prevalent in the spring (Beltaos *et al.* 1989). Locations susceptible to icejams are common in wandering rivers and include shallow river reaches, channel constrictions, island and channel confluences. Physical evidence of ice jams is common on Miramichi rivers with frequent scars on trees and ice push marks on channel banks and boulder pavements along channel margins. Boulder pavements, the most common and stable feature formed by river ice, are composed of a thin veneer of boulders that protect the weaker underlying material. Boulders are aligned with their long axis downstream and have many striations caused by overriding ice (Mackay and Mackay 1977).

The Little Southwest Miramichi River had a mean annual flood (estimating bankfull discharge) of 272 $m^3 s^{-1}$ based on 1952 - 1997 data (Environment Canada 1997) and a bankfull stage of 2.44 m above gauge datum. Ice events created higher stages at lower discharges than during open water events (Figure 2-6A). In fact, the lowest ice influenced annual high stage event was approximately equal to the highest open water stage for the same period. The mean annual flood stage had a recurrence interval of two years based on these data (Figure 2-6B). The stage of the 2.33 year recurrence from ice influenced events was 3.42 m above the datum or 0.96 m above the mean annual flood. Therefore, on the Little Southwest Miramichi, if we assume that mean annual flood corresponds to bankfull stage, icejams frequently (one year in two) create stages 1 m above bankfull level, thereby potentially triggering avulsions.

Anabranches within Miramichi wandering rivers may occur as avulsions created by icejams more often than by the emergence of mid-channel bars that form vegetated islands. Icejams may force flow over the floodplain into abandoned channels, initiating avulsions. Also, avulsions commonly occur at the outside of a bend apex where channels have migrated to contact abandoned channels (Leddy *et al.* 1993, Smith *et al.* 1989). All

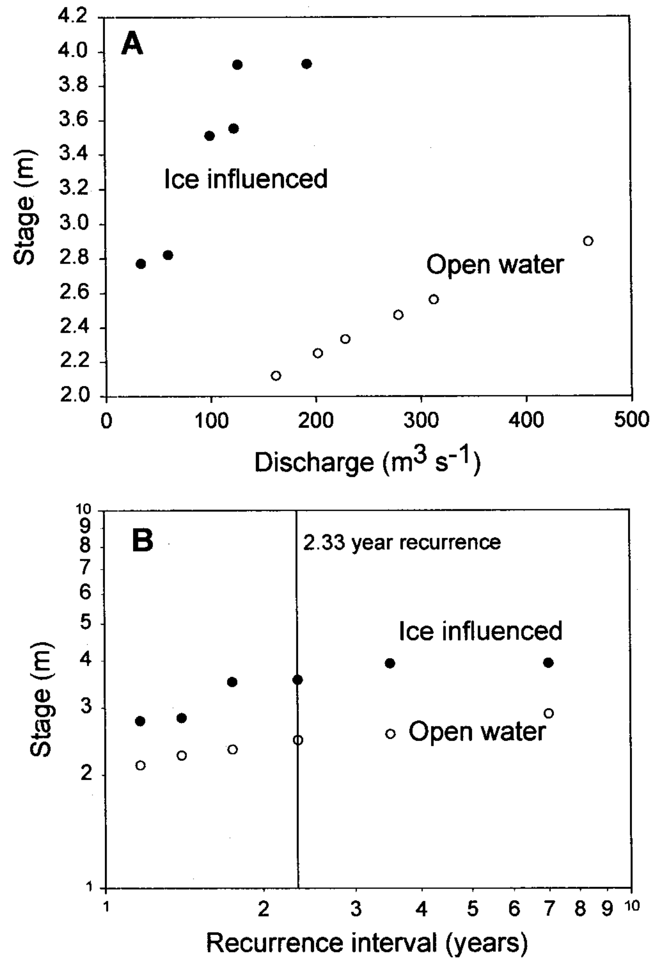


Figure 2-6. (A) Stage-discharge plot for highest annual ice influenced and open water stages per year, for 1995-2001 on the Little Southwest Miramichi at Lyttleton, New Brunswick. Ice influenced stages are greater for the same discharge than open water stages. (B) Stage-frequency plot for peak annual ice influenced and open water stages for 1995-2001. The 2.33 year recurrence ice influenced stage is 0.96 m higher than the open water stage of the same recurrence and probably is an avulsion trigger.

avulsions observed on aerial photographs or during reconnaissance within the Miramichi were of this type. The outsides of bends are common avulsion sites because of water surface super elevation and higher velocities in the outer bank, directing overbank flow onto floodplains.

4.2.4. Wandering river pattern characteristics

Wandering Miramichi rivers displayed a similar range of pattern characteristics. Results of the channel pattern characteristics for river sections measured from the orthomaps and averaged for each river are presented in Table 2-2 (see appendix 1 for scatter plots of correlations). The braid index ranged from 1.08 - 1.26 and was lower than wandering sections of the Bella Coola (4.5 – 1.7) and Peace rivers (2.4 - 1.6) (Desloges and Church 1989, Jiongxin 1997). Few statistically significant differences were seen among rivers due to variance within the characteristics of each river. In general, larger rivers had higher indices of anabranching than smaller rivers (Table 2-2). Braid index, normalized wavelength, number of channels across valley and highest order in the two larger rivers showed greater channel braiding than the three smaller rivers.

The main-channels of Miramichi wandering rivers are relatively straight with sinuosity values between 1.02 and 1.44 (Table 2-2). The Renous displayed the greatest sinuosity, the Dungarvon and little Southwest Miramichi had intermediate sinuosity and the Southwest Miramichi and Taxis had equally low sinuosity (Table 2-2, Anova, $p = 0.0001$). Sinuosity values were within the same range documented for other wandering rivers (from Nanson and Knighton 1996).

A Pearson correlation matrix with Bonferroni probabilities showed significant correlations among channel pattern variables (Table 2-3). The four braiding indices,

Table 2-2. Mean values and standard error of the mean for ten channel characteristics averaged for the five study rivers. n refers to number of 100 channel width sections in each river. Bold values denote at least one significant difference ($p < 0.05$) from other rivers. Means followed by a different letter are significantly different (ANOVA, $p < 0.05$) and ranking of means is indicated by: a > b > c. Significance determined using Bonferrni post hoc tests.

	Southwest Miramichi		*Little Southwest Miramichi*		*Renous*		*Dungarvon.*		*Taxis*	
	(n = 13)	*Std.*	*(n = 5)*	*Std.*	*(n = 2)*	*Std.*	*(n = 5)*	*Std.*	*(n = 2)*	*Std.*
Wandering sections	*mean*	*Error*	*mean*	*Error*	*mean*	*Error*	*mean*	*Error*	*mean*	*Error*
Main channel width	**108.32**	4.22a	**79.90**	5.39b	**43.93**	1.93c	**40.86**	1.56c	**36.90**	1.90c
Valley width	386.38	34.86	**494.96**	87.21a	347.17	91.21	**223.77**	33.49b	196.60	56.60
Norm. valley width	3.64	0.33	6.14	0.94	7.80	1.80	5.57	0.92	5.40	1.80
Wandering dist. (km)	61.8		**18**		6.8		30.7		8.4	
Braid index	**1.26**	0.08a	**1.20**	0.04a	1.10	.05	**1.04**	0.02b	1.14	0.02
Norm. wavelength	**12.83**	2.91b	15.00	4.09	17.90	2.00	**38.63**	15.27a	37.25	1.15
# channels across valley	1.63	0.15	1.48	0.12	1.40	0.10	1.14	0.07	1.30	0.00
Diffluence order	2.62	0.27	2.60	0.40	2.00	0.00	2.14	0.26	2.50	0.50
Sinuosity	**1.03**	0.01d	**1.15**	0.03b	**1.44**	0.09a	**1.10**	0.02bc	**1.03**	0.03bcd
Abandoned index	0.44	0.12	0.81	0.32	0.93	0.36	0.61	0.12	0.36	0.25

Table 2-3. Pearson correlation matrix comparing wandering river characteristics is shown in regular font in the bottom left. The matrix of Bonferroni probabilities are italicised in the top right and correlations where $p < 0.05$ are bold.

Wandering sections (n = 27)	*Main channel width*	*Norm. valley width*	*Braid index*	*Norm. wavelength*	*# channels across valley*	*Highest order*	*Sinuosity*	*Abandoned channel index*
Main channel width	1.00			*0.46*				
Norm. valley width	-0.41	1.00					*0.61*	*0.01*
Braid index	0.32	0.04	1.00	*0.002*	*0.0002*	*0.26*		
Norm. wavelength	-0.47	0.24	**-0.70**	1.00	*0.00001*	*0.07*		
# channels across valley	0.30	-0.04	**0.76**	**-0.82**	1.00	*0.07*		
Highest order	0.04	-0.15	**0.50**	**-0.56**	**0.57**	1.00		
Sinuosity	-0.40	0.45	-0.15	0.34	-0.23	-0.34	1.00	
Abandoned index	-0.07	**0.65**	0.04	-0.04	0.05	-0.15	0.16	1.00

braid index, normalized wavelength, number of channels across valley and highest order, were significantly correlated. Correlations between braid index, number of channels across valley and highest order were positive. Normalized wavelength showed negative correlations with the other variables because it decreases as the pattern becomes more braided as the number of diffluences per channel length increases. These variables were significantly interdependent, as correlation coefficients ranged between 0.50 to - 0.82. This indicates that river pattern variables do not provide the same information but instead each characteristic emphasizes a different aspect of a multiple channel river pattern.

Braid index may change over time as the main channel sinuosity adjusts due to channel switching and migration. By definition, braid index increases with the length of secondary channels and decreases with main-channel sinuosity (longer main-channels). Normalized braid wavelength was negatively correlated (- 0.47) with main-channel width, indicating that larger rivers have more diffluences. Normalized wavelength was highly correlated with number of channels across valley (-0.82), because the number of diffluences increases with the number of channels. Braid index may display high values with few channels (diffluences) if the secondary channels are long. Normalized braid wavelength may therefore provide the best single variable to quantify degree of splitting in multiple channel river patterns.

Interestingly, the highest diffluence orders (4 and 5) did not occur in the same sections as the highest braid index or average number of channels across valley, indicating that the highest order a section attains may be site specific. Factors that may influence highest order may include sediment routing through a section or the relative timing and location of icejams among anabranch channels, causing channel avulsions within anabranches.

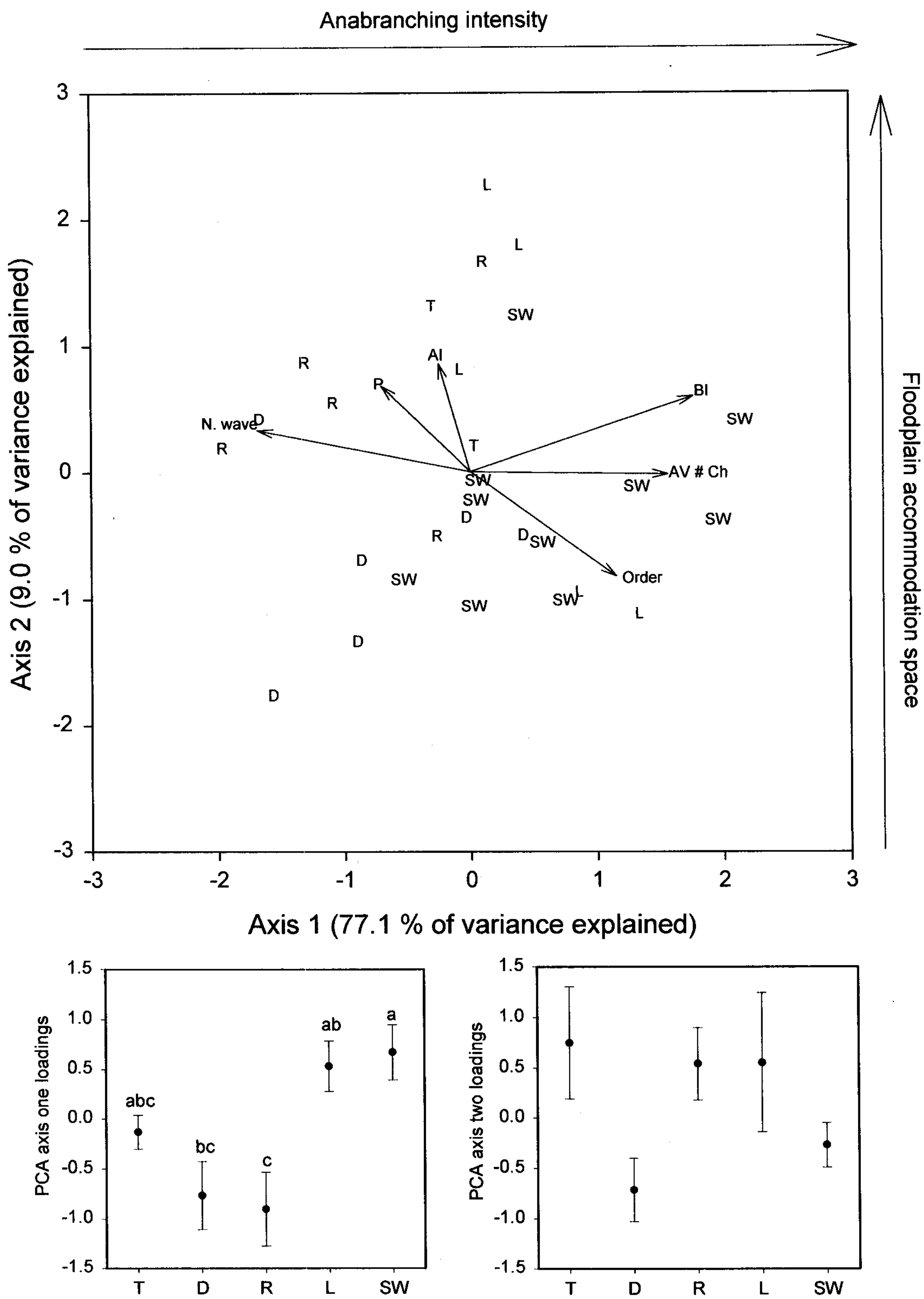
Sinuosity and abandoned channel index were not significantly correlated to any other pattern characteristic, indicating that they are independent of anabranching within river sections (Table 2-3). The Little Southwest Miramichi and Renous rivers had the greatest length of abandoned channels, while the Southwest Miramichi, Dungarvon and Taxis rivers had lower values. Abandoned channel index was only correlated with normalized valley width. Wider valleys have greater accommodation space for abandoned channels within floodplains.

2.4.5 Principal component analysis

Principal component analysis explained 86.1 % of the variance in channel characteristics in the first two axes (77.1 % and 9.0 %, respectively, Figure 2-7). Variables related to anabranching intensity such as braid index, number of channels across valley, and diffluence order, occurred high on axis one, while normalized braid wavelength occurred low on the axis. Abandoned index, and main channel sinuosity occurred high on axis two, while highest order occurred low on axis two.

Axis one is interpreted as being influenced by anabranching intensity (increasing number of multiple channels). Axis one was positively correlated with braid index, number of channels across valley and highest order, and negatively correlated with normalized wavelength (Table 2-4). The Southwest and Little Southwest Miramichi had significantly higher axis one loadings than the Renous, and the Southwest Miramichi had higher loadings than the Dungarvon (ANOVA, $p < 0.05$). Main-channel width was positively correlated with axis one (Table 2-4), suggesting that anabranching intensity

Figure 2-7. Principal component analysis of six river pattern variables showing 86.1 % of the variance explained in the first two axes. On the outside of the plot is shown the interpretation showing the relationship between PCA axis one and anabranching intensity, and PCA axis two and floodplain accommodation space. Below the PCA are plots showing average loadings for each river, error bars showing standard errors and differences determined through ANOVA lettered as a > b. (SW is Southwest Miramichi, L is Little Southwest Miramichi, R is the Renous, D is Dungarvon, T is Taxis, N.wave is normalized braid wavelength, PMC is main-channel sinuosity, AV # Ch is the average number of channels across valley, AI is abandoned channel index, VW ratio is normalized valley-width, Order is highest channel order, and BI is braid index).



Anabranching intensity
Floodplain accommodation space
Axis 2 (9.0 % of variance explained)
Axis 1 (77.1 % of variance explained)
N. wave
AI
BI
AV # Ch
Order
PCA axis one loadings
PCA axis two loadings
abc
bc
c
ab
a
T
D
R
L
SW

Table 2-4. Pearson correlation matrix between PCA factor loadings and main-channel width, normalized valley width and variables input to the PCA. Bold values denote $p < 0.05$.

Variable (n = 28)	*Axis 1*	*Axis 2*
Braid index	**0.93**	0.31
N. wavelength	**-0.95**	0.18
Highest order	**0.68**	**-0.42**
# channels across valley	**0.87**	-0.03
Abandoned index	-0.07	**0.42**
Sinuosity	-0.36	0.34
Main channel width	**0.46**	-0.04
N. valley width	-0.22	**0.55**

(high number of multiple channels) is greater in larger rivers. This is shown by the two largest rivers, the Southwest and Little Southwest Miramichi rivers, having high loadings on axis one and the smaller rivers, the Dungarvon and Renous, having low loadings (Figure 2-7). Going against the trend, the smallest river, the Taxis, had intermediate values.

Normalized valley width was positively correlated with axis two (Table 2-4), suggesting that these variables increase with accommodation space on floodplains. The largest river, the Southwest Miramichi, had the lowest normalized valley width and low loadings on PCA axis two, however much scatter occurred with other rivers (Figure 2-7). Axis two is interpreted as being driven by accommodation space within the floodplain. Much variability occurred on axis two, with Dungarvon sections plotting low on the axis, Southwest Miramichi sections in the middle of the axis and Taxis, Renous and Little Southwest Miramichi sections high on the axis. No significant differences among rivers were seen on axis two. Axis two was positively correlated with abandoned index, sinuosity and braid index, and negatively correlated with diffluence order (Table 2-4).

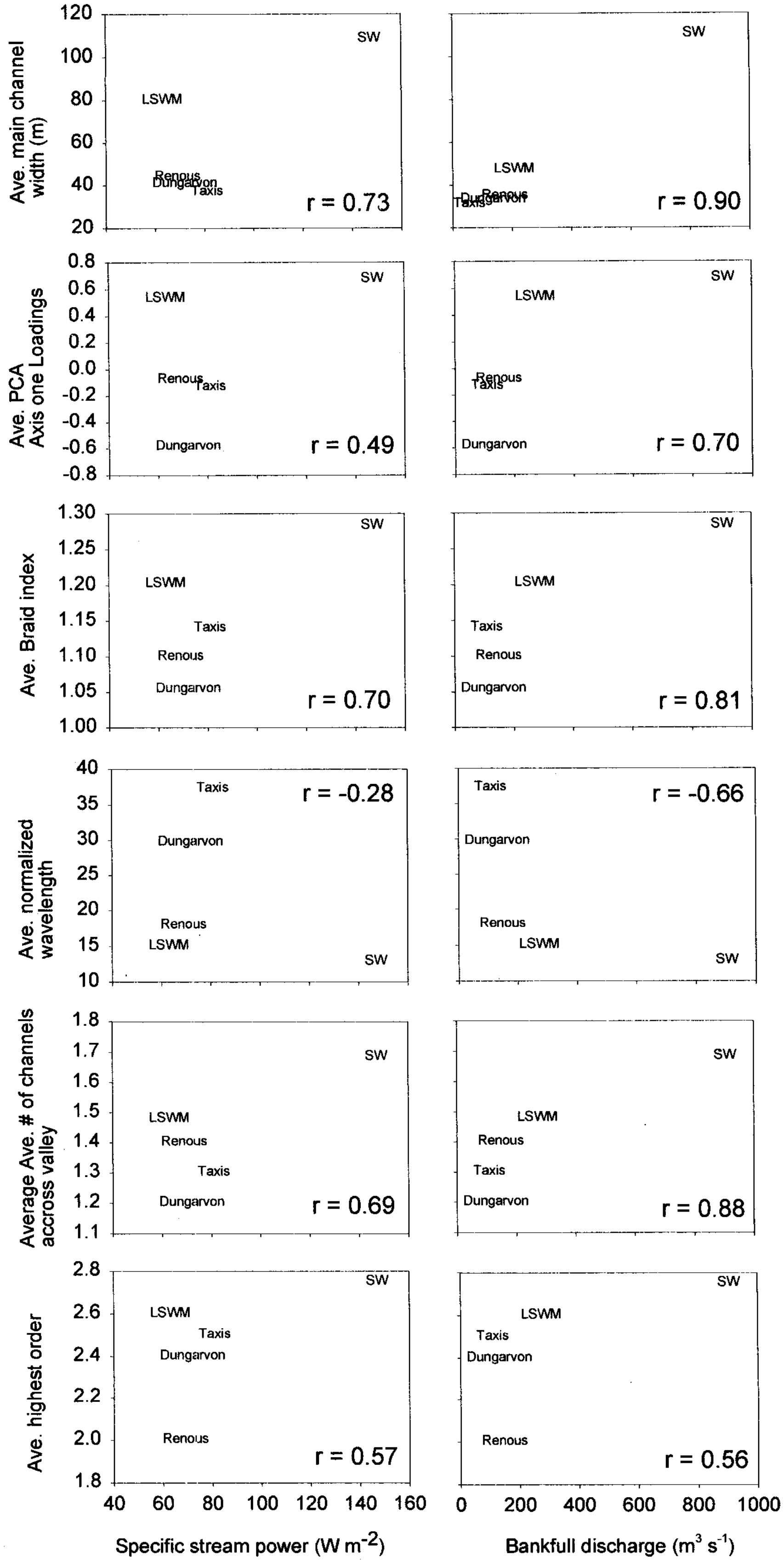
2.4.6 Influences on anabranching intensity in wandering rivers

Two processes that may influence anabranching intensity are channel energy and icejam height. Anabranching intensity may increase with channel energy (Leopold and Wolman 1957), where higher channel energy may increase sediment mobility causing thalweg shoaling and avulsions, similar to braided river processes (Ashmore 1991). The presence of icejams has also been linked to anabranching (Hicks 1993). High stage icejams may increase anabranching intensity by triggering avulsions and slowing the abandonment of abandoning channels. Average specific stream power and potential icejam height were calculated for each of the five rivers. PCA axes loadings and channel characteristics were averaged for each river and correlated with average stream power and potential icejam height (Figure 2-8). Unfortunately, this resulted in only five sample points, with four points clustered, for this analysis and therefore these results may be viewed as preliminary.

Average main-channel width was more highly correlated with potential icejam height than average specific stream power (Figure 2-8), indicating that height of icejams may be more related to river size than specific stream power. The potential icejam height displayed higher correlations with all pattern characteristics than average specific stream power (Figure 2-8). Highest diffluence order displayed the same correlations with both specific stream power and potential icejam height.

It appears from these few data points that potential icejam height better explained the anabranching intensity than specific stream power. Icejams are larger within larger rivers, resulting in greater anabranching intensity than smaller rivers. This suggests that avulsion triggers other than high sediment transport rates and thalweg shoaling are important in maintaining wandering rivers in some regions. The low occurrence of thalweg shoaling is consistant with the observation of few mid-channel bars within wandering Miramichi rivers and lower width-depth ratios than other wandering rivers with greater sediment input. Wandering rivers may therefore be viewed as a product of equifinality or convergence, where high rates of sediment input causes multiple channels in some regions and other avulsion triggers, such as icejams, may create similar patterns in other regions.

Figure 2-8. Correlations between pattern characteristics and PCA axis one loadings averaged for all sections in each river (n = 5), and average specific stream power and potential icejam height estimated using the icejam height model of Prowse and Beltaos (2002). (SW is the Southwest Miramichi and the LSWM is the Little Southwest Miramichi)



Ave. main channel width (m)
Ave. PCA Axis one Loadings
Ave. Braid index
Ave. normalized wavelength
Average Ave. # of channels accross valley
Ave. highest order
SW
LSWM
Renous
Dungarvon
Taxis
r = 0.73
r = 0.90
r = 0.49
r = 0.70
r = 0.70
r = 0.81
r = -0.28
r = -0.66
r = 0.69
r = 0.88
r = 0.57
r = 0.56
Specific stream power (W m-2)
Bankfull discharge (m3 s-1)

2.4.7 Effect of valley width on wandering rivers

Abandoned index, sinuosity, diffluence order and braid index were correlated with PCA axis two (Table 2-4). PCA axis two was also correlated with normalized valley width (Table 2-4). Axis two was not highly correlated with specific stream power or potential icejam height. The variables correlated with PCA axis two increased with accommodation space in valley bottoms. The greatest length of abandoned channels occurred in wide valleys that provided accommodation space for the abandoned channels. The sinuosity of the main channel increases as channels had space to meander within larger valleys. Braid index also depends on valley width because large valleys create space for long secondary channels to occur. Although axis two explained only a small percent of the variance in the data (9.0 %), the accommodation provided by valleys that are much wider than the channels which flow through them is an important factor for wandering river formation.

2.5. Conclusions

For a river to become wandering three factors appear to be needed: (1) wide valleys, (2) channel energy levels between braiding and meandering, and (3) avulsion triggers. Wandering rivers within the Miramichi occurred within larger valleys located downstream of a regional change in bedrock from hard to soft bedrock lithology. These larger valleys allow accommodation space for the formation of multiple channels. On a slope–discharge plot, Miramichi wandering rivers plotted in the same range as other wandering rivers and displayed similar specific stream power values. Icejams within Miramichi rivers appear to cause avulsions that create the multiple channel anabranches that define the pattern. Other wandering rivers have been shown to be produced by thalweg shoaling due to high sediment loads (Church 1983, Carson 1984b). Wandering rivers therefore may be a product of equifinality or convergence, where different processes produce a similar pattern.

Larger rivers within the Miramichi displayed greater anabranching intensity than smaller rivers. Potential icejam height better explained anabranching intensity than specific stream power. Icejams are larger within larger rivers, resulting in greater anabranching intensity than smaller rivers. Wider valleys within the Miramichi showed higher values in some pattern characteristics because of increased accommodation space for abandoned and active channels.

2.6. Wandering river management

The ability of a stream to produce fish depends not only on the amount and accessibility of habitat, but also on the distribution of habitat types. Wandering rivers offer diverse habitat that changes through the seasons. This study increased knowledge that will aid in conserving these vital habitats in regulated basins. To maintain wandering systems, avulsion triggers should be allowed to occur by creating artificial floods from dam releases if necessary. To slow channel abandonment and create new channels through avulsions, icejams may also be created by dam releases during winter. Avulsions should be allowed to happen when they initiate. To limit flood damage during the natural maintenance of multiple channels by high stages, construction should be limited on these floodplains. Also, where possible roads should be built on high ground to prevent their flooding and limit interference with natural river processes . Abandoned channels should not be infilled so that they may provide future avulsion sites and side-channel habitat.

Future research using canonical correspondence analysis (CCA) could relate pattern variables and energy variables for each section, not just as averages for each river as in this study. This may provide a more robust analysis of the factors controlling different aspects of multiple channel river patterns. Other energy characteristics as well as grain size and sediment mobility could also be added to this analysis. Other channel characteristics such as bank strength, log input and icejam frequency could also be used as explanatory variables to compare rivers among regions. Although ambitious, this analysis would provide valuable insight and continue to investigate hypotheses on the controls of multiple channel river patterns that have been suggested for decades.

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Preface to chapter three

Chapter three investigates the dynamics of channels, nested within the wandering river pattern investigated in chapter two (Figure 1-5B, Figure 1-6). Chapter three investigates how channels within the wandering river pattern change over time. Chapter two analysed five wandering rivers at one time period to investigate the regional characteristics that influence their location and controls on differences among the rivers. Chapter three investigated two research questions: (1) can the pattern characteristics of wandering rivers be in dynamic equilibrium? (2) If so how is dynamic equilibrium maintained? Chapter three investigates the dynamics of the Renous River through a time series analysis of channel dynamics to determine whether channel characteristics change through time. Then, a conceptual model is developed to understand the dynamics of anabranches.

3. Chapter three: The anabranch cycle model: understanding wandering river channel temporal dynamics

3.1. Abstract

Wandering river patterns are maintained as the location of individual anabranch channels change. Wandering rivers are composed of multiple channels that divide into individual anabranches around semi-permanent stable islands, linked by single channel reaches. Anabranches are important because they provide habitat complexity for aquatic organisms, including salmonids. To quantify system dynamics, the wandering Renous River was mapped from aerial photographs taken in 1999, 1983, 1965, and 1945 and channel pattern statistics were determined for each year. From these data and field observations, a conceptual model called the anabranch cycle was developed to illustrate the temporal dynamics of wandering rivers.

The wandering pattern will change if the frequency of anabranch creation or abandonment changes. If the creation frequency increases, the total number of channels will increase, and may force the system to increase anabranching. If the abandonment frequency increases the total number of channels will decrease, until perhaps only a single channel remains. Within the Renous study area, channel creation and abandonment frequencies were similar over the 50 years of analysis, indicating that the wandering pattern is in a state of dynamic equilibrium.

The anabranch cycle model, based on observations from the Renous River and literature, explains how the wandering pattern is maintained as river sections change from a single channel to multiple channels and return to a single channel. Anabranches display

a cycle of creation, stability and abandonment. The anabranch cycle begins with a floodplain scarred with abandoned channels that are possible avulsion paths. Anabranches may be created by avulsions or deposition of bars that stabilize to become islands. Avulsions are triggered by large floods, logjams, or icejams, forcing water over the floodplain into abandoned channels. Where an avulsion course is much shorter than the course of the main-channel, the main-channel quickly switches into the avulsion channel, leading to a single channel. Stable anabranches may occur where avulsion and main-channel lengths are similar. Stable anabranches may become unstable if the balance of sediment and water entering each anabranch is disturbed. One anabranch may be abandoned if it receives more sediment than it can transport due to changes in diffluence geometry or due to an overload of sediment from upstream. Channel abandonment leaves low semi-filled channels scarring floodplains. These abandoned channels may become future avulsion sites, restarting the anabranch cycle and allowing the multiple channel system to be maintained.

3.2. Introduction

Wandering systems are relatively common, with concentrations in the Canadian Cordillera and the Canadian Maritimes. Analysis of multiple channel rivers has concentrated on correlations among average system statistics (e.g. slope, discharge, grain size, bank strength) (e.g. Leopold and Wolman 1957), and historical case studies of channel change (e.g. Church 1983, Bristow 1999), but more recent studies have attempted to understand the mechanisms controlling these patterns (e.g. Ashmore 1993). Wandering rivers, like anastomosed rivers, appear to be a product of convergence or equifinality where different processes produce similar patterns (Makaske 2001).

Wandering rivers provide complex hydraulic and channel structures, consisting of larger main-channels with perennial flow, smaller side-channels with seasonal flow and abandoned channels. Channel complexity provides diverse habitat for many aquatic organisms including salmonids and offers over-wintering habitat for adult Atlantic salmon (Komadina-Douthwright *et al* 1998) and juvenile salmonids (Peterson 1982, Tschaplinski and Hartman 1983, Brown and Hartman 1988, Nickelson *et al.* 1992). River regulation may decrease channel complexity within wandering rivers by causing abandonment of side-channels, leading to a simplified river pattern (Desloges and Church 1989, Ligon *et al.* 1995). Side-channels may also be cut off to protect roads and bridges.

Wandering rivers display a mosaic of channel types that may be maintained through time. Wandering rivers are composed of multiple channel reaches that divide into individual anabranches around semi-stable forested islands, connected by single channel reaches (Neill 1973, Church 1983). Side-channels may be created, maintained or abandoned through time and thereby create a variable river pattern. In multiple channel systems, channels move, new channels form and old channels are abandoned, but if the river pattern is in dynamic equilibrium, the pattern remains. The wandering river pattern will persist when the long-term rate of side-channel creation equals side-channel abandonment.

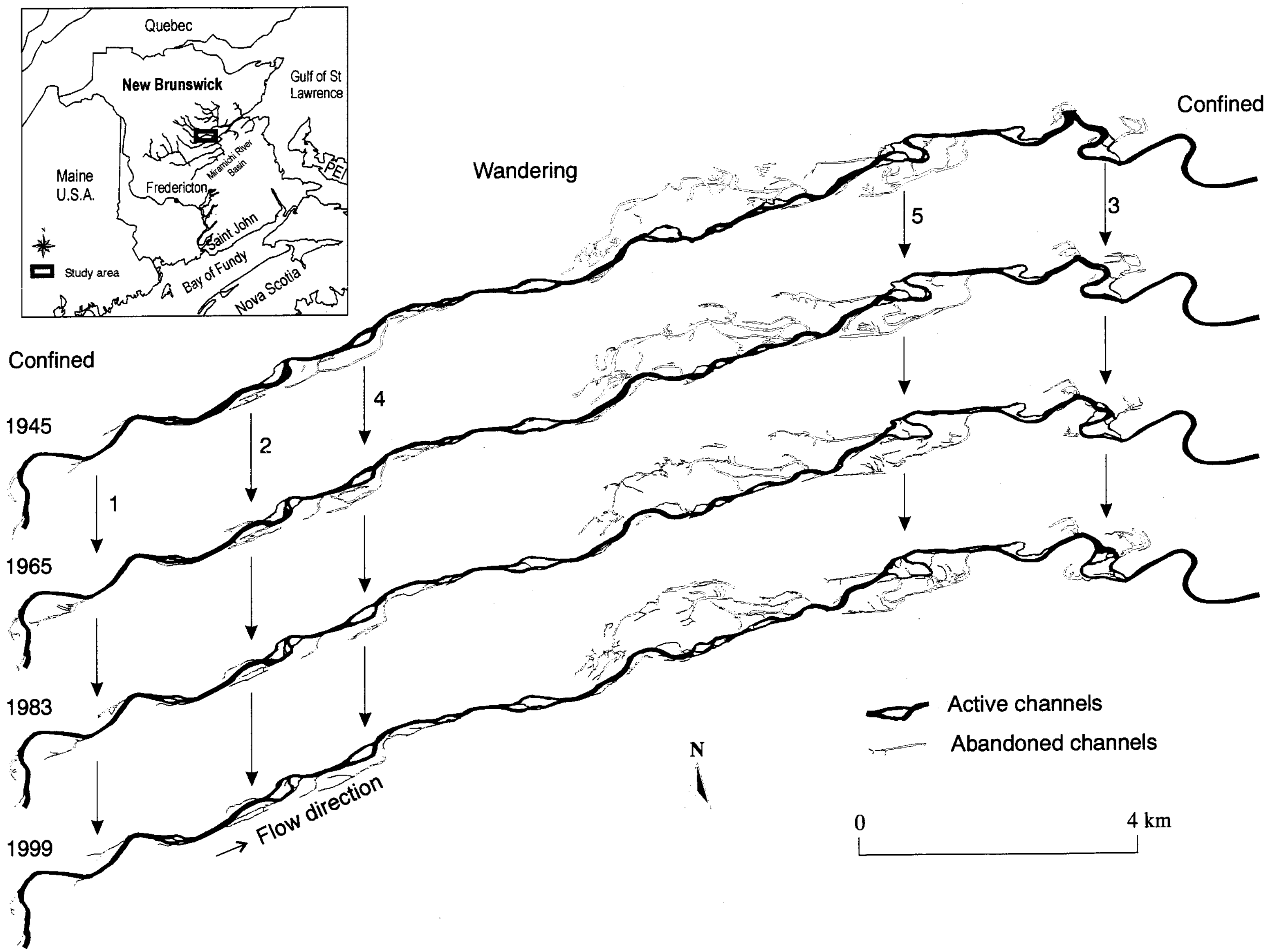
The research question was: how is a wandering river pattern maintained through time? The study had two objectives: (1) to examine how the pattern of a wandering river changes through time, and (2) to develop a conceptual model to explain the system dynamics.

3.3. Study area

Research was conducted on the Renous River located near the centre of the Miramichi drainage basin, New Brunswick (Figure 3-1, inset). The Renous shows a classic wandering pattern for 11.5 km, with multiple channels around islands, and abandoned channels within the floodplain (Figure 3-1). The Renous is 60 m wide, has a mean annual flood of 147 m^3/s (Environment Canada 1997), an average bankfull specific stream power of 69 W m^{-2}, a mean D_{50} of 67 mm at riffles and drains 611 km^2 of the Miramichi plateau. Wandering begins where valley width increases to accommodate multiple wandering channels and ends where valley width decreases downstream. Confined sections with single channels and few islands occur where narrow valley bottoms restrict channel migration and limit space for the production of multiple channels. Multiple channel reaches within the Renous are not explained by local perturbations in bedrock, or the entrance of large tributaries or alluvial fans into the valley. The 11 km wandering Renous section shows a concave long profile (from 0.36% to 0.19% slope) and downstream fining of sediment (from 77mm to 47mm). The wandering section of the Renous is not located between braided upstream and meandering downstream like the Bella Coola (Church 1983) and the Squamish (Brierly 1989) rivers in British Columbia.

At McGraw Brook, in the centre of the study reach, the mean monthly air temperature varies between -11.8°C in January and 18.8°C in July, with April to October temperatures above freezing (Caissie and El-Jabi 1995). During winter, Miramichi rivers form a thick (50 cm) ice cover, that commonly forms ice jams during spring break-up and occasionally during winter melts (Beltaos *et al.* 1989). Within the wandering reach of

Figure 3-1. Maps of the wandering section of the Renous River for 1945, 1965, 1983 and 1999 created from aerial photographs. Arrows point to specific system states discussed in the text and are enlarged in Figure 3-5. Arrow 1 displays a stable single channel, arrow 2 displays an unstable single channel, arrow 3 displays unstable anabranches gaining stability, arrow 4 displays stable anabranches, and arrow 5 displays unstable anabranches losing stability.



Quebec
New Brunswick
Gulf of St Lawrence
Maine U.S.A.
Fredericton
Miramichi River Basin
PEI
Saint John
Bay of Fundy
Nova Scotia
Study area
Wandering
Confined
Confined
1945
1965
1983
1999
1
2
3
4
5
Flow direction
Active channels
Abandoned channels
N
0
4 km

the larger neighbouring Main Southwest Miramichi, break-up occurs between March 22 and May 2, with the average break-up date on April 14 (Allen and Cudbird 1971). Evidence of ice jams is common on the Renous with frequent scars on trees, boulder pavements, and ice push marks on channel banks.

3.4. Methods

Channel locations of the Renous River were digitized from scanned (300 dpi) and warped 1:12 000 aerial photographs from 1945, 1965, 1983 and 1999 using Arcview 3.2 and image analysis (ESRI 1999) to produce maps. Main-channel length, side-channel length, and the number of diffluences were determined. **Braid index** (total length of all channels / length of the main-channel), **main-channel sinuosity** (main-channel length / valley length) and **normalized braid wavelength** ([main-channel length / total number of diffluences] / main-channel width) were determined for each year. The frequency of channels created through avulsion and the emergence of forested islands from mid-channel bars and channel abandonment was determined for each time interval.

3.5. Results and discussion

3.5.1 Channel pattern dynamics

Several changes were seen in Renous River channels between 1945 and 1999 (Figure 3-1). Eight new channels were created through avulsion, five channels were created through emergence of islands due to mid-channel deposition, and eleven channels were abandoned over the fifty-four year study period. The wandering pattern should change if the frequency of anabranch creation or abandonment changes. If the creation frequency increases, the total number of channels will increase, and may force the system to increase anabranching. If the abandonment frequency increases the total number of channels will decrease, until perhaps only a single channel remains. Avulsion and emergence frequency increased then decreased and abandoned frequency decreased then increased over the study period (Figure 3-2A). Within the Renous study area, channel creation and abandonment frequencies were similar over the 50 years of analysis (0.04 more channels created per year than abandoned) (Figure 3-2A). The difference between channel creation and abandonment frequencies may not be significant because only two additional channel segments were created than abandoned through the study period.

The braid index ranged from 1.36 to 1.50 and generally increased through the 54-year study period (Figure 3-2B). Braid index increased because avulsions cut off two large meanders, decreasing the main-channel length while increasing the length of secondary channels. Sinuosity ranged from 1.16 to 1.23 through the study period (Figure 3-2B). Sinuosity was consistent between 1945 and 1965, then decreased in 1983 and remained constant until 1999, opposite to the trend in braid index and related to the meander cut offs.

Braid wavelength, normalized by the channel width, ranged between 10.1 and 11.6 channel widths and increased between 1945 and 1965, decreased between 1965 and 1983 and increased between 1983 and 1999 (Figure 3-2B). Braid wavelength depended more on the number of diffluences than main-channel length but increased with main-channel length and with channel abandonment.

3.5.2 The anabranch cycle

Although not static, the river pattern characteristics of the Renous River appears to be in a state of dynamic equilibrium because the frequency of channel creation and

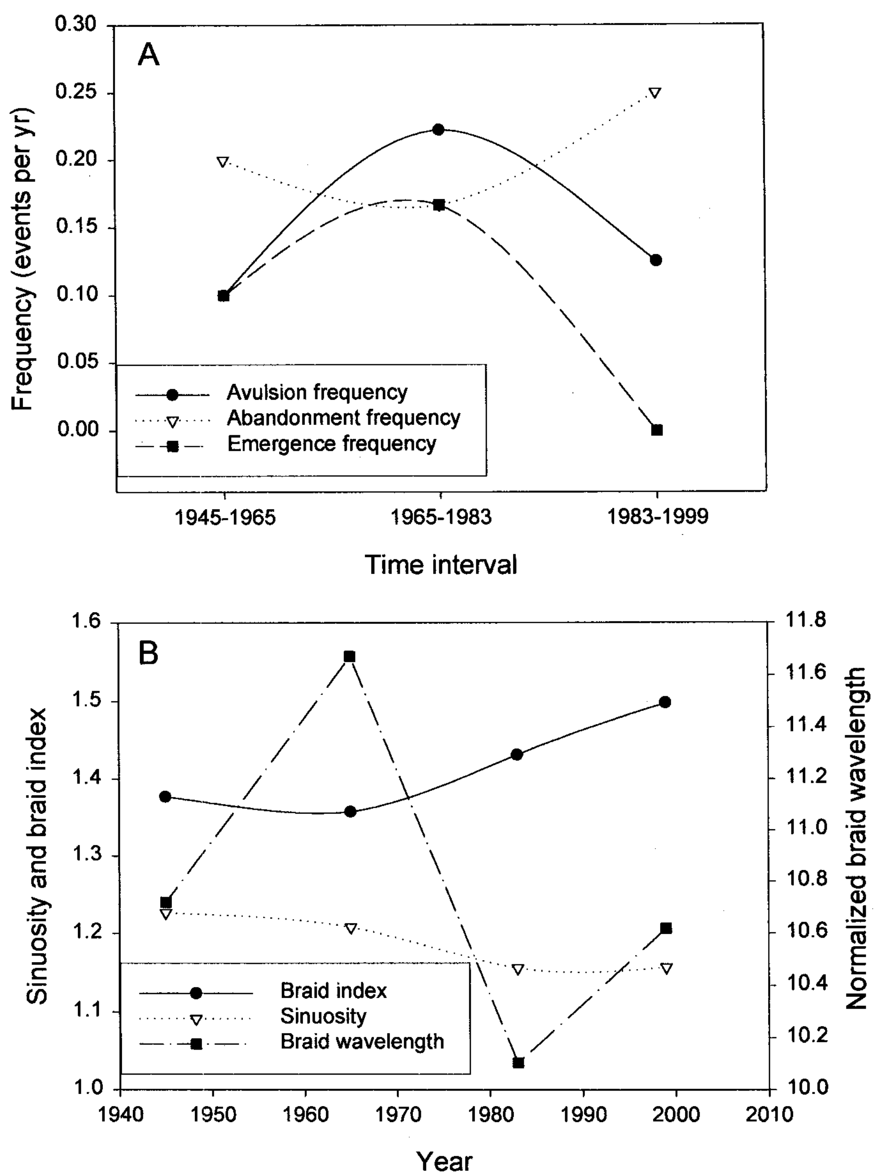


Figure 3-2. (A) Avulsion, island emergence and abandonment frequency for years between aerial photographs. (B) Braid index, main-channel sinuosity, abandoned channel index, and braid wavelength normalized by main-channel width between 1945 and 1999 for the wandering section of the Renous River, New Brunswick.

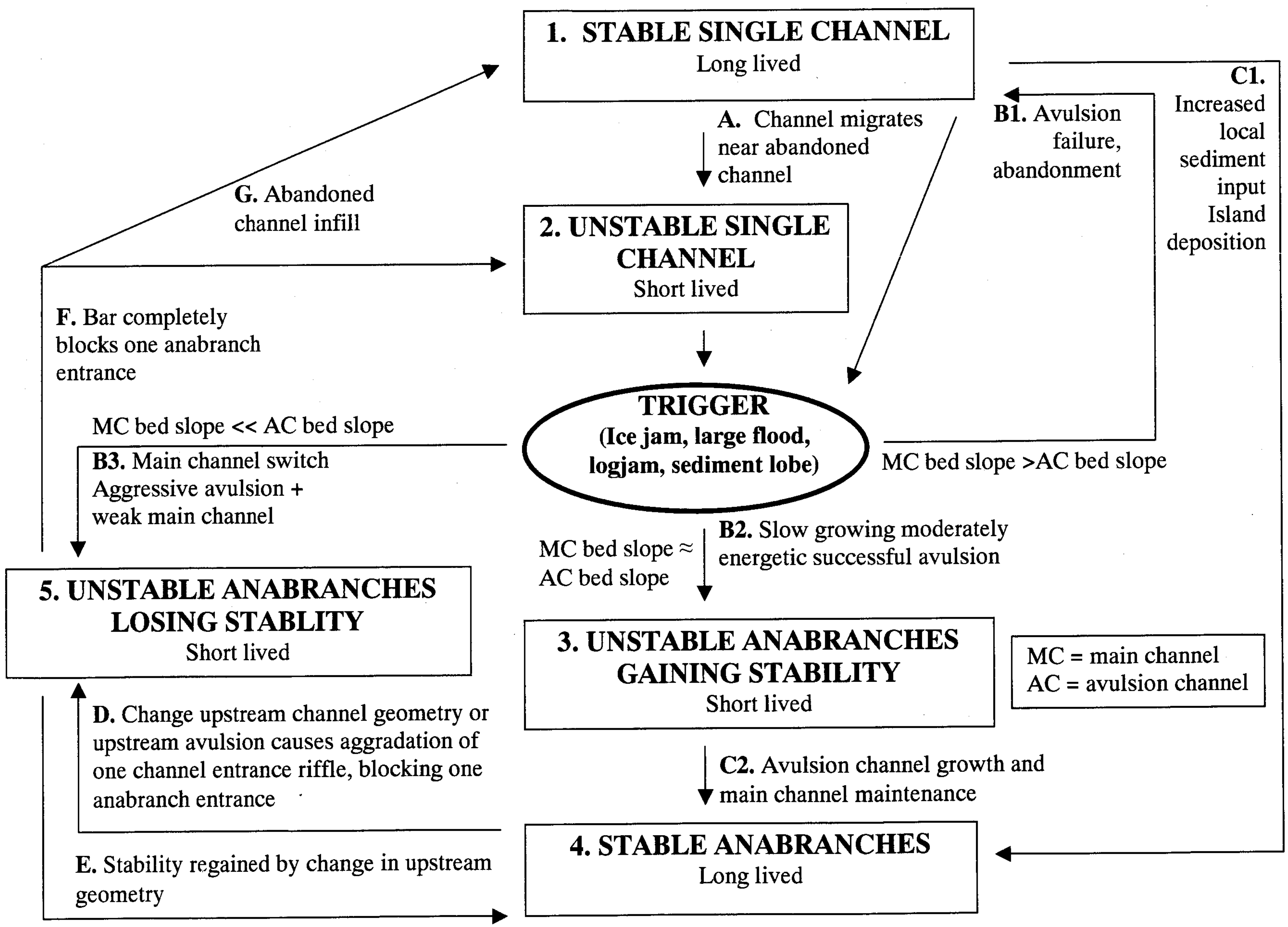
abandonment were essentially equal. The wandering pattern of vegetated islands and multiple channels remained while the location of individual channels and islands changed (Figure 3-1). This equilibrium may be maintained by the diversion of flow into avulsion channels and the equal decrease of flow in the remaining channels. The frequency of avulsions may not exceed a theoretical limit imposed by the loss of discharge into new avulsions. As new avulsions are created, discharge decreases in the other channels. This decreases the likelihood of another avulsion occurring within this section by decreasing the channel energy within the remaining channels. At the same time, the decrease in flow increases the likelihood of the least efficient anabranch channel becoming abandoned by deposition of less mobile sediment. Diverting flow into new channels and decreasing flow into old channels may regulate the number of channels within wandering rivers.

Creation and abandonment processes occurring at the scale of the individual anabranch maintains the wandering pattern. A conceptual model called the anabranch cycle is proposed to explain the maintenance of the wandering river pattern (Figure 3-3). The model is explained using examples from the maps of the Renous River. The model displays five system states represented by numbered boxes that are linked by lettered arrows that indicate the processes that shift channels between states. Unstable states are short lived and adjust relatively quickly to stable states. Stable states are long lived and may adjust to unstable states following a long period of stability. Finally, avulsion triggers, represented by an oval in the model, may force unstable single channels to change states to unstable multiple channels.

3.5.3 Avulsion triggers

Central to the anabranch cycle model are avulsion triggers that displace flow onto

Figure 3-3. Anabranch cycle model illustrating how anabranch channels are created, maintained, and abandoned through time. Boxes indicate channel states and arrows indicate processes moving channel sections between states.



1. STABLE SINGLE CHANNEL
Long lived
A. Channel migrates near abandoned channel
2. UNSTABLE SINGLE CHANNEL
Short lived
G. Abandoned channel infill
F. Bar completely blocks one anabranch entrance
B1. Avulsion failure, abandonment
C1. Increased local sediment input Island deposition
TRIGGER
(Ice jam, large flood, logjam, sediment lobe)
MC bed slope << AC bed slope
B3. Main channel switch Aggressive avulsion + weak main channel
MC bed slope >AC bed slope
MC bed slope ≈ AC bed slope
B2. Slow growing moderately energetic successful avulsion
5. UNSTABLE ANABRANCHES LOSING STABILITY
Short lived
3. UNSTABLE ANABRANCHES GAINING STABILITY
Short lived
MC = main channel
AC = avulsion channel
D. Change upstream channel geometry or upstream avulsion causes aggradation of one channel entrance riffle, blocking one anabranch entrance
C2. Avulsion channel growth and main channel maintenance
4. STABLE ANABRANCHES
Long lived
E. Stability regained by change in upstream geometry

floodplains during high stages to generate avulsions. Avulsion frequency is controlled by the interaction between the rate of the various processes that move a river toward unstable channel geometry and the frequency of triggering events (Jones and Schumm 1999). If the combined processes that lead to instability proceed rapidly relative to triggering events, the frequency of triggering events controls avulsion frequency. If triggering events occur frequently relative to the rate the river becomes unstable, the rate that processes create instability will control avulsion frequency (Jones and Schumm 1999).

In the Miramichi basin, icejams are common (Baltaos *et al.* 1989) and initiate avulsions. The 2.33 recurrence ice influenced stage was 3.42 m above the datum or 0.96 m above the mean annual flood. Icejams occur at tight bends, shallow cross- sections, island heads, and constrictions, and are common in many northern rivers (Beltaos *et al.* 1989). Icejam stages are much greater than open water stages for a given discharge because increased roughness within the ice jam decreases velocity, thereby increasing stage (Beltaos 1995). Icejams may also physically block channels, decreasing their cross-sectional area. Flow into secondary channels may be caused by flow restriction from ice accumulation in the main-channel during break-up (Smith 1980, Hicks 1993). The Mackenzie River at Fort Providence, NWT, is thought to experience icejam-initiated avulsions because of the frequent high stages caused by icejams (Hicks 1993).

Logjams may be another avulsion trigger particularly in systems prone to anabranching (Smith *et al.* 1989). Floodplain splays or avulsion channels are commonly formed by logjams that back-up flow until levees are overtopped (Smith 1980). In some small-scale anabranching systems, individual trees may block channels (Harwood and Brown 1993). The frequency of logjams depends on the release of large woody debris to the river and the channel size; larger channels are less susceptible to logjams than smaller channels. The release of large woody debris also depends on the size of trees and the channel migration rate.

A highly seasonal or extremely episodic flow regime was argued to be a common characteristic of anabranching rivers and may cause avulsions (Nanson and Knighton 1996). Major flooding may be due to tropical summer rain (e.g. Okavango River) (McCarthy *et al.* 1992), seasonal snowmelt regimes (e.g. Columbia and Alexandria rivers) (Smith 1973, Smith 1983, Smith and Smith 1980), or a bimodal flood peak (e.g. Magdalena River) that inundates the floodplain for prolonged periods (Smith and Smith 1980). The combination of frequent or high-magnitude flooding in channels that cannot readily alter their flow capacity is a precondition for avulsion (Nanson and Knighton 1996). For example, secondary channels within the Fitzroy River are maintained by the overbank flow dominated regime that has existed for over 3000 years (Taylor 1999). Construction of dams may decrease the number of anabranches by decreasing flood peaks and avulsion frequency in anabranching rivers (Desloges and Church 1989, Ligon *et al.* 1995). Decrease in anabranching following dam construction was seen on the Peace River, British Columbia (Desloges and Church 1989) and the McKenzi River, Oregon (Ligon *et al.* 1995). There are many rivers with a highly variable flow regime that do not anabranch, so other conditions must combine to develop multiple channels (Nanson and Knighton 1996).

Sediment lobes may migrate downstream as a wave and cause instability and avulsions (Church and Jones 1982). Sediment lobes that create choking avulsions (Leddy *et al.* 1993), are commonly caused by an avulsion upstream (Payne and Lapointe 1997, Ashmore 2001), scour at confluences (Ashmore 1993), or through the erosion of terraces that add excess bedload into systems (Church 1983, Carson 1984). Channel beds aggrade and bars are deposited as the wave approaches, and degrade after it passes (Wathen and Hoey 1998). Sediment lobes may cause the thalweg to shoal, creating overbank flow that leads to avulsion. Sediment waves do not always cause avulsions, but instead may interact with and change the recipient morphology, depending on the local morphological stability and the wave magnitude (Wathen and Hoey 1998).

In some very low gradient systems, avulsions may result from high stages created through inefficient channels (Riley 1975). Mechanisms creating inefficient channels, such as sediment accretion and growth of vegetation within channels may gradually reduce their flow capacity and cause avulsions (Taylor 1999). For example, even at well above bankfull, velocities in the largest channels of Cooper Creek are very low and cannot convey all of the flow, forcing water onto the floodplain (Nanson and Knighton 1996). Backwaters created on very low gradient systems close to their baselevel or with a rising baselevel may cause flooding of the floodplain and possibly avulsions. This mechanism is not related to channel efficiency but simply decreasing the flow velocity in the downstream direction. This mechanism may be common in anabranching anastomosed deltas or systems with rising baselevel, like the Columbia (Smith 1983), however, is unlikely to be the mechanisms in higher slope wandering systems.

3.5.4 Stable single channel

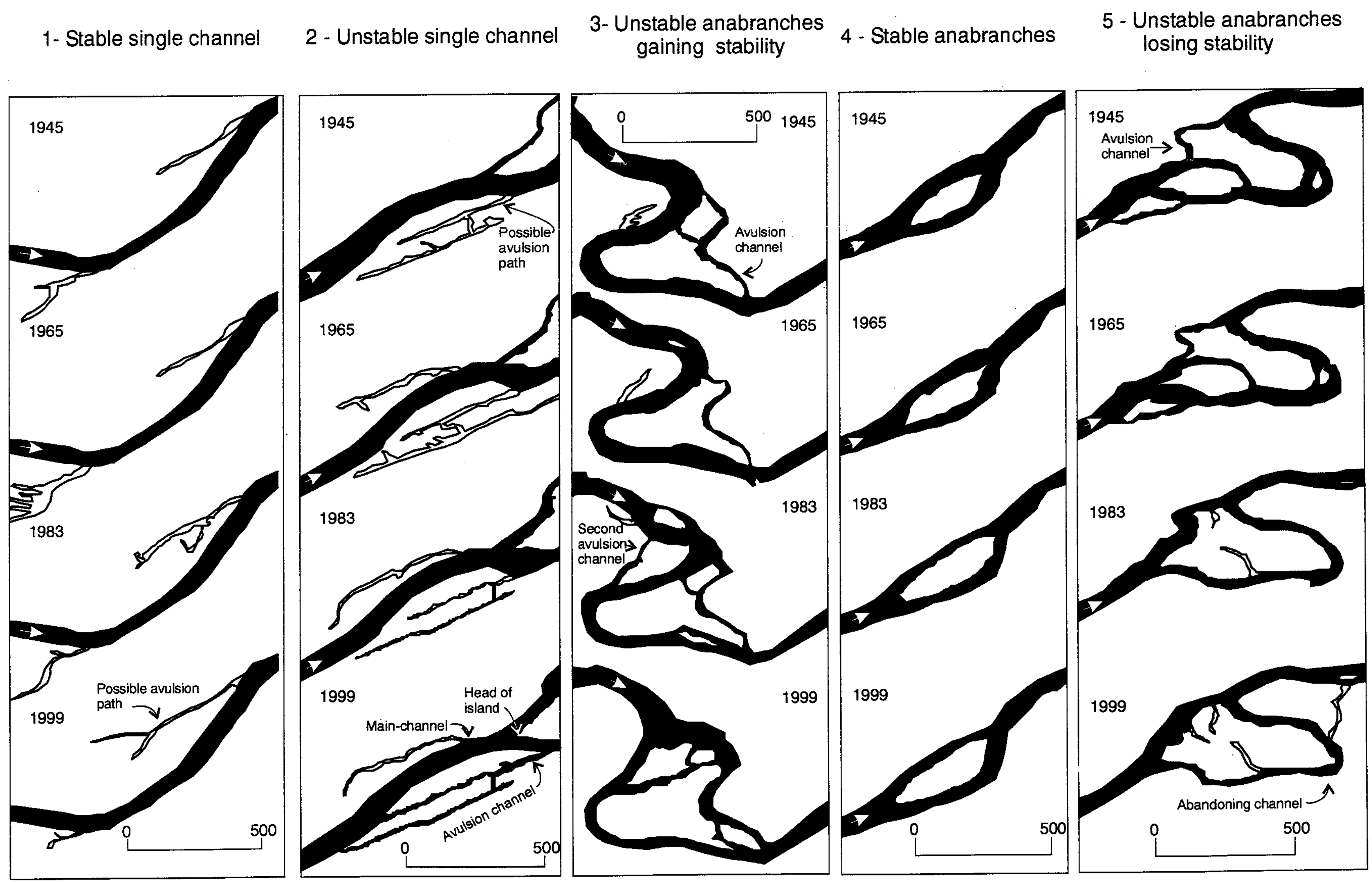
The first system state in the proposed anabranch cycle is a stable single channel (Figure 3-3 box 1). This state is stable because the slope of possible avulsion paths is the same or less than that of the single channel. Abandoned channels are common on many floodplains and may be used as avulsion paths when encountered by main-channels during channel migration. If a trigger event occurs during this system state it will not create anabranches (Figure 3-3 path B1). For example, if the single channel is blocked by an ice jam, flow may not enter an abandoned channel if there is a great distance between the main-channel and the abandoned channel. Also, if a high stage trigger event occurs where the avulsion course is longer than that of the single channel, the avulsion channel will be abandoned when stage decreases and a single channel will be maintained. This creates a failed avulsion (Guccione *et al.* 1999) because the system reverts back to a single channel.

Stable single channels occurred within sections of the Renous River confined by the valley walls. Panel 1 of Figure 3-4 shows a single channel that remained between 1945 and 1999. The length of the main-channel around the meander bend was 760 m while the length of the possible avulsion path down an abandoned channel was 725 m. This produced a ratio of possible avulsion path length to main-channel length of 0.95. Also, the abandoned channel occurred 250 m from the main-channel, making flow into that channel unlikely. An avulsion is unlikely with this channel geometry because the channel has to migrate quite far to contact the abandoned channel. No avulsion occurred through the fifty-four year study period, even during high stage events.

3.5.5 Unstable single channel

A stable single channel may migrate so that an avulsion course is much shorter than the main-channel or may it migrate to contact an abandoned channel (Figure 3-3 box 2). If an avulsion-triggering event occurs where there is an unstable single channel an anabranch will be created.

Figure 3-4. Enlarged maps from Figure 3-1 displaying (1) a stable single channel, (2) an unstable single channel, (3) unstable anabranches gaining stability, (4) stable anabranches, and (5) unstable anabranches losing stability for the study period (1945 – 1999).


1- Stable single channel
2 - Unstable single channel
3- Unstable anabranches gaining stability
4 - Stable anabranches
5 - Unstable anabranches losing stability
1945
1965
1983
1999
Possible avulsion path
Avulsion channel
Second avulsion channel
Head of island
Main-channel
Abandoning channel
0
500

Unstable single channel sections occurred within the Renous River. Panel 2 of Figure 3-4 displays an unstable single channel between 1945 and 1983 and an avulsion channel that formed between 1983 and 1999. The main-channel migrated to within 70 m of an abandoned channel by 1983, creating a single channel that was prone to an avulsion. The length of the main-channel was 550 m while the length of an abandoned channel was 490 m, producing a ratio of the possible avulsion path length to the main-channel length of 0.89. This created a larger slope through the possible avulsion path than the main-channel and allowed the use of the abandoned channel by an avulsion.

3.5.6 Anabranch creation

The anabranch cycle may begin with anabranches created directly from a stable single channel (stable in terms of avulsion potential) or through local sediment deposition and island emergence. Island emergence occurs due to local increases in sediment supply into reaches or decreases in the sediment transport out of the reach. Sediment supply to the reach may increase because of terrace erosion or a recent avulsion upstream (Church 1983, Carson 1984, Gottesfeld and Johnson-Gottesfeld 1990). Causes of decreased sediment transport out of a reach include decreased slope due to base level change, an alluvial fan pinching the channel (Church 1983, Smith 1983), interactions with valley walls downstream, or local channel widening due to a local decrease in bank strength. Mid-channel bars develop as sediment is deposited within the channel. Islands develop from the mid-channel bars that split the flow and eventually emerge to allow vegetation to establish and stabilize the bars (Ashworth 1996). Vegetation increases deposition until a permanent island develops.

The anabranch cycle may also begin with a single unstable channel and a floodplain scarred with abandoned channels that are possible avulsion paths. A trigger, such as large floods, logjams, icejams, or sediment lobes force flow over the floodplain into an abandoned channel initiating an avulsion (Figure 3-3 path B2 or B3). Avulsions commonly occur at the outside of a bend apex where channels have become unstable following migration to contact abandoned channels (Figure 3-3 box 2) (Leddy *et al.* 1993, Smith *et al.* 1989). The outside of bends are also common avulsion sites because of water surface super elevation and higher velocities in the outer bank, overbank flow directed into the floodplain by inertia and, in some cases, levees on the outer bank may have lower elevations than on the inside bend (Smith *et al.* 1989).

Many avulsions were seen on the Renous River. As channels migrate they may contact abandoned channels, creating a possible avulsion path. This occurred at the site displayed in panel 2 of Figure 3-4 between 1983 and 1999, where an avulsion occurred at the outside of a channel bend into an abandoned channel. Icejams that may trigger avulsions commonly occur at island heads. An island head occurred between the entrance and exit of the avulsion channel. The avulsion was therefore probably triggered by a large icejam that occurred at the head of the island downstream between 1983 and 1999. The difference in length between the path of the avulsion channel and the path of the main-channel was small, the ratio of the avulsion-channel length to the main-channel length was 0.89, and therefore this avulsion channel may eventually create stable anabranches.

3.5.7 Unstable anabranches gaining stability

A period of instability, during which anabranches gain stability (Figure 3-3 box 3), may occur following an aggressive avulsion. Stability increases as discharge and sediment input decreases to the main-channel and increases to the side-channel until stable anabranches develop (Figure 3-3 path B2).

Anabranches gaining stability were seen on the Renous. Panel 3A of Figure 3-4 displayed two anabranches that were created following an avulsion that began prior to 1945 on the outside of a meander bend. The lengths of the two anabranches have become more similar through time (Figure 3-5). The length of the initial avulsion in 1945 was 475 m while the length of the main-channel was 840 m, producing an avulsion-channel to main-channel ratio of 0.57. A similar geometry remained until 1983 when a small avulsion occurred into an abandoned channel upstream of the original avulsion. This increased the length of the avulsion-channel to 595 m and decreased the length of the main-channel to 800 m, producing an avulsion-channel to main-channel length ratio of 0.74. By 1999, the widths of the two anabranches had become similar and the newer avulsion channel had grown to carry most of the flow into the main-channel. The length of the original avulsion-channel had grown to 630 m and the main-channel length had also grown, to 890 m, producing a ratio of 0.71. If this trend continues this anabranch pair may become stable and remain indefinitely.

3.5.8 Stable anabranches

Stable anabranches (Figure 3-3 box 4) are created through island emergence (Figure 3-3 path C1) or after unstable anabranches created through avulsion that gained stability (Figure 3-3 path C2). When anabranches are stable, the length of the two anabranches is similar. The creation of stable anabranches appears to be less common than the creation of unstable

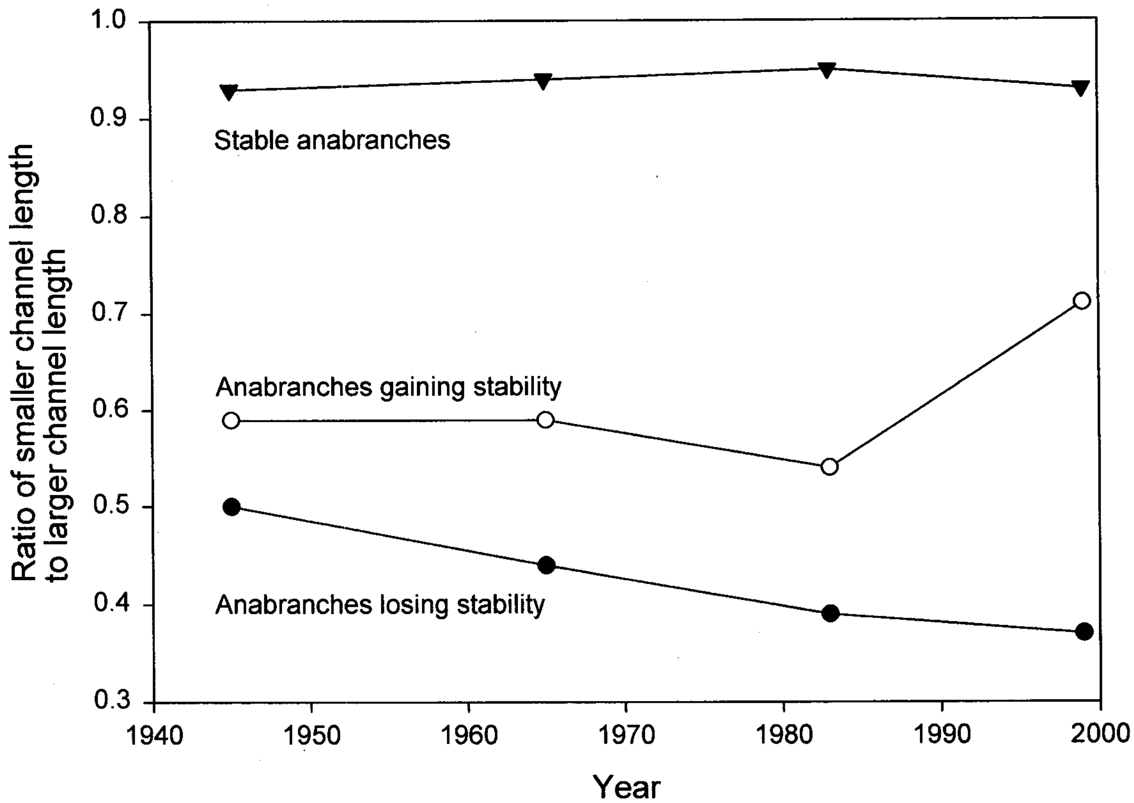


Figure 3-5. Plot of the ratio of the length of the smaller anabranch channel to the length of the larger anabranch channel through time for panels 3, 4 and 5 in Figure 3-4. The lengths of stable anabranches are similar and remain constant through time. The lengths of anabranches that gain stability become more similar through time, while the lengths of anabranches that lose stability become more dissimilar through time.

anabranches, however their influence on the pattern is long lasting and important due to their persistence.

Stable anabranches occurred within the Renous. Panel 4 of Figure 3-4 displays an anabranch pair that was stable throughout the fifty-four year study period. Its geometry did not change substantially during this time. The lengths of the two anabranches were similar. The ratio of the shorter channel to the longer channel ranged between 0.93 and 0.95 (Figure 3-5). The length of the shorter north channel increased from 345 m in 1945 to 355 m between 1945 and 1999, while the longer south channel increased in length from 370 m to 430 m. The dominant channel switched from the north to the south channel through the study period. This anabranch pair is stable and will probably remain stable into the future.

3.5.9 Unstable anabranches losing stability

Unstable anabranches losing stability (Figure 3-3 box 5) may be created following many years of stability (Figure 3-3 box 4), or following an aggressive avulsion, where the path of the avulsion is much shorter than the path of the main-channel (Figure 3-3 path B3). Stable anabranches may become unstable where sediment transport patterns are altered. Sediment input into one anabranch channel may increase or decrease due to avulsion or terrace erosion upstream or the migration of an upstream meander, altering diffluence entrance geometry (Figure 3-3 path D). Where sediment input to one anabranch increases beyond its transport capacity the deposition of a bar at the entrance of an anabranch may occur and block flow. Where sediment input to one anabranch decreases, degradation of the entrance to the anabranch might occur, causing the anabranch to capture more flow. Stability may be regained with a change in upstream channel geometry that allows sediment to divide evenly between the two anabranch channels. Although not documented, stability may also be regained when a sediment lobe, created by increased terrace erosion or an avulsion upstream, exits the reach (Figure 3-3 path E).

Where an avulsion course is much shorter than the primary channel, avulsions are aggressive and the primary channel may quickly switch into the avulsion channel, causing the eventual abandonment of the former primary channel. These aggressive avulsions may create a short period of unstable anabranches while the primary channel switches and the former primary channel becomes abandoned (Figure 3-3 box 5). As diffluence stability breaks down, a bar may form to block an abandoning channel.

While unstable anabranches lose stability, channel characteristics are out of balance and the abandoning channel loses flow while the other channel gains flow. Anabranches are abandoned when flow of sediment and water into a channel decreases due to channel inefficiency, changes in entrance geometry (Bridge 1993), or where an anabranch is choked by sediment lobes, or logjams. The abandonment of an anabranch may be rapid or slow depending on the abandonment process. Channels may abandon where the diffluence angle becomes large and inefficient (Bridge 1993). Where this occurs, the channel at a high angle to the main flow will become abandoned, and a zone of flow separation may occur at the channel entrance enhancing deposition, promoting further abandonment. Once an anabranch becomes less efficient it becomes susceptible to blockages from logjams at its entrance that further encourage its decline. In some western Canadian wandering systems, the former entrance to abandoned channels commonly show evidence of logjams that blocked one channel (Gottesfeld and Johnson-

Gottesfeld 1990). Channel abandonment leaves low semi-filled channels scarring floodplains.

Unstable anabranches losing stability occurred within the Renous. Panel 5 of Figure 3-4 displays an anabranch pair that was unstable and continued to lose stability throughout the fifty-four year study period. Its geometry changed substantially during this time. The ratio of the shorter channel to the longer channel decreased in the same period from 0.50 to 0.37 (Figure 3-5). An avulsion occurred prior to 1945 that initiated a cut off of a meander loop. Four separate small channels were seen near the head of the island in 1945. The avulsion channel continued to grow and became larger than the former main-channel by 1983 when all but the two largest channels were abandoned. The length of the avulsion channel decreased from 390 in 1945 to 330 m in 1999, while the length of the main-channel increased from 785 to 885 m over the same period. The dominant channel switched from the southern meander loop to the northern avulsion-channel. The anabranch pair has been losing stability through the study period and the former main-channel is being abandoned.

3.5.10 Anabranch infill

Where channels are not reoccupied for long periods, the rate at which abandoned channels infill is determined by the size and amount of sediment carried into the channel and the growth of vegetation within the channel (Figure 3-3 path G). The size and amount of sediment entering an abandoned channel is largely controlled by how connected the abandoned channel is to an active channel. The more connected a channel is, the coarser the material entering the channel and the faster it infills. If a channel is not connected to an active channel, the suspended load of the river during flood largely controls the infill rate. The greater the suspended load, the faster the infill rate. The filling process is preserved in channel fill sediments. When they are abandoned slowly, oxbow lake deposits are coarser in the upstream arms of meander loops, while channels that are rapidly abandoned fill with mud (Piet 1992). Channel fills fine upward from horizontal and cross-bedded fine gravel and sand to poorly bedded or massive sand, silt and clay-silt (Passmore and Macklin 2000). Beaver head ponds on abandoned channels enhance deposition of suspended sediment due to decreased water velocities during floods and the growth of aquatic plants (Butler and Malanson 1995). Beaver dams may eventually become beaver meadows. Yet, even without the aid of beavers, abandoned channel fills may be largely organic due to the growth of water plants (Smith 1983), the amount and type controlled largely by climate. Where abandoned channels completely infill, a stable single channel (Figure 3-3 box 1) is more likely to be maintained.

Although channels become abandoned, they remain important because they provide sites for future avulsions. The Renous River floodplain has many abandoned channels. The total length of all abandoned channels were on average 2.5 times longer than the main-channel and therefore provide many possible avulsion sites. If abandoned channels become avulsion sites they restart the anabranch cycle, allowing multiple channel systems to be maintained indefinitely.

3.6. Conclusions

The mosaic of channel types within wandering rivers is maintained as side-channels were developed, maintained and abandoned. Channel characteristics of the Renous River changed through time while the pattern remained. The anabranch cycle model was created to investigate how sections within a wandering river may change from a single channel to multiple channels and back to a single channel. The cycle may begin with the creation of an anabranch by avulsion into an abandoned channel, triggered by an ice jam, logjam or large flood or the emergence of a mid-channel bar that forms an island. Anabranches may be short lived or stable over long periods depending on local conditions but eventually one anabranch will be abandoned, creating a single channel. Anabranches are abandoned when sediment clogs the diffluence of one of the channels. The anabranch cycle explains how river pattern characteristics may appear stable through time while individual anabranch channels within channel sections change.

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Preface to chapter four

Chapter four further investigates channels within the wandering river pattern, the emphasis is now on the processes driving the channels themselves (Figure 1-5B, Figure 1-6). Chapter three showed that the wandering pattern is maintained through time through a cycle of anabranch creation, maintenance and abandonment. Chapter four investigated two questions: (1) how do bedwaves influence the energy and sediment mobility within wandering river channels? (2) How do the processes of the creation, maintenance and abandonment of side-channels influence these characteristics? A multivariate analysis was conducted on 45 reaches of the Renous River, New Brunswick to investigate the relationship among the hydraulic geometry, hydraulic energy, sediment mobility and grain size characteristics within the channels to understand how bedwaves and side-channel dynamics affect wandering river channels.

4. Chapter four: Influences of bedwaves and side-channel processes on wandering river channels examined using Principal Component Analysis

4.1. Abstract

The definition of wandering describes a river pattern of multiple channel sections, with seasonal or perennial anabranches around semi-permanent islands, connected by single channel reaches. The location of islands, seasonal and perennial anabranches and single channel reaches change through time as channels are created and abandoned. Research was conducted on the Renous River, Miramichi drainage, New Brunswick, that shows a classic wandering pattern for 11.5 km, with multiple channels around islands, connected by single channel reaches. Wandering is bracketed upstream and downstream by single confined channels that occurs where narrow valley bottoms restrict channel migration.

Forty-five reaches within 15 km of the Renous River were divided into three main-channel types (confined, single and primary) that contained the thalweg and three side-channel types (avulsion, secondary and abandoning) that did not contain the thalweg. In-channel characteristics, including hydraulic geometry (Bankfull width, depth, width-depth ratio, normalized length, friction factor and bed slope), hydraulic energy (water surface slope, shear stress, discharge, stream power, and specific stream power), grain size (riffle D_{50}, bedload D_{50}), and sediment mobility (mobility ratio, unit sediment transport rate), were analyzed using principal component analysis (PCA), Pearson correlations and Analysis of Variance (ANOVA). Differences between stoss and lee sides of bedwaves were determined using two tailed paired-sample t tests.

The first two PCA axes captured 86.2 % (63.2 % and 23.0 %, respectively) of the total variance. PCA axis one was interpreted as being driven by channel energy and was highly correlated with specific stream power, shear stress, water surface slope, bed slope and normalized length. Axis two was interpreted as being driven by channel size and hydraulic efficiency (width-depth ratio and channel friction) and was negatively correlated with bed D_{50}, bedload D_{50}, width-depth ratio, and friction factor. ANOVA showed that the PCA axis two loadings for main-channels and side-channels were different.

Within side-channels, their creation, stability, and abandonment control hydraulic energy and sediment mobility. Within main-channels, differences in hydraulic energy and sediment mobility may be associated with bedwaves, occurring within long single channel reaches or associated with a diffluence. Bedwaves occurring within long single channel reaches display a low slope stoss side and a high slope lee side with high or low hydraulic energy and sediment mobility, respectively. Three of seven diffluences not associated with an abandoning or avulsion channel contained bedwaves. These bedwaves did not display the same differentiation seen in other bedwaves. The partitioning of hydraulic energy and sediment mobility upstream and downstream of diffluences, including the formation of bedwaves, requires further study.

4.2. Introduction

This study examines the variability in hydraulic geometry, hydraulic energy, sediment mobility and bed grain size among different channel types within a wandering river. I employed a multivariate analysis of a large field based data set to investigate the interrelationship among characteristics of channels within one river pattern. To my knowledge, this application of a multivariate approach is unique, even though the interdependent nature of fluvial variables is well established. In fluvial geomorphology of river patterns, multivariate analyses are rarely conducted due to the difficulty in obtaining large field data sets with a large number of measured variables.

Wandering describes a river pattern with many different channel types including multiple channel sections, with seasonal or perennial anabranches around semi-permanent islands, and single channel reaches (Neill 1973, Church 1983). Wandering rivers are common in the Cordilleran region of western Canada (Desloges and Church 1989), and parts of Atlantic Canada, among other regions in the world. Wandering rivers are thought to be a transitional pattern between braided and meandering (Church 1983), commonly transition downstream from braided to meandering (Church 1983, Carson 1984, Brierly and Hickin 1989) and exhibit features of braided and meandering channels (Church 1983). Wandering rivers have energy levels intermediate between braiding and meandering, plotting between braided and meandering on a slope-bankfull discharge scatter plot (Desloges and Church 1989). Much of what is known about wandering rivers is derived from western Canadian wandering rivers, like the Bella Coola (Church 1983) and the Squamish (Brierly and Hicken 1988) located in glacierized basins that transition downstream from braided to wandering.

The location of islands, seasonal and perennial anabranches and single channel reaches change through time as channels are created and abandoned. Side-channels begin as high-energy avulsion channels cutting into the floodplain, commonly re-activating abandoned channels within the floodplain. Some side-channels become stable and are maintained through time. However, other channels become old, have low-energy levels and are abandoned to the floodplain. Side-channel dynamics affect the within channel characteristics of reaches as channels grow or die.

Bedwaves are longer than the pool riffle spacing and appear to be a common wandering river feature (Church and Jones 1982, Church 1983). Church and Jones (1982) proposed a river long profile model for bedwaves that showed convex waves of mobile bed sediment stored in sedimentation zones superimposed on an overall concave long profile (Figure 4-1). Bedwaves have also been associated with a discrete increase in sediment input and may pass downstream as a sediment "bore" or "plug" (Wathen and Hoey 1998). Instability, which has been defined by anabranching intensity (Church and Jones 1982), is thought to correspond to the relative magnitude of local deposition within sedimentation zones. Transportation zones, located between sedimentation zones, rejoin the concave profile. Sedimentation zones and transportation zones are common on multiple channel rivers (Church 1983, Desloges and Church 1987, Desloges and Church 1989, Jiongxin 1997).

Similar to other smaller bedforms, bedwaves have an upstream, low-slope, stoss side and a downstream, high-slope, lee side (Figure 4-1). Higher channel energy and sediment mobility occurs on the high-slope lee side than the low-slope stoss side. Intermediate energy levels and channel stability may occur in the absence of bedwaves. Deposition occurs on the upstream stoss side of bedwaves and erosion occurs on the downstream end of the sediment wedge (Church and Jones 1982). The model therefore implies that bedwaves migrate upstream. If multiple channels were located where deposition occurs, they should have relatively lower slopes. However,

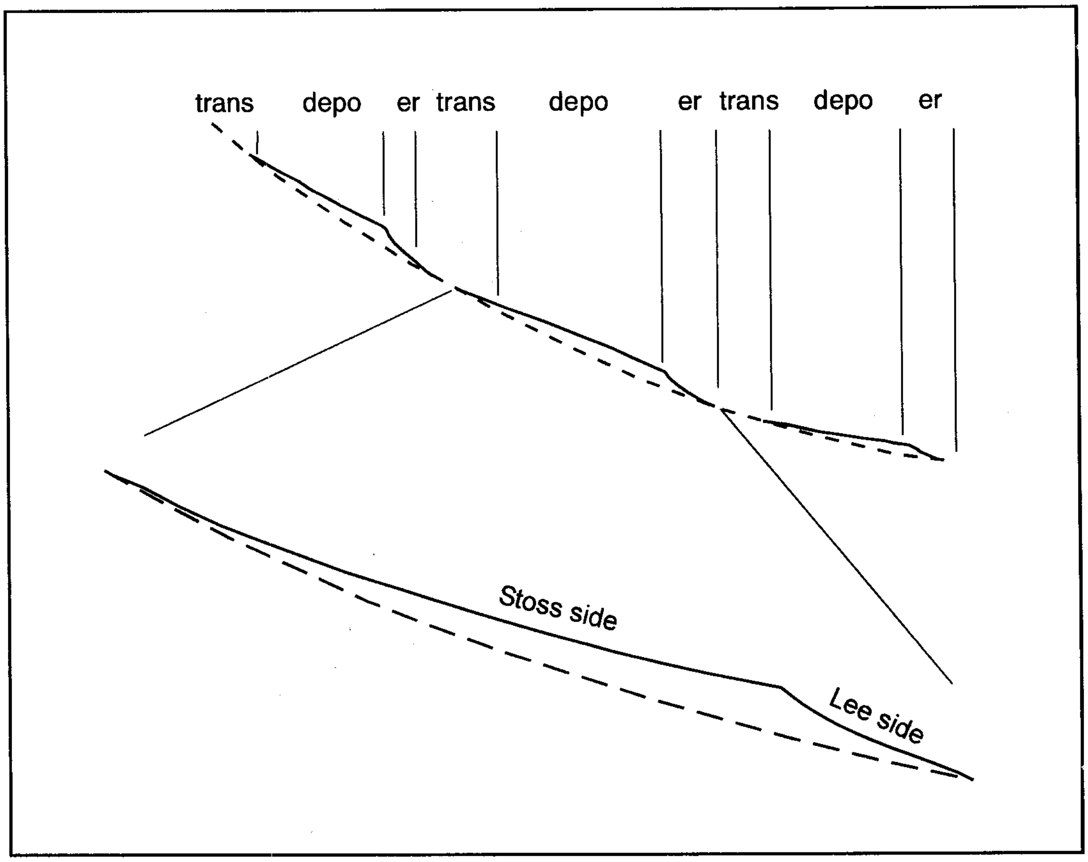


Figure 4-1. Bedwave model of Church and Jones (1982) showing depositional (depo) and erosional (er) sections of bedwaves and sections without bedwaves, called transportation reaches (trans). Bedwaves are superimposed on a general concave profile. Note the long, upstream, low slope stoss side and the short, downstream, lee side of the example bedwave. Deposition occurs on the upstream stoss side, while erosion occurs on the downstream lee side.

Desloges and Church (1989) described multiple channel reaches having greater slopes than single channel reaches. In their benchmark paper, Leopold and Wolman (1957) detail the increase in slope that occurs within multiple channel anabranches downstream of an island head diffluence. There seems to be an association with multiple channels and bedwaves but it remains unclear, both empirically and mechanistically, how single and multiple channel sections are located within bedwaves.

Downstream of channel divisions the total friction within all channels of a valley cross-section increases due to an increase in total wetted perimeter. The wetted perimeter increases because the sum of the width of two channels is often greater than that of the single channel upstream (Leopold and Wolman 1957) and there is also an addition of two channel banks. However, the same discharge must be passed through the two channels. Bed slope has been shown to increase within individual anabranches (Leopold and Wolman 1957) and this may increase the average velocity and thereby increase the discharge a channel may carry.

Channels may also modify their hydraulic efficiency to compensate for changes in discharge downstream of diffluences. At a given slope channel with high hydraulic efficiency will have a higher average velocity for a given cross-sectional area than a channel with low hydraulic efficiency. This may be achieved by changing the roughness of the channel bed or the width-depth ratio of the channel. If we refer to Manning's equation ($v = R^{3/2} S^{1/2} / n$, where v is the average velocity, R is the hydraulic radius (area/wetted perimeter, S is the slope of the energy line and n is the Manning's roughness coefficient) (Knighton 1998) we see that, average velocity increases as channel bed roughness (n) decreases, providing other variables remain constant. Channel bed roughness depends largely on grain size and flow depth.

Average velocity may also increase by optimizing the width-depth ratio. We can investigate the width-depth ratio that provides the highest average velocity for a given cross-sectional area (A) using Manning's equation and the relationship between discharge and cross-sectional area ($Q_{bf} = v\ A$). If slope, channel bed roughness, and cross-sectional area remain constant, the maximum velocity, and therefore hydraulic efficiency, is achieved at a width-depth ratio of two for a rectangular cross-section. Under this definition a width depth ratio of 20 is 1.5 times more efficient, as defined by greater velocity, than a channel with a width depth ratio of 40. Therefore, decreasing the width-depth ratio, but not past its optimum, increases the channel efficiency.

The research question was: what controls the spatial variation in hydraulic geometry, energy, grain size and sediment mobility characteristics of channel reaches within wandering rivers. Two objectives were addressed: 1) to determine the reach scale hydraulic geometry, hydraulic energy and sediment mobility characteristics within all the channels of a wandering river; 2) to investigate the relationships among the various channel types through a multivariate statistical analysis of hydraulic geometry, hydraulic energy, grain size and sediment mobility variables; and 3) to investigate what factors control these relationships.

4.3. Study area

Research was conducted on the Renous River located near the centre of the Miramichi drainage basin, New Brunswick (Figure 4-2). The Renous study area shows a classic wandering pattern for 11.5 km, with multiple channels around islands, and abandoned channels within the floodplain. The Renous channel is 60 m wide, has a mean annual flood of 147 m^3/s, with an average bankfull specific stream power of 69 W m^{-2} within the main-channel and drains 611 km^2 of the Miramichi highlands. Wandering begins where valley width increases to accommodate multiple wandering channels and ends where valley width decreases and limits space for the production of multiple channels (Figure 4-2). Within wandering sections of the Renous, multiple channel reaches are not explained by local differences in bedrock, or the entrance of large tributaries or alluvial fans into the valley.

At McGraw Brook, in the centre of the study reach, the mean monthly air temperature varies between -11.8°C in January to 18.8°C in July, where April to October is above freezing (Caissie and El-Jabi 1995). During winter, Miramichi rivers form a thick (50 cm) ice cover, that often cause icejams during spring break-up and occasionally during winter melts (Beltaos *et al.* 1989). Icejams are thought to trigger avulsions that commonly utilize abandoned channels within the floodplain and thereby produce the side-channels that create the wandering pattern. Within the wandering reach of the larger neighbouring Main Southwest Miramichi, break-up occurs between March 22 and May 2, with an average break-up date of April 14 (Allen and Cudbird 1971). Evidence of ice jams is common on the Renous with scars on trees and push marks on channel banks.

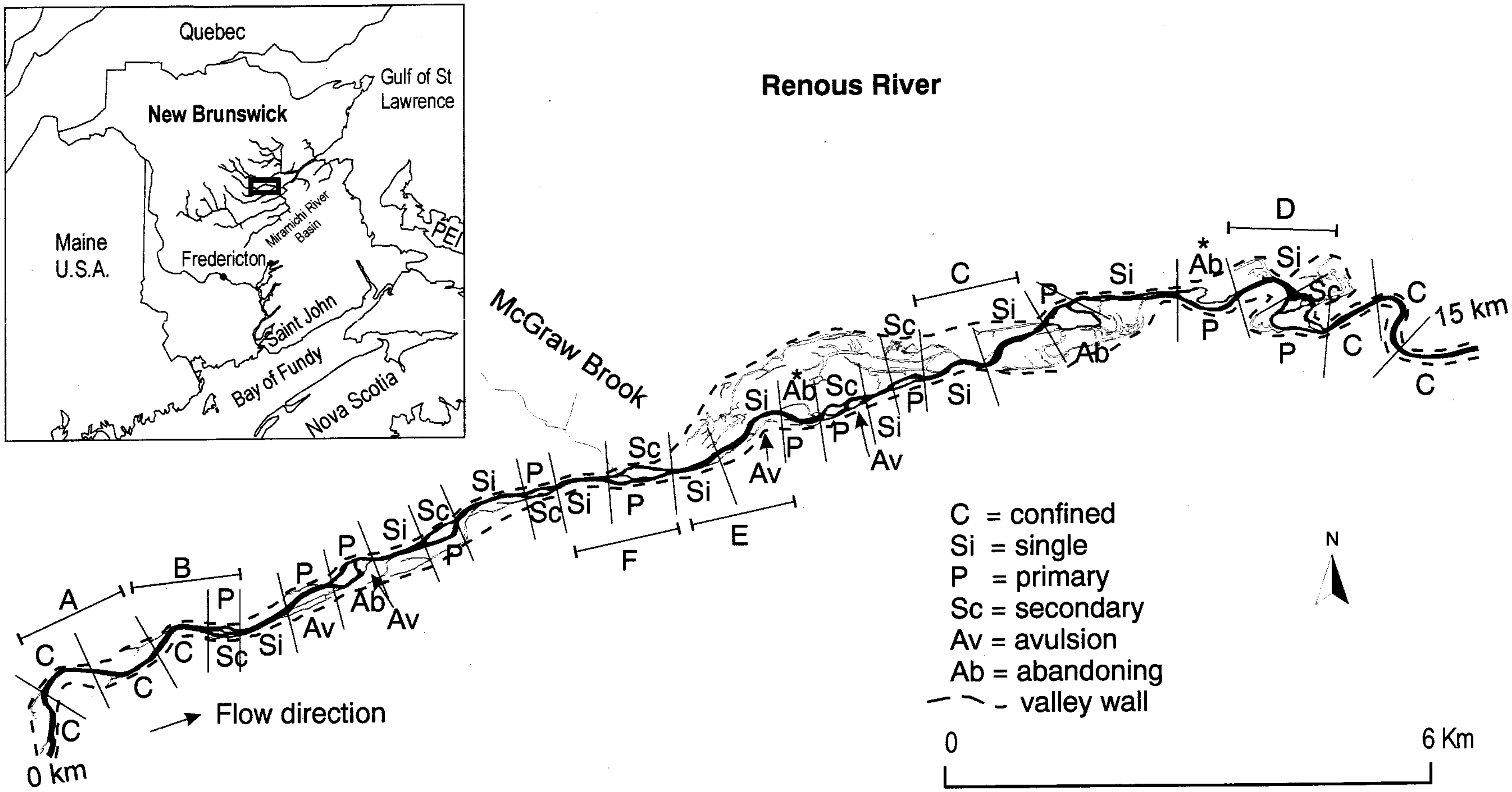


Figure 4-2. Location of the 45 reaches used in the Renous River analysis. Active channels are black and abandoned channels are unfilled. * indicates field data not collected. Measured river distances begin at km 0 and end at km 15. Flow is from left to right. Map created from 1:12000 aerial photographs taken in 1999, georeferenced to base map supplied by services New Brunswick. Letters with lines denote locations of bedwaves on Figures 4-6 and 4-7.

4.4. Methods

Forty-five reaches within 15 km of the Renous River were divided into three main-channel categories (confined, single and primary) that contained the main thalweg and three side-channel categories (avulsion, secondary and abandoning) that did not contain the thalweg (Table 4-1, Figure 4-2). **Confined channels** were single channel sections confined by narrow valley walls located upstream and downstream of wandering. **Single channel** reaches occurred within the wandering pattern between a confluence upstream and a diffluence downstream. Bed slope within long single channel reaches, greater than 500 m between an upstream confluence and downstream diffluence, were divided into areas with constant bed slope to investigate the presence of bedwaves. These reaches started or ended with a confluence or diffluence or the point where the greatest change in slope occurred. Each of these reaches contained at least three riffles.

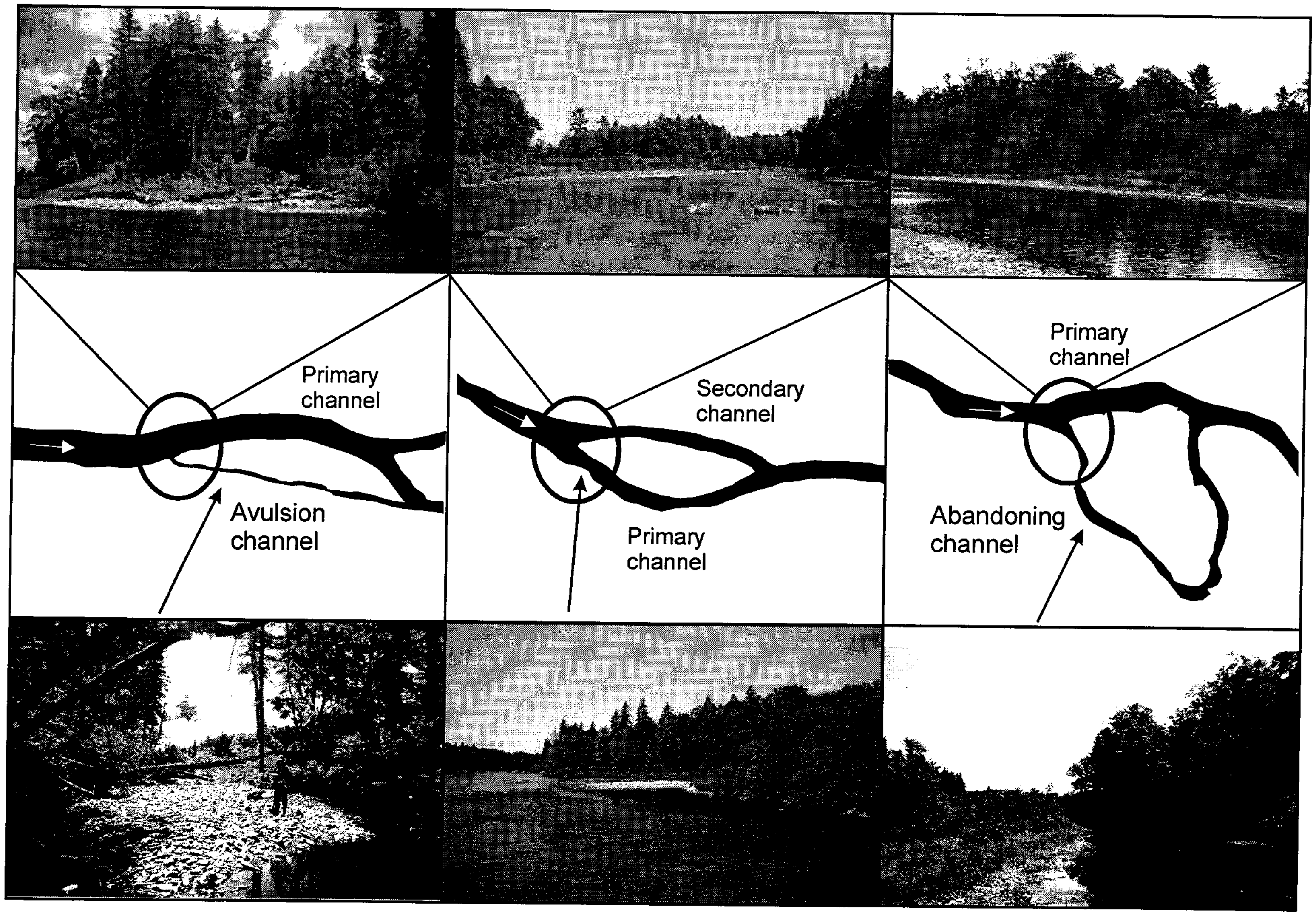
Multiple channel reaches were defined by an upstream diffluence and a downstream confluence and individual anabranches were categorized as primary, and three side-channel types (secondary, avulsion and abandoning). **Primary channels** were perennial having the lower thalweg elevation of the two channels at the diffluence. **Secondary channels** were seasonal channels that contained the higher thalweg elevation at the diffluence (Figure 4-3). **Avulsion channels** were young seasonal anabranch channels with steep cutbanks on both banks and commonly contained fallen trees (Figure 4-3). **Abandoning channels** were old seasonal anabranch channels, infilling with sediment and contained young vegetation (Figure 4-3).

For each channel reach, hydraulic geometry, hydraulic energy, grain size and sediment mobility characteristics were determined. Bankfull hydraulic geometry

Table 4-1. Descriptions of six channel types.

Channel type	Main or side channel	Channel description
Confined	Main	Single channel sections located upstream and downstream of wandering confined by narrow valley walls divided into homogeneous reaches of bed and water surface slope.
Single	Main	Single channel sections located within wandering pattern between a confluence upstream and a diffluence downstream. If single for long distances, channel divided into homogeneous reaches of bed and water surface slope.
Primary	Main	Perennial anabranch channels with the lower thalweg elevation of the two channels at the diffluence.
Avulsion	Side	Young seasonal anabranch channels with steep cutbanks on both banks and commonly containing fallen trees
Secondary	Side	Seasonal anabranch channels containing the higher thalweg elevation at the diffluence.
Abandoning	Side	Old seasonal anabranch channels, infilling with sediment, containing young vegetation.

Figure 4-3. Maps displaying the three side-channel types (avulsion, secondary and abandoning). Photographs and maps of avulsion, secondary and abandoning channel paired with primary channels. Top photographs display the channel diffluences at the heads of islands. The lower photograph displays the morphology of each channel. The avulsion channel is narrow with undercut banks and trees falling into the channel. Avulsion channels are short and have high energy levels. The secondary-primary channel pair is stable. The secondary channels have similar lengths to their paired anabranches. This secondary channel is relatively wide and dry at this stage, while the primary channel shown carries all the flow. Abandoning channels are long and have low energy levels. This abandoning channel is narrow with young vegetation on the left bank and large trees and a cutbank on the right.


Primary
channel
Avulsion
channel
Secondary
channel
Primary
channel
Primary
channel
Abandoning
channel

characteristics included width, depth, width-depth ratio, normalized reach length, friction factor, and bed slope. Hydraulic energy characteristics included the slope of the water surface, bankfull shear stress, bankfull discharge, total stream power, and bankfull specific stream power. Grain size and sediment mobility characteristics included riffle D_{50}, mobility ratio, unit sediment transport rate and bedload D_{50} (see appendix 2 for data used in analysis). Three of the forty-five reaches (two abandoning and one single) were not surveyed in the field or were too short to determine meaningful values. Therefore, only width, length, bed slope, and water surface slope were determined for these channels

4.4.1. Channel geometry

The Renous River was mapped from 1:12 000 aerial photographs taken in 1999 using Arcview 3.2 with image analysis (ESRI 1999). During the summers of 2000 and 2001, elevations of the thalweg at riffles and bankfull water levels were surveyed in the field with a laser level and downstream distances measured with a hip-chain. Bankfull water levels were surveyed using the highest elevation of leaves and grass deposited by the previous springs flows. This elevation was usually equal to the floodplain elevation, indicating bankfull flow. The long profile of the Renous River was plotted based on the elevation at riffles down the thalweg. Large-scale bedwaves on the long profile were identified as undulations above and below the mean slope trend for riffles.

Bankfull channel widths were measured in the field at riffles and were supplemented with measurements from the map of the Renous. Water surface and bed slopes were determined using regression equations of bed (thalweg at riffles) or water surface elevations and downstream distances. At least three elevation points per reach were used for each slope calculation. Bankfull depth was determined at the midpoint of each reach by subtracting bankfull water surface elevation from the bed riffle thalweg elevation, calculated using regression equations. Bankfull width-depth ratio was determined using average bankfull width and depth for each reach.

For confined and single reaches, length represented the distance between an upstream confluence and downstream diffluence or the length of constant bed slope. For multiple channels, length was the distance between upstream diffluences and downstream confluences. Length was then normalized by the average width of single channels (average single channel width for Renous = 60 m). Bankfull discharge was determined using the mean annual maximum daily discharge from 1966-1994 for the McGraw Brook gauge (Environment Canada 1997). Discharge within each anabranch was approximated based on the proportion of the cross-sectional area of each reach to the total area of all channels across the valley. Finally, flow resistance was estimated using a friction factor (ff) ($1/ff^{1/2} = 1.36\ (D/D_{50})^{0.281}$), where, D is the average bankfull channel depth and D_{50} is the median grain size (Bray 1979).

4.4.2 Hydraulic energy

The hydraulic energy within each channel was estimated in three ways: bankfull water surface slope, stream power, and shear stress. Stream power ($\Omega = \gamma Q_{bf} S$, where Q_{bf} is bankfull discharge within a reach, and S is water surface slope) is the rate of energy supply at the channel bed for overcoming friction and transporting sediment per unit length (Knighton 1998). Specific stream power ($\omega = \Omega / w$, where w is channel width) is the energy availability per unit area of the bed (Knighton 1998). Shear stress [$\tau_o = \rho gRS$, where, ρ is the density of water, g is the acceleration due to gravity, R is hydraulic radius (area / wetted perimeter), and S is reach energy slope] (Knighton 1998) was calculated using the bankfull water surface slope as the energy slope and average bankfull depth at riffles as R.

4.4.3 Sediment grain size and mobility

The grain size distribution of the surface of the bed was determined at the heads of at least two, on average four and up to ten riffles per channel reach. The B-axis of 100 randomly chosen clasts was measured on each riffle and then averaged for each reach. The mobility of the bed was estimated using a mobility ratio [Mr = τ_o / τ_c, where τ_c is the critical shear stress, ($\tau_c = 0.06\ (\rho_s - \rho)\ g\ D_{50}$, where ρ_s is the density of sediment) approximated by D_{50} in mm] (Eaton and Lapointe 2000). Mobility ratio divides the bankfull shear stress by riffle grain size; high values indicate greater bed mobility than low values. Nominal sediment transport rates were estimated using ACRONYM 1 (Parker 1990) applied to mean bankfull shear velocity ($U_* = (\tau_o/\rho)^{1/2}$) and the average D_{84}, D_{50} and D_{16} values for riffles in each reach. The ACRONYM set of sediment transport equations have been shown to give useful insight into river transport variations when applied consistently (Talbot and Lapointe 2002). The ACRONYM output for nominal unit transport rate, and bedload D_{50} were computed for each reach.

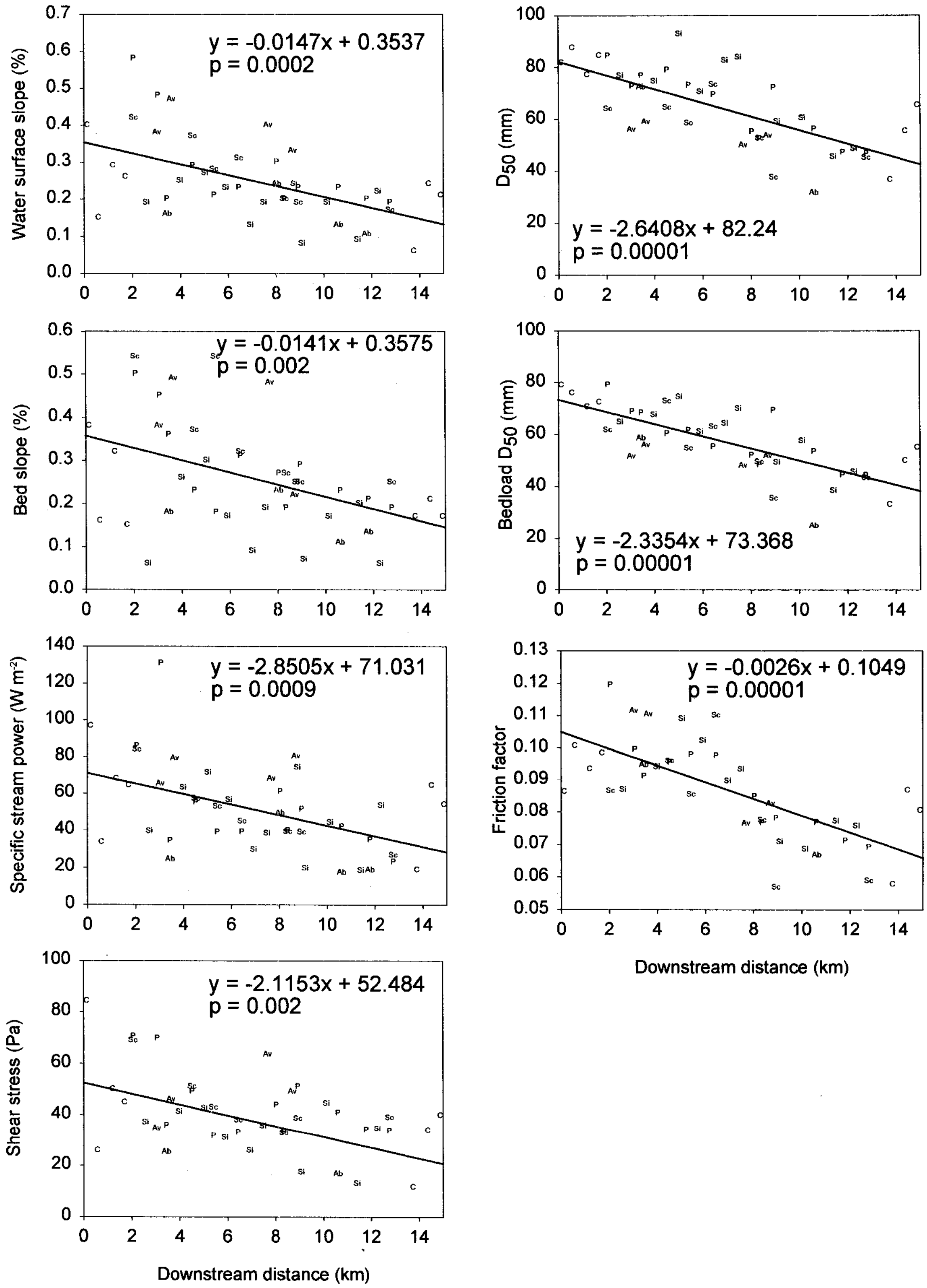
4.4.4 Statistical analysis

Principal component analysis (PCA) was conducted on all reaches using CANOCO (ter Braak and Ŝmilaur 1999). PCA partitions sample variance into a few explanatory principal components, allowing the investigation of the entire dataset, including collinear variables (Dunteman 1989). PCA was conducted on specific stream power, shear stress, water surface slope, mobility ratio, unit sediment transport rate, bed slope, normalized length, D_{50}, D_{50} of the bedload, width-depth ratio and friction factor. Channel size related variables, such as depth, total stream power and width, were excluded from the analysis because a preliminary PCA showed size related variables dominated the PCA when included and provided little information other than larger channels had larger total stream power and width.

Water surface slope, bed slope, shear stress, D_{50}, stream power, specific stream power, friction factor, and D_{50} bedload showed downstream trends and were detrended using residuals of a statistically significant ($p < 0.05$) linear regression with each variable and downstream distance (Figure 4-4). Linear equations were used because non-linear trends did not provide a better fit to the data. Residuals were then used in the PCA. A Pearson correlation matrix with Bonferroni probabilities was conducted to determine relationships between PCA axes and input variables using SYSTAT (SPSS 1998). To further investigate the relationship among variables, a Pearson correlation matrix was created for PCA input variables, with Bonferroni probabilities using SYSTAT (SPSS 1998). Analysis of variance was used to test for differences in channel characteristics among channel types, with Bonferroni post hoc tests, using SYSTAT (SPSS 1998).

The influence of bedwaves on main-channel characteristics was investigated using two tailed paired-sample t tests ($\alpha = 0.05$), to test for differences between the stoss and lee sides of bedwaves. Two types of bedwaves were identified: those within single channels ($n = 4$) and those with the stoss side located in a single channel and the lee side located in an adjacent primary channel downstream ($n = 3$). Bedwaves were identified where channel bed slope increased in two adjacent single or confined channel sections, or were associated

Figure 4-4. Downstream trends in water surface slope, bed slope, shear stress, D_{50}, stream power, specific stream power, friction factor, and D_{50} bedload. These variables were detrended using residuals of a statistically significant ($p < 0.05$) linear regressions with each variable and downstream distance and then used in the analysis.


Water surface slope (%)
y = -0.0147x + 0.3537
p = 0.0002
D50 (mm)
y = -2.6408x + 82.24
p = 0.00001
Bed slope (%)
y = -0.0141x + 0.3575
p = 0.002
Bedload D50 (mm)
y = -2.3354x + 73.368
p = 0.00001
Specific stream power (W m-2)
y = -2.8505x + 71.031
p = 0.0009
Friction factor
y = -0.0026x + 0.1049
p = 0.00001
Shear stress (Pa)
y = -2.1153x + 52.484
p = 0.002
Downstream distance (km)
Downstream distance (km)

with long lived anabranches where a diffluence was not connected with an abandoning or avulsion channel. The PCA axis scores for stoss and lee sides of each bedwave were plotted and interpreted.

4.5. Results

Non-detrended average values with standard errors and results of ANOVA difference tests for all variables measured for the six channel types ($n = 43 - 45$) are presented in Table 4-2. Confined, single and primary reaches were wider than secondary, avulsion and abandoning reaches ($p < 0.005$), and secondary reaches were wider than avulsions ($p < 0.005$). Confined, single and primary reaches had greater width-depth ratio than avulsions ($p < 0.001$) and, single reaches had greater width-depth ratio than secondary reaches ($p < 0.01$). Single and abandoning reaches were longer than primary, secondary and avulsions ($p < 0.04$). Total stream power of single and primary reaches was greater than avulsion and abandoning reaches ($p < 0.04$). Specific stream power was greater in avulsions than abandoning reaches ($p < 0.04$). D_{50} within single reaches were larger than secondary and avulsions ($p < 0.04$) and confined reaches were larger than avulsions ($p < 0.05$). Mobility ratio of secondary and avulsions were greater than single reaches ($p < 0.02$).

4.5.1 Correlations

Many correlations were seen between channel energy and sediment mobility variables ($n = 43 - 45$) (Table 4-3). Channel energy (water surface slope, shear stress, specific stream power and bed slope) and sediment mobility characteristics (mobility ratio and unit transport rate), were highly positively correlated ($r > 0.8$). Indicating channels

Table 4-2. Mean values and standard errors of channel types for 16 variables. Bold values denote at least one significant difference (ANOVA, $p < 0.05$) from other variables. Means followed by a different letter are significantly different ($p < 0.05$) and ranking of means is indicated by: a > b > c. ANOVA analysis was conducted on residuals where downstream trends were present.

	Confined $n = 7$			*Single* $n = 11$			*Primary* n = 12			*Secondary* $n = 7$			Avulsion $n = 4$			*Abandon* n=2-4		
	Mean	Std. Error		Mean	Std. Error		Mean	Std. Error		Mean	Std. Error		Mean	Std. Error		Mean	Std. Error	
Depth (m)	**1.82**	0.08	a	**1.82**	0.11	a	1.67	0.08	ab	1.71	0.14	ab	**1.27**	0.18	b	1.46	0.16	ab
Width (m)	**57.5**	2.3	a	**60.8**	2.1	a	**52.0**	3.0	a	**35.5**	3.1	b	**13.8**	1.2	c	**23.4**	7.9	bc
Width-depth ratio	**32.0**	2.0	ab	**35.1**	2.2	a	**31.9**	2.4	ab	**22.0**	3.4	bc	**11.9**	2.5	c	24.1	2.9	ab
Normalized length	8.3	0.9	abc	**9.9**	0.8	ab	**6.8**	0.6	c	**6.1**	0.8	c	**5.1**	1.2	c	**11.3**	1.4	a
Friction factor	0.086	0.005	a	0.087	0.004	a	0.088	0.004	a	0.082	0.007	a	0.091	0.009	a	0.081	0.014	a
Bed slope (%)	**0.22**	0.03	bc	**0.17**	0.03	c	**0.28**	0.03	ab	**0.36**	0.05	a	**0.39**	0.06	a	**0.16**	0.03	bc
Water slope (%)	**0.23**	0.04	b	**0.19**	0.02	b	**0.28**	0.04	b	0.28	0.04	ab	**0.40**	0.03	a	**0.16**	0.03	b
Shear stress (Pa)	41.4	8.6	a	32.2	3.4	a	43.8	4.0	a	44.4	4.6	a	48.3	6.0	a	20.9	4.3	a
Specific stream power (W m^{-2})	56.9	9.6	ab	46.0	5.8	ab	52.8	8.5	ab	48.9	6.9	ab	**73.1**	3.8	a	**27.2**	7.5	b
D_{50} (mm)	**70**	7	ab	**69**	5	a	65	4	abc	**56**	5	bc	**55**	2	c	52	20	ab
Mobility ratio	0.58	0.09	ab	**0.47**	0.05	b	0.68	0.05	ab	**0.81**	0.08	a	**0.90**	0.14	a	0.44	0.09	ab
D_{50} bedload (mm)	**62**	6	a	**59**	4	a	**59**	3	a	54	5	ab	52	2	ab	**42**	17	b
Unit sediment trans. (g s^{-1} m^{-1})	1.00	0.72	ab	**0.24**	0.11	b	1.02	0.30	ab	**1.41**	0.55	a	**2.27**	1.18	a	0.05	0.03	ab

Table 4-3. Pearson correlation matrix among variables included in PCA (n = 43-45). Significance determined using Bonferroni post hoc test. Bold numbers are significantly different ($p < 0.05$) while underlined numbers are near statistical significance ($0.5 > p < 0.1$).

	Specific stream power	*Shear stress*	*Water level slope*	*Mobility ratio*	*Unit Sed. trans rate*	*Bed slope*	*Norm. length*	*D_{50}*	*D_{50} load*	*Width depth ratio*	*Friction factor*
Specific stream power	1.000										
Shear stress	**0.798**	1.000									
Water level slope	**0.829**	**0.800**	1.000								
Mobility ratio	**0.662**	**0.868**	**0.749**	1.000							
Unit sed. trans. rate	**0.598**	**0.800**	**0.613**	**0.847**	1.000						
Bed slope	**0.530**	**0.602**	**0.741**	**0.648**	**0.560**	1.000					
Normalized length	-0.477	**-0.504**	**-0.541**	**-0.549**	-0.472	**- 0.517**	1.000				
D_{50}	0.029	0.031	-0.140	-0.403	-0.275	-0.300	0.176	1.000			
D_{50} load	0.267	0.339	0.139	-0.089	-0.051	-0.046	-0.039	**0.872**	1.000		
Width-depth ratio	-0.111	-0.217	-0.151	-0.466	-0.370	-0.346	0.378	0.458	0.384	1.000	
Friction factor	-0.096	-0.192	0.067	-0.112	-0.147	0.085	-0.105	0.034	0.040	-0.126	1.000

with high energy have high sediment mobility. Hydraulic energy and sediment mobility variables were negatively correlated with normalized length, indicating that longer channels have lower channel energy and sediment mobility. Bed D_{50} and Bedload D_{50} were positively correlated because the material on the bed is entrained during transport. Width-depth ratio and mobility ratio were weakly correlated ($p = 0.1$), perhaps indicating that channels with more mobile beds are more hydraulically efficient than channels with less mobile beds.

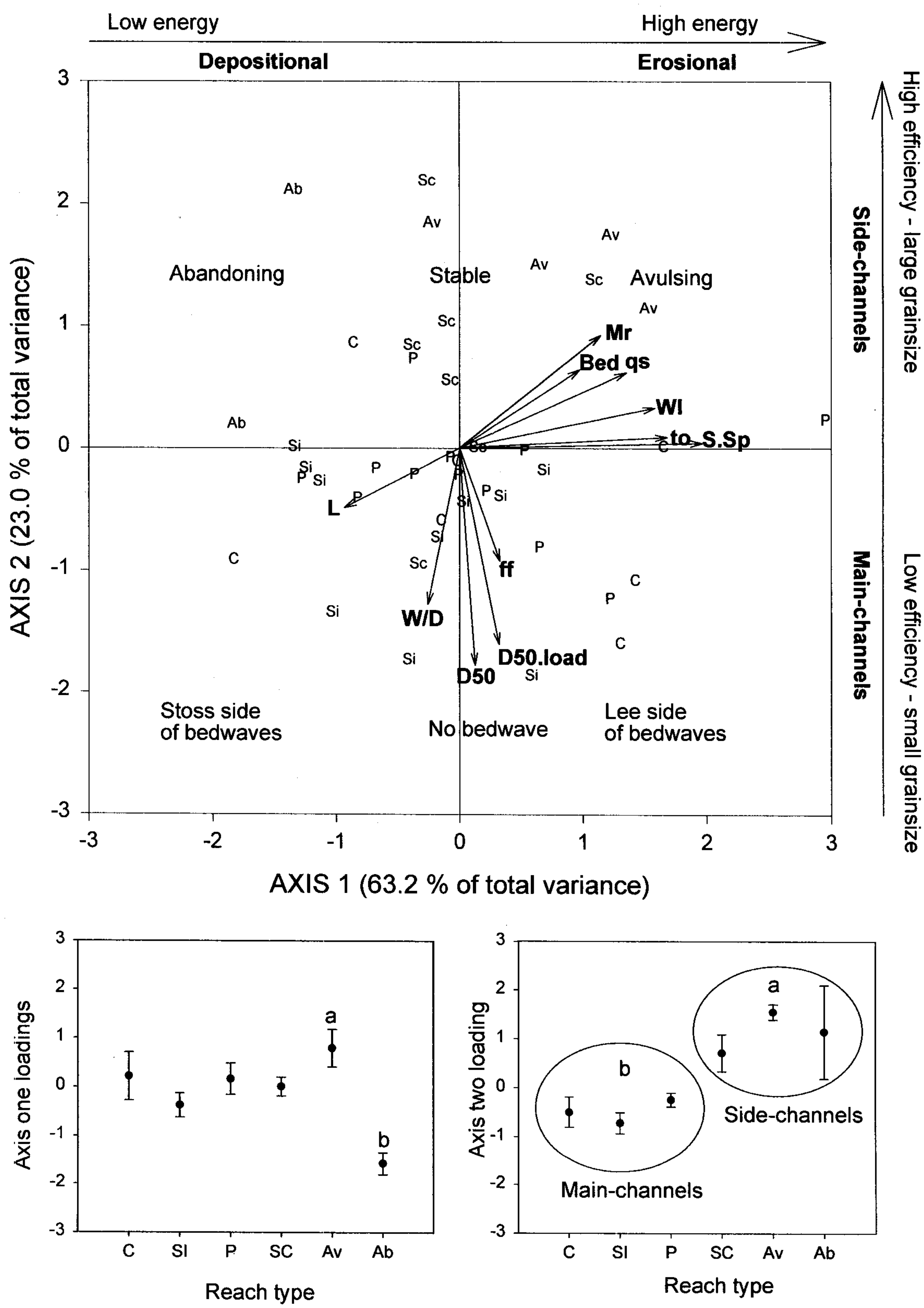
4.5.2 Principal component analysis

Relationships seen in the correlation matrix were consistent in the PCA. The PCA of the channels showed the first two axes captured 86.2 % (63.2 % and 23.0 %) of the total variance ($n = 43$) (Figure 4-5). Interpretations of the PCA axes are shown in Figure 4-5.

4.5.3 Principal component axis one

PCA axis one was interpreted as being driven by hydraulic energy and sediment mobility. PCA axis one was highly positively correlated with specific stream power, shear stress, water surface slope, mobility ratio, unit sediment transport and bed slope (Table 4-4). Interestingly, PCA axis one was negatively correlated with normalized channel length indicating that longer channels have lower channel energy and sediment mobility. Low values on axis one indicate low energy and sediment mobility channels, high values indicate high energy and sediment mobility channels, and intermediate values indicate moderate energy and sediment mobility channels that are stable. On axis one, avulsions displayed higher loadings than abandoned channels (ANOVA $p <$

Figure 4-5. First two axes of PCA with variables for all Renous River wandering and confined reaches. Plots of loadings of channel types on PCA axis one and two. Axis one shows greatest variability in confined channels and primary with higher values than single. Axis two differentiated main-channels from side-channels. Error bars indicate standard error and differences determined through ANOVA ($p < 0.05$) are lettered as a > b. (C represents confined, Si represents single wandering, P represents primary wandering, Sc represents secondary wandering, Av represents avulsion reaches, and Ab represents abandoning reaches; S.Sp represents specific stream power, to represents shear stress, Wl represents water surface slope, Bed represents bed slope, qs represents unit sediment transport rate, Mr represents mobility ratio, ff represents friction factor, L represents normalized length, W/D represents width-depth ratio, D50 represents D_{50} and D50.load represents the D_{50} of the bedload).



Low energy
High energy
Depositional
Erosional
High efficiency - large grainsize
Low efficiency - small grainsize
Side-channels
Main-channels
Abandoning
Stable
Avulsing
Stoss side of bedwaves
No bedwave
Lee side of bedwaves
Mr
Bed qs
WI
to
S.Sp
L
ff
W/D
D50.load
D50
AXIS 2 (23.0 % of total variance)
AXIS 1 (63.2 % of total variance)
Axis one loadings
Reach type
Axis two loading
Main-channels
Side-channels
Reach type

Table 4-4. Pearson correlation matrix of PCA input values and first three PCA axes (n = 43). Bold numbers are significant ($p < 0.05$) and underlined values are near statistical significance ($0.5 > p < 0.1$).

	Axis one	*Axis two*	*Axis three*
Specific stream power (S.SP)	**0.982**	0.025	-0.150
Shear stress (to)	**0.894**	0.034	0.282
Water level slope (Wl)	**0.850**	0.159	-0.059
Mobility ratio (Mr)	**0.739**	**0.464**	0.240
Unit sed. trans. rate (qs)	**0.674**	0.348	0.228
Bed slope (Bed)	**0.504**	0.304	0.113
Norm length (L)	**-0.507**	-0.259	-0.208
D_{50} (D50)	0.066	**-0.945**	0.224
D_{50} bedload (D50.load)	0.335	**-0.865**	0.282
Width-depth ratio (W/D)	-0.147	**-0.703**	**-0.610**
Friction factor (ff)	0.191	**-0.507**	0.319

0.05, Figure 4-5), however no other channel types displayed statistical differences on the axis. The interpretation is supported by the location of abandoning channels low on the axis, stable secondary channels mid-axis and avulsion channels high on the axis. Confined, single and primary channels showed a greater range on the axis, indicating variable energy levels.

4.5.4 Principal component axis two

PCA axis two was negatively correlated ($p < 0.05$) with bed D_{50}, bedload D_{50}, friction factor and width-depth ratio, and positively correlated with mobility ratio (Table 4-4). Axis two is interpreted as representing the hydraulic efficiency of channels and grain size. Side-channels (avulsions, secondary and abandoning) had higher axis two loadings than main-channels (confined, single and primary) (ANOVA $p < 0.05$, Figure 4-5 bottom). Sediment grain size and hydraulic efficiency (width-depth ratio and friction factor) of channels appears to be related to channel size. PCA axis two also was negatively correlated with bed D_{50} and bedload D_{50} indicating that side-channels had smaller D_{50} than main-channels. Since, PCA axis two differentiated main-channels from side-channels, the next section will investigate these groups separately.

4.5.5 Main-channels

If axis one represents hydraulic energy and sediment mobility then, within main-channels, primary channels were associated with moderate channel energy, sediment mobility, and moderate to high grain size, width-depth ratio and friction factor (Figure 4-5). Single channels were associated with low to moderate channel energy levels and sediment mobility, moderate to high grain size and low channel efficiency. Confined channels were associated with low to high channel energy and sediment mobility, high grain size and low channel efficiency. Although not statistically significant, primary channels had higher water surface slope, shear stress and mobility ratio than single and confined channels (Table 4-2). Main-channels had similar values of width-depth ratio and friction factor (Table 4-2).

4.5.6 Bedwaves

Four examples of bedwaves on the long profile of the Renous River are shown in Figure 4-6 and Figure 4-7. The stoss side of bedwaves had low slopes while the lee side of bedwaves displayed high slopes. Bedwaves may occur with or without a diffluence downstream. Four bedwaves were identified within single channels (Figure 4-6 A and C, and Figure 4-7 E). Bedwaves within single channels displayed a relatively simple pattern on the PCA, with stoss sides occurring low on axis one (the energy and sediment mobility axis) and the lee side occurring high on the axis (Figure 4-7). Two tailed paired-sample t tests ($n = 4$) showed differences ($P < 0.1$) between the stoss and lee sides of bedwaves in bed slope, three hydraulic energy, two sediment mobility variables and PCA axis one (Table 4-5).

Three bedwaves occurred in the seven locations where an upstream single channel and an adjacent downstream primary long-lived channel occurred (Figure 4-6 B and D, and Figure 4-7 F). In such locations with bedwaves, slope was low within single channels upstream of diffluences and increased within downstream primary channels. The inflection point of these bedwaves occurred at diffluences (Figure 4-7 F). On the PCA, only one bedwave associated with a diffluence displayed the same trend as the single channel bedwaves, with the other two displaying the opposite trend (Figure 4-7).

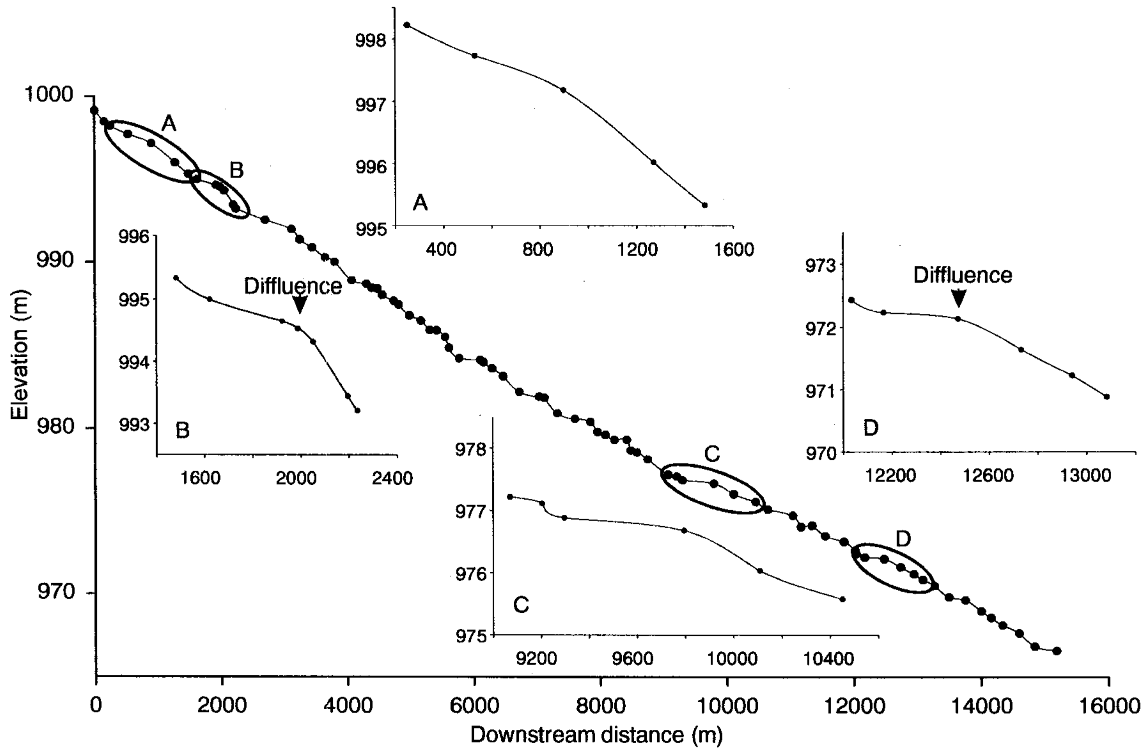


Figure 4-6. Long profile of the Renous River main-channel highlighting four example bedwaves (locations shown of Figure 4-2). Bedwaves A and C are in confined and single channels, respectively. Bedwaves B and D are single and primary channels with the arrow denoting the location of the diffluence. Small circles on the long profiles indicate locations of riffles.

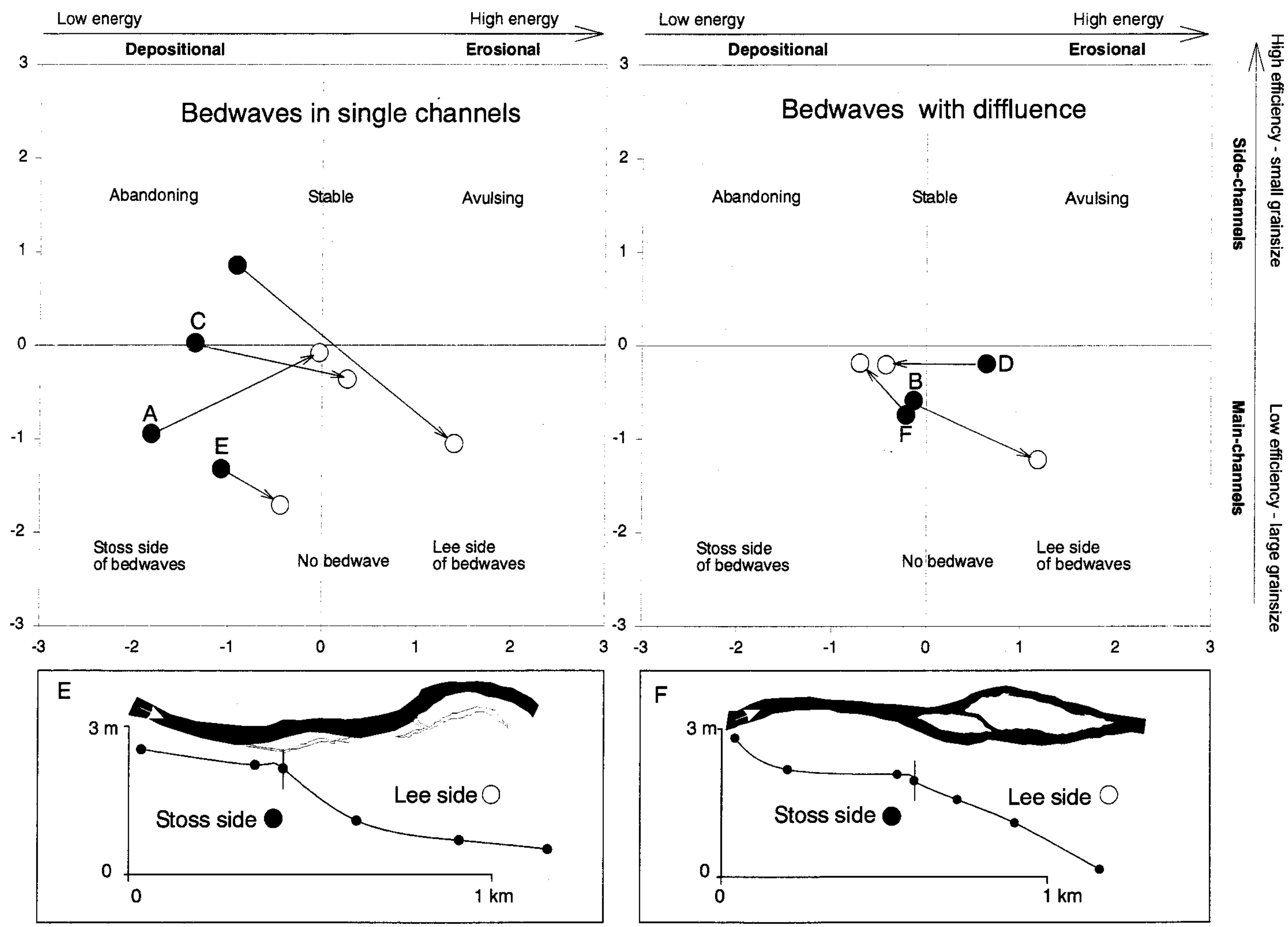


Figure 4-7. PCA axis one and two loadings for stoss and lee sides of four bedwaves occurring in long single channel reaches and for three bedwaves associated with diffluences. Letters (A D) on PCA plots denote bedwaves in Figure 4-6 or bedwaves (E and F) with maps below PCA plots

Only one difference in bed slope ($p = 0.1$) was seen between the stoss and lee sides of the three bedwaves associated with a diffluence (Table 4-5).

4.5.7 Side-channels

Within side-channels, avulsion channels were associated with high channel hydraulic energy, sediment mobility, and low grain size, width-depth ratio and friction factor (Figure 4-5 and Table 4-2). Secondary channels were associated with moderate channel energy and sediment mobility, and small to moderate grain size and moderate hydraulic efficiency (Figure 4-5 and Table 4-2). Abandoning channels were associated with low channel energy, sediment mobility, and moderate to small grain size and high hydraulic efficiency (Figure 4-5 and Table 4-2). Side-channels displayed lower width-depth ratios than main-channels, however friction factor was not significantly different (Table 4-2).

4.6. Discussion

The principal component analysis of hydraulic energy, sediment mobility, hydraulic efficiency and grain size characteristics within channel reaches of the Renous River was compressed into two explanatory axes. Axis one displayed differences in hydraulic energy and sediment mobility while axis two differentiated main-channels from side-channels.

Smaller grain size in side-channels than main-channels (Figure 4-5) may be due to differential sediment routing. Smaller sediment may be preferentially routed into secondary channels as the larger grain sizes follow the thalweg to remain in main-channels (Figure 4-8). At diffluences, where sediment is routed into downstream multiple

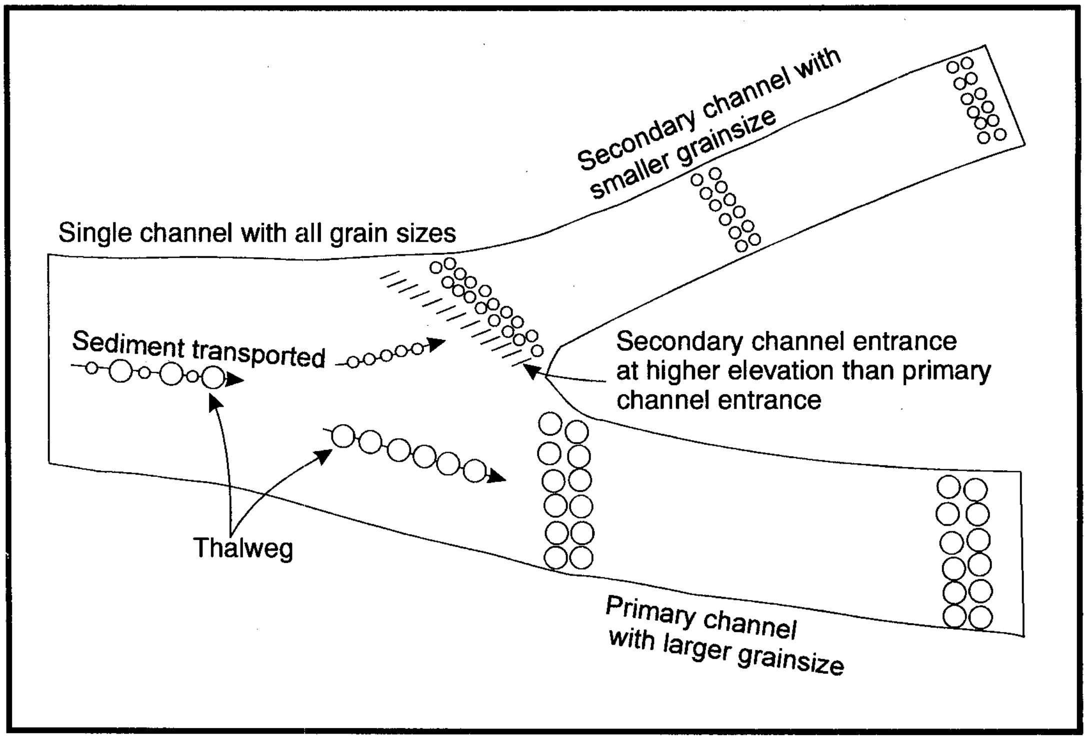


Figure 4-8. Model showing sediment routing into anabranch channels explaining how the grain size in secondary channels is smaller than in primary channels.

channels, the thalweg occurs in the main-channel, with the entrance to the side-channel at a higher elevation. Therefore, large particles follow the thalweg, allowing only smaller particles to be transported over the higher elevation entrance of the side-channel. Also, deposition of fine sediment within abandoning channels may explain the smaller grain size of some side-channels, while the erosion into smaller grain size floodplain deposits during avulsions may explain smaller grain size of other side-channels.

Width-depth ratio was smaller in side-channels than main-channels (Figure 4-5) suggesting that smaller side-channels are more hydraulically efficient. Channels with low width-depth ratios have greater hydraulic efficiency than high width-depth ratio channels because they have a smaller wetted perimeter, and therefore greater depth for a given cross-sectional area. Channel depth was very similar among channels, indicating that channel width influenced width-depth ratio more than channel depth. Friction factor was not different among channels.

On the PCA, bed slope plotted near mobility ratio and unit transport rate, higher on axis two than water level slope. Water surface slope plotted closer to shear stress and specific stream power. This suggests that the bed slope and water surface slope in some channels are out of balance, causing erosion where water level slope is greater than bed slope or deposition where water level slope is less than bed slope. The highest sediment mobility occurred where bed slope is steepest and channels are shortest. These areas may be the location of the downstream sides of bedwaves.

The PCA loadings for main-channels and side-channels were significantly different for axis two, indicating that different processes maintain main-channel and side-channel characteristics (Figure 4-5). Previous literature suggests that bedwaves are common within main-channels. Therefore, main-channels characteristics are hypothesized to be maintained by bedwaves superimposed on the long profile (Figure 4-6). Side-channel characteristics appear to be maintained by the processes that create, maintain and abandon side-channels (Figure 4-3).

4.6.1 Bedwaves in main-channels

Bedwaves are mega bedforms with lengths greater than the channel width, seen as bulges on the long profile (Church and Jones 1982). Bedwaves are common on the long profile of the Renous River and drive differences in channel energy and sediment mobility within some main-channel sections. Figure 4-6 and Figure 4-7 display six bedwaves on the long profile of the Renous River. Confined sections had the greatest range in values in axis one loadings (Figure 4-5). This variability in the axis loadings for confined main-channels is driven by four bedwaves (Figure 4-7) because high-slope, erosional, lee sides of bedwaves plotted high on axis one while low-slope, depositional, stoss sides of bedwaves plotted low on the axis (Figure 4-7).

Bedwaves were present in three of seven channels where single channels divided into primary channels, where the other channel was not abandoning or avulsing. The apex of these bedwaves occurred at diffluences. These three bedwaves are consistent with other documentation of bed slope increasing downstream of channel divisions (Leopold and Wolman 1957). Slope in a primary anabranch may increase due to aggradation at its head or degradation at its downstream end, near a confluence. Bedwaves associated with diffluences do not however follow the simple trend of those found within single channels. Only one of the three bedwaves displayed the same pattern as bedwaves within single channels, with the stoss side low on axis one and the lee side high on the axis. From these few data points, hydraulic energy and sediment mobility between stoss and lee sides of bedwaves associated with a diffluence appear to be similar or even lower in lee sides than stoss sides. This could be because of discharge lost to the other channel at diffluences, decreasing specific stream power and shear stress within the primary channel that forms the lee side of the bedwave. The response of channels to diffluences, including the development of bedwaves, is complex and requires further study.

The bedwave model of Church and Jones (1982) shows the stoss side of bedwaves much longer than the lee. Within this study, the normalized length of all single channels was significantly longer than all primary channels (Table 4-2). Also, the Pearson correlation matrix showed that normalized length was significantly negatively correlated to bed slope, mobility ratio, water surface slope and shear stress (Table 4-3), perhaps indicating that the low slope sides of bedwaves within single channels were longer than the lee sides in primary channels (as displayed in the bedwave model in Figure 4-2). However, normalized length was not greater within single channels than primary channels within the three bedwaves associated with diffluences, indicating that there may be a range of bedwave forms, with long or short stoss sides, in nature.

4.6.2 Side-channel creation, maintenance and abandonment

Side-channel characteristics reflect creation, maintenance and abandonment processes (Figure 4-3). As discussed above, side-channels are smaller and have higher efficiency than main-channels. The PCA axis one loadings were not significantly different between avulsion and secondary channels, because avulsions may grow to become secondary channels over time. Similarly, the PCA axis one loadings were not significantly different between secondary and abandoning channels because secondary channels may become abandoning channels over time. This creates a gradation of channel hydraulic energy and sediment mobility, with avulsions displaying the highest energy and sediment mobility, followed by stable secondary channels, and abandoning channels having the lowest levels (Table 4-2).

Avulsion channels are erosional, with high channel energy and the highest sediment mobility, occurring high on axes one and two (Figure 4-5). Avulsion channels are created as icejams create high stages that force flow into abandoned channels whose path is shorter than that of the main-channel (See Chapter 2). This causes high energy and sediment mobility levels until avulsion channels capture enough flow to become secondary channels. Secondary channels have moderate energy and sediment mobility levels (Table 4-2), occurring high on axis two and mid way on axis one. Secondary channels are larger than avulsion channels (Table 4-2), but still receive significant seasonal flow and may be stable through time. Abandoning channels, occurring high on axis two but low on axis one, are depositional, with low energy and sediment mobility levels (Table 4-2). When a secondary channel becomes inefficient compared to its paired main-channel, it may be abandoned. Sediment will continue to deposit within an abandoning channel, causing it to infill and eventually join the floodplain.

4.7. Conclusions

The processes creating variability within wandering channel reaches are unevenly distributed among channel types within wandering channels. Differences between main-channels and side-channels drive differences in width-depth ratio and grain size. Within side-channels, hydraulic energy and sediment mobility is influenced by the stage of development of the anabranch (avulsion, stable or abandoning). Within main-channels, differences in hydraulic energy and sediment mobility may be associated with bedwaves. Bedwaves occurring within long single channel reaches display a low slope stoss side with low hydraulic energy and sediment mobility and a high slope lee side with high hydraulic energy and sediment mobility. Three of seven diffluences not associated with an abandoning or avulsion channel contained a bedwave. These bedwaves did not show the same differentiation in hydraulic energy and sediment mobility between stoss and lee sides as bedwaves in long single channel reaches. The partitioning of hydraulic energy and sediment mobility upstream and downstream of diffluences, including the formation of bedwaves, is complex and require further study.

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Preface to chapter five

Chapter five investigates smaller channel elements, diffluences, nested within the channel segments investigated in chapter three and four (Figure 1-5C, Figure 1-6). Chapter four showed that the routing of water and sediment into anabranches influences their grain size and hydraulic characteristics. Chapter five investigates two questions: (1) how is the stability of diffluences reflected in their morphology and surface grainsize? (2) What are the processes that maintain stable diffluences through time? Chapter five investigates island head diffluence zones where the flow of water and sediment is divided into downstream anabranches. To understand how diffluences route sediment into anabranches and how they may remain stable, the evolution of the morphology, surface grain size distribution and dynamics of diffluence zones were investigated.

5. Chapter five: Wandering river island head diffluences from creation to abandonment, Renous River, New Brunswick

5.1. Abstract

This study presents the first detailed analysis of diffluence morphology and surface grain size patterns within wandering rivers. Diffluences, occurring at island heads, are present in all multiple channel systems and divide the flow of water and sediment into downstream anabranches. On many wandering rivers anabranch pairs may exist for decades or centuries. For anabranch channels to be long lived, diffluences must direct water and sediment into both anabranches for long periods. Two aspects of wandering river diffluences on five rivers within the Miramichi basin, New Brunswick were investigated. To investigate controls on the geometry of island head diffluences, factors influencing the angle between two anabranches at their diffluence were examined. To investigate the dynamics of diffluences, detailed morphologic, flow direction and bed grain size characteristics of five diffluences on the Renous River, New Brunswick were analyzed and from these data a chronosequence of diffluence development was created.

The location of diffluences in main or subordinate anabranches and the relative length of the anabranches explained some variance (adj. $R^2 = 0.21$) in diffluence angle. A chronosequence using five diffluences with different site histories illustrated diffluence dynamics. Diffluences created by avulsions may develop a bar at the island head that may grow to become an island head bar if the diffluence stabilizes. Island head bars divide flow into anabranches and are hypothesized to provide a reservoir of sediment that buffers degradation of either entrance anabranch, thereby creating stable anabranches. At

stable diffluences, island head bars accrete upstream between 0.9-2.5 m/yr, as determined through dendrochronology. The bar accretes as larger particles are deposited on the upstream facing accretion surfaces while smaller particles are redirected into anabranches by secondary flow. The location of a large bar upstream or downstream of diffluences enhances diffluence stability or instability, respectively. Diffluences are dynamic river elements that may remain stable over long periods or they may destabilise resulting in the abandonment of one anabranch. Diffluence dynamics are integral in maintaining the wandering river pattern.

5.2. Introduction

This study presents the first detailed analysis of the morphology and surface grain size patterns of wandering river diffluences. Diffluences occur in all multiple channel rivers where flow divides into downstream anabranch channels around islands. Diffluences not only divide the flow of water but also of sediment and thereby influence the dynamics of the downstream anabranches. Stable anabranches are maintained where diffluences direct a balance of sediment and water into each anabranch so that they neither significantly degrade nor aggrade their beds. When the division is out of balance, downstream anabranches may be short-lived. Multiple channel sections within gravel-cobble wandering rivers contain seasonal or perennial anabranches around semi-permanent islands (Neill 1973, Church 1983) that change through time (see chapter 3). Therefore, wandering rivers provide an opportunity to study the dynamics of the diffluences upstream of these anabranch channels.

Multiple channel rivers create habitat heterogeneity important for maintaining healthy ecosystems. However, side-channels in some rivers are being lost due to flow regulation (Desloges and Church 1989, Ligon *et al.* 1995). Side-channels provide critical refuge from the high velocity main-channels during winter high flows for juvenile salmonids, particularly Coho salmon (*Oncorhynchus kisutch*), which are endangered in many rivers, (Nickelson *et al.* 1992). In fact, the production of wild Coho salmon smolt in most salmon spawning streams is probably limited by the availability of adequate winter habitat (Nickelson *et al.* 1992). Side-channels also provide over wintering-habitat for adult Atlantic salmon (*Salmo salar*) (Komadina-Douthwright *et al.* 1997) and thermal refuge for Atlantic salmon juveniles (Burge unpublished data). Understanding diffluence zones and their role in creating and maintaining side-channels is critical for the conservation of side-channel salmonid habitat.

What is known of diffluence processes comes mostly from literature on mid-channel bar growth associated within braided rivers (Ashmore 1991, Ashmore 1993, Lane *et al.* 1995, Ashworth 1996, Lane and Richards 1998, Nicholas and Sambrook Smith 1999). Generally, at mid-channel bars, modelled flow vectors diverge into anabranches at diffluences, but near the bar head, flow is directly up the bar (Lane *et al.* 1995, Lane and Richards 1998, Nicholas and Sambrook Smith 1999). Deposition at mid-channel bars occurs at the bar head where particles are transported by the downstream flow up the bar toward the island head (Ashworth 1996). Smaller particles are redirected into downstream anabranches by topographical steering of flow (Dietrich and Smith 1984) or secondary flow, while particles too large to be redirected stall on the bar surface (Ashworth 1996).

Mid-channel bar growth within braided rivers is often associated with upstream confluences (Ashmore 1993). Within wandering rivers however, diffluences are often unrelated to confluences, rather occurring where avulsions cut into older mature floodplain (Church 1983). The sedimentology and surface grain sizes at diffluences are not well known but gravel deposits at an island head just upstream of the diffluence on the wandering Fraser River, British Columbia, were recently imaged using ground penetrating radar (Wooldridge 1999). These deposits dipped upstream at an angle of $< 1^{\circ}$ and were interpreted as upstream accretion deposits produced by the migration of gravely bedload sheets on to the bar surface.

The angle between the two channels at a diffluence may reveal information about the stability of the diffluences themselves. Diffluences with large angles, perhaps at the entrance of an abandoning channel (Bridge 1983), may be inefficient at transferring water and sediment into the abandoning channel and may therefore be unstable. Diffluence instability may be enhanced by sediment deposited in a zone of flow separation with a vertical axis near such a sharp channel entrance (Bridge 1983). In contrast, diffluences with smaller angles may remain stable by dividing water and sediment more evenly between the anabranches. Anabranches of similar length may be long lived, implying that they have stable diffluences (chapter three). Characteristics of anabranches downstream of diffluences (e.g. long abandoning channels) may provide insight into diffluence processes.

Previous to this study, the morphology and surface grain size pattern of diffluences within wandering rivers was undocumented. What is known about diffluence processes comes from mid-channel bars within braided rivers. However, the processes occurring at mid-channel bars within braided rivers may not be analogues to diffluences within wandering rivers. Therefore, processes occurring at wandering river diffluences need to be established through interpreting the morphology and surface grain size of a number of diffluences with different site histories.

The question investigated was: what processes influence the dynamics of diffluence zones within wandering rivers? The research had three specific objectives: (1) to examine the relationship between diffluence angle and the characteristics of downstream anabranches (e.g. relative length); (2) to develop a chronosequence of diffluence development to investigate under what conditions diffluences are stable or unstable; (3) to investigate the processes occurring at stable diffluences to understand what insures their longevity.

5.3. Study area

The study area is within the Miramichi drainage basin in central New Brunswick, Canada (Figure 5-1, inset). Miramichi rivers are in a natural state with little river engineering and no dams and are used extensively recreationally for canoeing and angling. Wandering reaches of the Southwest Miramichi (108 m), Little Southwest Miramichi (80 m), Dungarvon (41 m) and Taxis Rivers (37 m) were analyzed. The majority of the research was conducted on the wandering section of the Renous River, a tributary of the Dungarvon and Southwest Miramichi Rivers near the village of Renous, New Brunswick (Figure 5-1). The Renous is 60 m wide, has a mean annual flood of 147 $m^3 s^{-1}$, and drains 611 km^2 of the Miramichi plateau near the centre of the Miramichi drainage basin. The Renous displays the wandering pattern for 11.5 km, between upstream and downstream confined sections. Confined sections have a single channel where parallel bedrock valley walls limit channel migration and space for multiple channels.

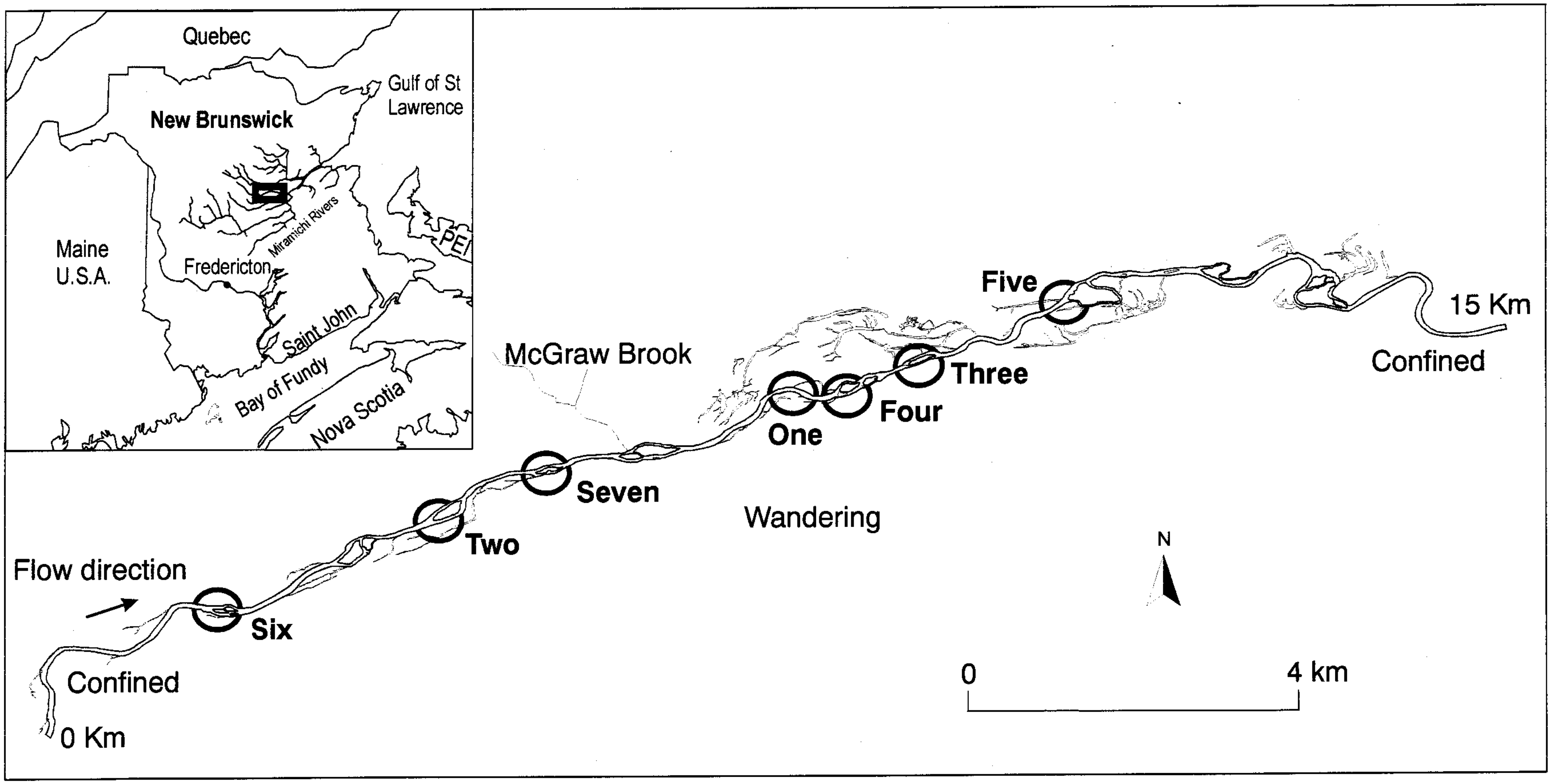


Figure 5-1. Study area location in central New Brunswick, Canada (inset). Locations of study diffluences one through seven on the wandering Renous River are indicated by a circle. Flow is from left to right.

At McGraw Brook, in the centre of the Renous River study area, the mean monthly air temperature varies between -11.8°C in January to 18.8°C in July, with April to October above freezing (Caissie and El-Jabi 1995). During winter, Miramichi rivers form a thick (50 cm) ice cover that commonly form icejams during winter and spring break-up (Beltaos *et al.* 1989). Icejams have been observed in several wandering sections of Miramichi rivers. On the Little Southwest Miramichi icejams occur every second year, obtaining a stage of 1 m above the mean annual flood (Chapter 2). Within the larger neighbouring Main Southwest Miramichi River, break-up occurs between March 22 and May 2; the average break-up date is April 14 (Allen and Cudbird 1971).

5.4. Methods

To investigate diffluence geometry, 117 diffluence angles were measured from 1:10 000 orthomaps on the Main Southwest Miramichi, Little Southwest Miramichi, Dungarvon, Renous and Taxis rivers. Diffluence angles were determined by drawing a line through the centre of each anabranch at its entrance and measuring the angle between the lines. Three measurements of channel width were taken above each diffluence and within each anabranch channel to obtain average channel widths. Where appropriate, variables were normalized for comparison among rivers. The ratio of the smaller to the larger anabranch width determined the anabranch width ratio. The length of anabranches around the islands was measured from diffluence to confluence. The ratio of the shortest to longest anabranch determined the anabranch length ratio. Larger anabranch ratios indicate more similar lengths of anabranches. Diffluence order was determined to quantify the hierarchy of a diffluence within a system. First order diffluences occurred within single channels, and second order diffluences occurred within an anabranch channel downstream of a first order diffluence. ANOVA was used to test differences in the diffluence angle among rivers. To investigate influences on diffluence angle, a multiple regression approach was used with diffluence angle as the dependent variable and anabranch length ratio, diffluence order, width of channel upstream, and anabranch width ratio as independent variables.

To further explore characteristics controlling diffluence morphology, a subset of five diffluences with different morphology and site history were chosen from the Renous River. To ensure the five diffluences were representative of the population, ANOVA was used to test for mean differences between the population of diffluence angles and the five diffluences selected for further study. Aerial photographs taken approximately every decade from 1945 - 1999 were used to reconstruct site histories. Lengths and widths of anabranch channels were determined from a map of the Renous based on 1999 aerial photographs. Bed morphology was determined through field surveys using a total station and the creation of digital terrain models (DTM) as triangular irregular network TINs using Arcview 3D analyst (ESRI 1999). Bar volumes were determined using Arcview 3D analyst (ESRI 1999) and represented the sediment volume above the pool elevation within the downstream anabranch that contained the main thalweg. Surface grain size, estimated using the visual method proposed by Latulipe *et al.* (2001) and pebble counts of 100 clasts, were referenced to the DTMs. Flow vectors were reconstructed from field surveyed lines of imbricated clasts on the bed. These five diffluences were then used to propose a chronosequence of diffluence development.

Floodplains at island heads were dated through dendrochronology using an increment borer to obtain tree cores from the base of trees growing on floodplains. Early successional species (willow, *Salix* sp. and Speckled alder, *Alnus rugosa* (L.) Moench.) located near the active channel and later successional species (American elm, *Ulmus americana* L.) located farther from the active channel were cored. The time for elm to colonize after willow and alder was not known, and therefore the age difference between species colonization was not corrected and dates represent minimum ages. Average upstream accretion rates were calculated using slopes of distance-age regression equations and represent maximum accretion rates.

To investigate controls on the accretion rate, univariate regressions were performed using accretion surface slope, drainage basin area (as a proxy for discharge), surface D_{50} of riffles at diffluences, and channel slope upstream of diffluences (SPSS 1998). The slope of the accretion surfaces (measured over 60 to 200 m) of six bars located at stable island heads from the Little Southwest Miramichi, Renous, and Taxis rivers were measured down the centre line of the bar upstream of the island head using a laser level or was extracted from DTMs. Surface grain size distribution was determined at the heads of at least three riffles directly upstream of the diffluence by measuring the B-axis of 100 randomly chosen clasts. Bankfull discharge was estimated as the mean annual maximum daily discharge for gauges on the Renous and Little Southwest Miramichi rivers (Environment Canada 1997). Mean annual maximum daily discharge for the ungauged Taxis River was determined using a regional relationship developed for the mean annual maximum daily discharge and drainage area for six rivers within the Miramichi drainage. The slope of the long profile immediately above each diffluence was determined by either surveying the elevation of at least three riffles (150 – 300 m) upstream of the diffluence using a laser level or differential GPS and determining the distance using a hip-chain or a map created using differential GPS.

5.5. Results

5.5.1 Diffluence angle

The average angle for all diffluences measured within the Miramichi river diffluences (n = 117) was 47° (SE 1.7°). Diffluence angles were not significantly different among the five Miramichi rivers (ANOVA, $p = 0.403$). Some variance in diffluence angle ($R^2 = 0.23$) was explained by diffluence order ($p < 0.000001$) and anabranch length ratio ($p = 0.000002$) using multiple regression (Table 5-1). Diffluence angle increased with diffluence order and decreased with anabranches of similar length.

A total of 16 diffluences occurred within the Renous river study area based on the interpretation of aerial photographs from 1945-1999 in 1999 (Figure 5-1). Six newly created (37%), four stable (25%), one unstable after being stable (6%), two unstable after creation (13%), and three abandoning (19%) diffluences were identified using aerial photographs. Of the subset of five diffluences studied in detail, mean diffluence angles (49° +/- 5°) were not significantly different from the larger population (ANOVA, p = 0.73). Of the five study diffluences, the newly created diffluence one displayed the largest angle (60°). Diffluences four and five, unstable after creation (53°) and abandoning (55°) respectively, also displayed large angles. Diffluences two and three, stable (42°) and unstable after stable (35°) respectively, displayed the smallest angles. This suggests that unstable newly created, unstable after creation and abandoning

Table 5-1. Multiple regression model showing the relationship between diffluence angle (dependant variable) and the relative length of the anabranches (length ratio) and channel order.

Effect	*Coefficient*	*SE*	*t*	*P*
Constant	81.6	10.5	7.73	0.000001
Length ratio	-53.5	11.8	-4.55	0.000001
Channel order	8.9	2.0	4.49	0.000002

N = 115, Adjusted $r^2 = 0.23$

diffluences have higher angles than stable or unstable after stable diffluences, although the sample size is very small.

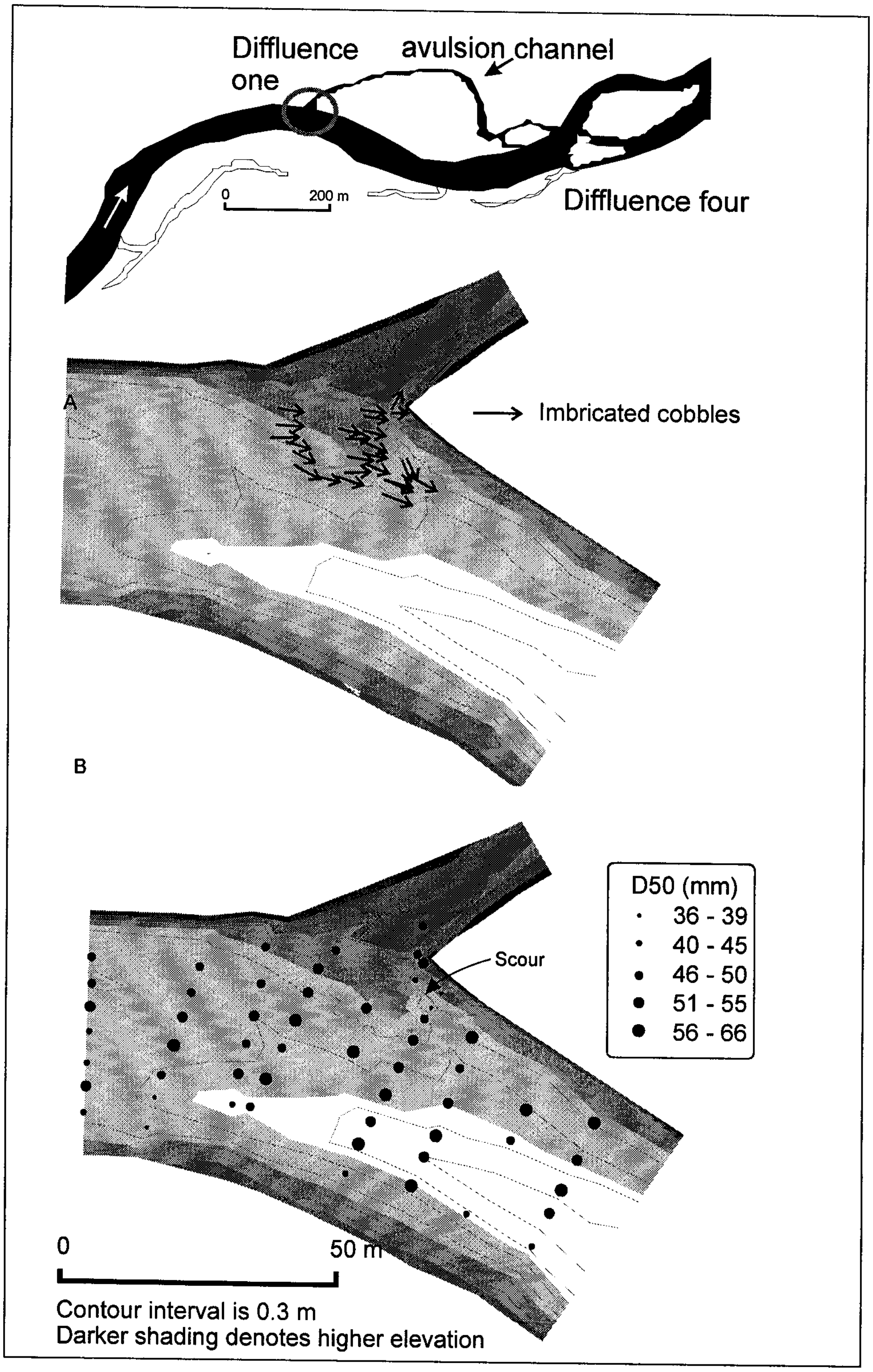
5.5.2 Study diffluences: case histories, morphology and surface grain size

The morphology and surface grain size distribution of five diffluences with different geometry and history are presented. Analysis of these diffluences will be used to create a chronosequence of diffluence morphology to better understand diffluence dynamics.

5.5.2.1. Newly created diffluence

Diffluence one was created between 1983 and 1999 by an avulsion after the main-channel migrated close to an abandoned channel. In 1999, the avulsion channel was 440 m long and 7 m wide and the main-channel was 360 m long and 64 m wide. The smaller left channel, located on the outside of a meander bend, divides from the larger right channel at an angle of 60° (Figure 5-2A). A bar, located just upstream of the diffluence within the right channel, ramped up to the elevation of the left channel entrance, perched above the right channel. The bar extended downstream in the right channel and had an area of 4490 m^2 and a volume of 2630 m^3, measured above the depth of the downstream pool. The right channel thalweg was located on the inside of the meander, close to its right bank. A linear scour into the bar occurred just downstream of the diffluence at a low angle (approx. 20°) from the channel bank. Imbrication lines at the entrance ramp, representing flow vectors, indicated that little flow enters the left channel at high stages and most of the flow remains downstream in the right, main-channel unaffected by the diffluence (Figure 5-2A). Flow vectors also showed flow at an angle to the main flow

Figure 5-2. (A) Morphology of diffluence 1 showing a bar near the entrance to the secondary channel and little flow entering that channel. (B) Map showing finer grain size on the bar and larger grain size in the thalweg. Flow is from left to right.



Diffluence one
avulsion channel
0
200 m
Diffluence four
A
Imbricated cobbles
B
Scour
D50 (mm)
36 - 39
40 - 45
46 - 50
51 - 55
56 - 66
0
50 m
Contour interval is 0.3 m
Darker shading denotes higher elevation

within the linear scour. The surface D_{50} was smallest on the bar, greater in the thalweg near the inside of the bend, and finer within the linear scour (Figure 5-2B).

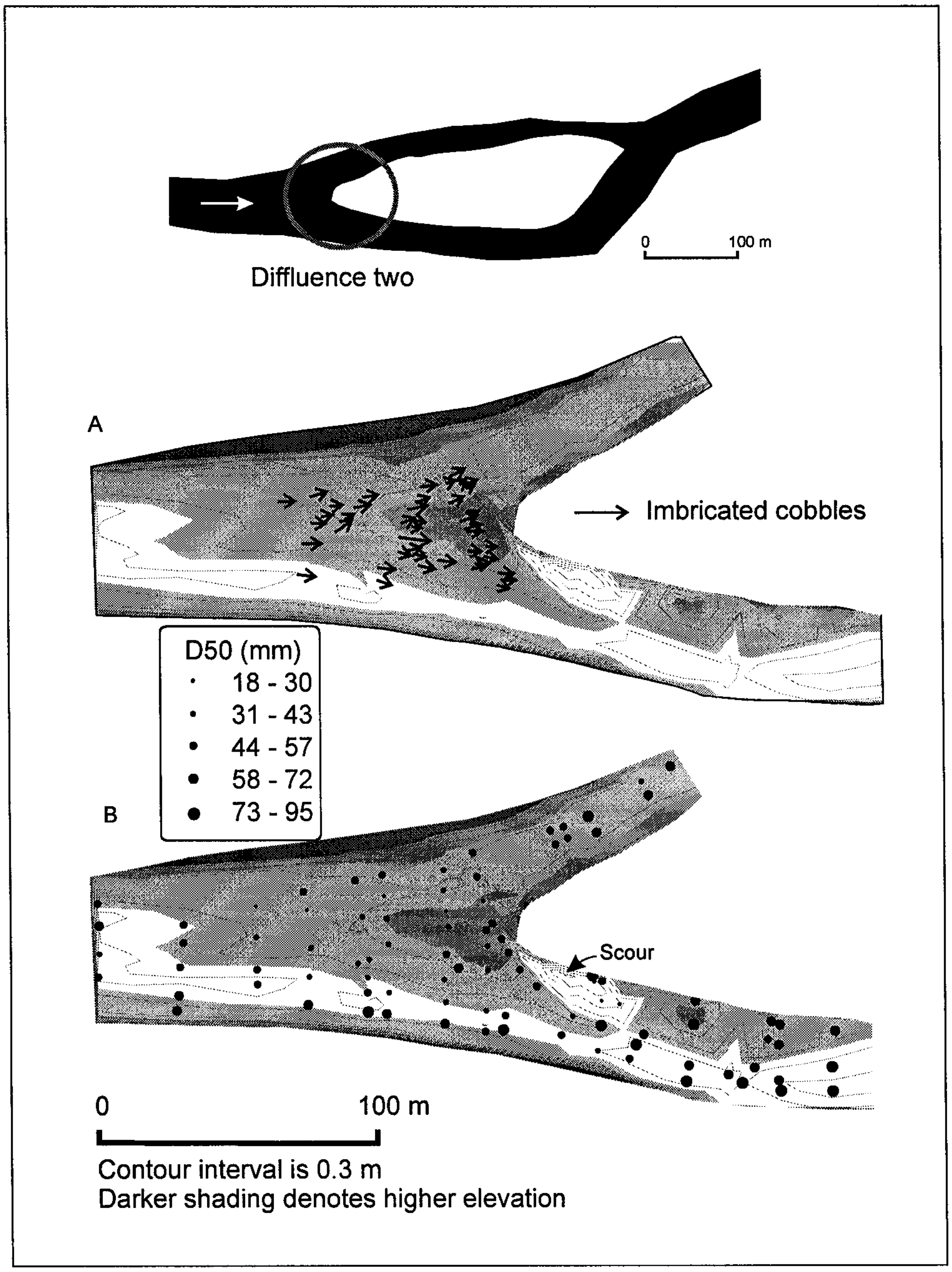
5.5.2.2. Stable diffluence

Diffluence two has been stable for more than 57 years but its date of creation is not known. Between 1945 and 1965 the right channel was slightly smaller than the left but in 1965 the right channel became larger and continued to grow until 1999. The anabranch widths and lengths were similar in 1999; the left channel was 39 m wide and 390 m long while the right channel was 45 m wide and 435 m long.

At diffluence two, the left channel divided from the right channel at an angle of 42° (Figure 5-3A). The morphology of the active channel bed when looking downstream resembled a ramp, increasing in elevation towards the island and arching downward into each anabranch channel, slightly beyond their entrances. The ramp formed a large bar extending 135 m upstream from the island head with a surface area of 11, 358 m^2 and volume of 4140 m^3. A large linear scour occurred within the right channel near the island head at a low angle (approx. 15°) from the channel bank. Flow vectors near the centre of the bar head was almost directly up the bar towards the island (Figure 5-3A). Imbrication lines near the edges of the bar diverged from the bar into each anabranch channel.

The surface D_{50} was finest on the bar (Figure 5-3B). Coarser sediment occurred in each thalweg on either side of the bar, with the right thalweg coarser than the left. Coarser sediment also occurred downstream of the diffluence in both channels.

Figure 5-3. (A) Morphology of diffluence two showing a large island head bar and flow towards the island head, split by the bar into the two channels. (B) Map showing finer grain size on the island head bar, slightly coarser in the secondary channel thalweg and coarsest in the right channel thalweg. Flow is from left to right.



0
100 m
Diffluence two
A
Imbricated cobbles
D50 (mm)
18 - 30
31 - 43
44 - 57
58 - 72
73 - 95
B
Scour
0
100 m
Contour interval is 0.3 m
Darker shading denotes higher elevation

5.5.2.3. Island head accretion rates

There are several processes that could cause the growth of young trees at the head of an island, including the stripping of vegetation by low frequency high magnitude icejams or logjams, followed by the regrowth of vegetation or a progressive decrease in bankfull flow. Stripping of vegetation at island heads would cause the trees to be approximately the same age. At stable diffluences, tree ages decreased away from island cores of older trees. Also, physical evidence, like large push mounds or uprooted trees were not found at these diffluences. Tree ages may decrease into channels where flooding of channel margins decreases through time, usually due to flow regulation, however these systems are not regulated and regularly reach bankfull stage. Therefore, the dendrochronological and physical evidence supports the interpretation that these island heads are accreting upstream.

At diffluence two, older floodplain formed an island core defined by mature soil and old trees (>150 years) (Figure 5-4). At the island head, trees near the island core were 42 years old and decreased in age, to one year old, at the active channel margin. Based on this dendrochronological evidence, the rate of upstream floodplain accretion at the island head was 0.53 m yr^{-1} (Figure 5-4A). Two other diffluences on the Renous River that displayed island head accretion are also presented in figure 5-4. Diffluence three also displayed decreasing tree ages away from the island core upstream towards the active channel and accreted upstream at a rate of 1.46 m yr^{-1} for approximately 70 years. Diffluence six showed a higher rate of 2.38 m yr^{-1} over approximately 60 years.

Five other stable diffluences from three rivers were also examined in greater detail to investigate factors that influence rates of upstream floodplain accretion at stable

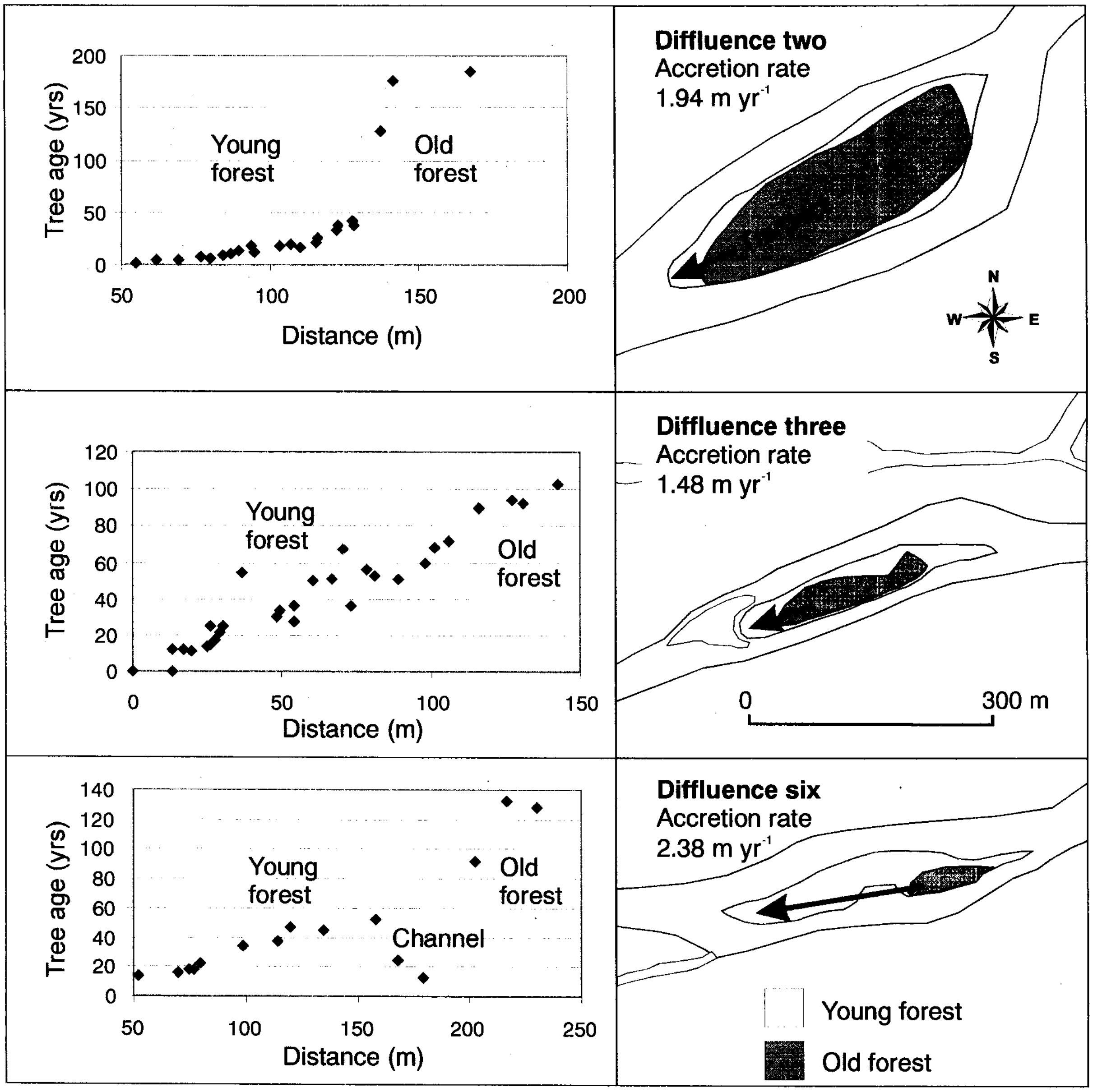


Figure 5-4. Tree ages plotted against distance and maps of islands for three diffluences on the Renous River. Older forest delineates island cores and young forest indicates accreted floodplain. Diffluence two and six are stable and diffluence three is unstable following a period of stability. Flow is from left to right.

diffluences. Three from the Renous (including diffluences one and six), two from the Little Southwest Miramichi, and one from the Taxis were analyzed. Average island head accretion rate, accretion surface slope, D_{50} of riffles at diffluences, mean D_{50} of riffles above diffluences and thalweg long profile slope above diffluences were determined. Univariate regression showed no significant results ($p < 0.05$), although some trends in this small data set were evident (Figure 5-5). Some variance in island head accretion rate was explained by accretion surface slope ($p = 0.08$, $R^2 = 0.49$). Since accretion surface slope appears to influence island head accretion, controls on accretion surface slope were investigated. No significant relationship was found with accretion surface slope, although some variance was explained by thalweg slope above the diffluence ($p = 0.14$, $R^2 = 0.46$) and D_{50} of the diffluence riffles ($p = 0.19$, $R^2 = 0.39$).

5.5.2.4. Unstable diffluence following stability

Diffluence three was present in 1945. This island was small at that time and grew until a large tongue shaped bar formed between 1983 and 1999 following an avulsion upstream (Figure 5-6A). The left channel was 28 m wide and 336 m long, while the right channel was 20 m wide and 312 m long. Diffluence four was located immediately upstream of diffluence three the site of an avulsion. The avulsion created the left channel within diffluence four and input a large amount of sediment into that side channel of the channel at the confluence. This caused an increase in the sediment supplied to the left channel at diffluence three because within the relatively straight reach above the diffluence, sediment would not cross into the right anabranch.

Diffluence three divided at an angle of 35° (Figure 5-6A). The diffluence displayed a small bar at the island head that graded into a larger tongue shaped bar within

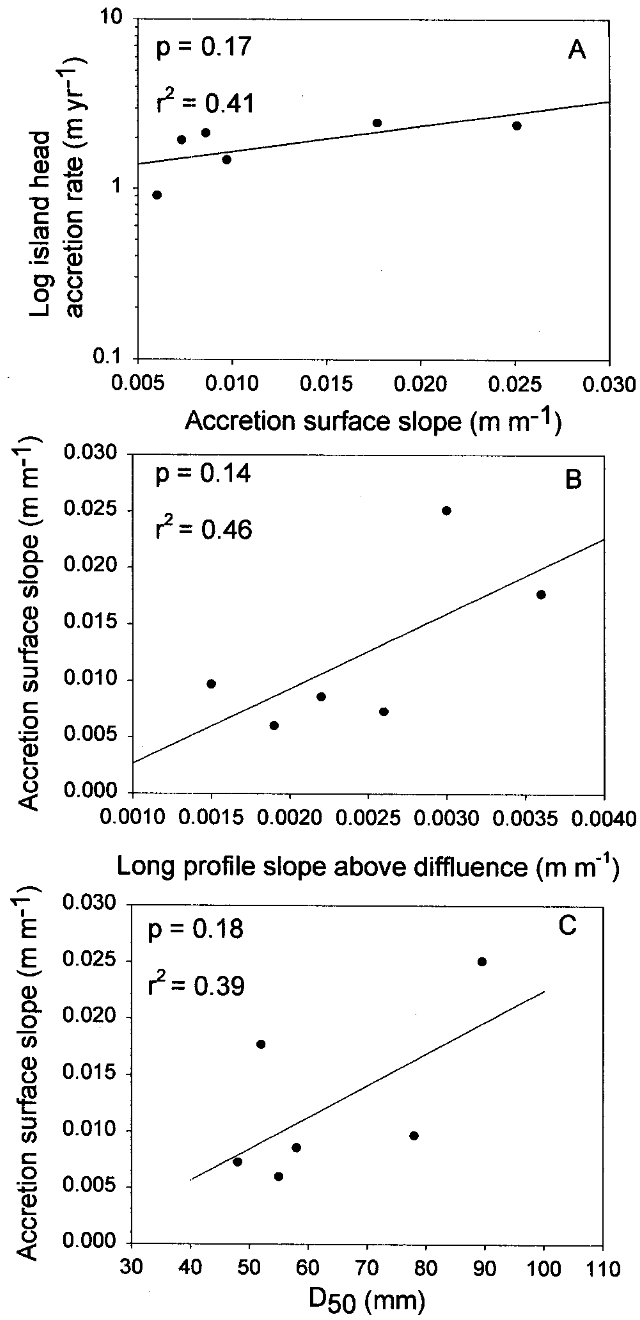
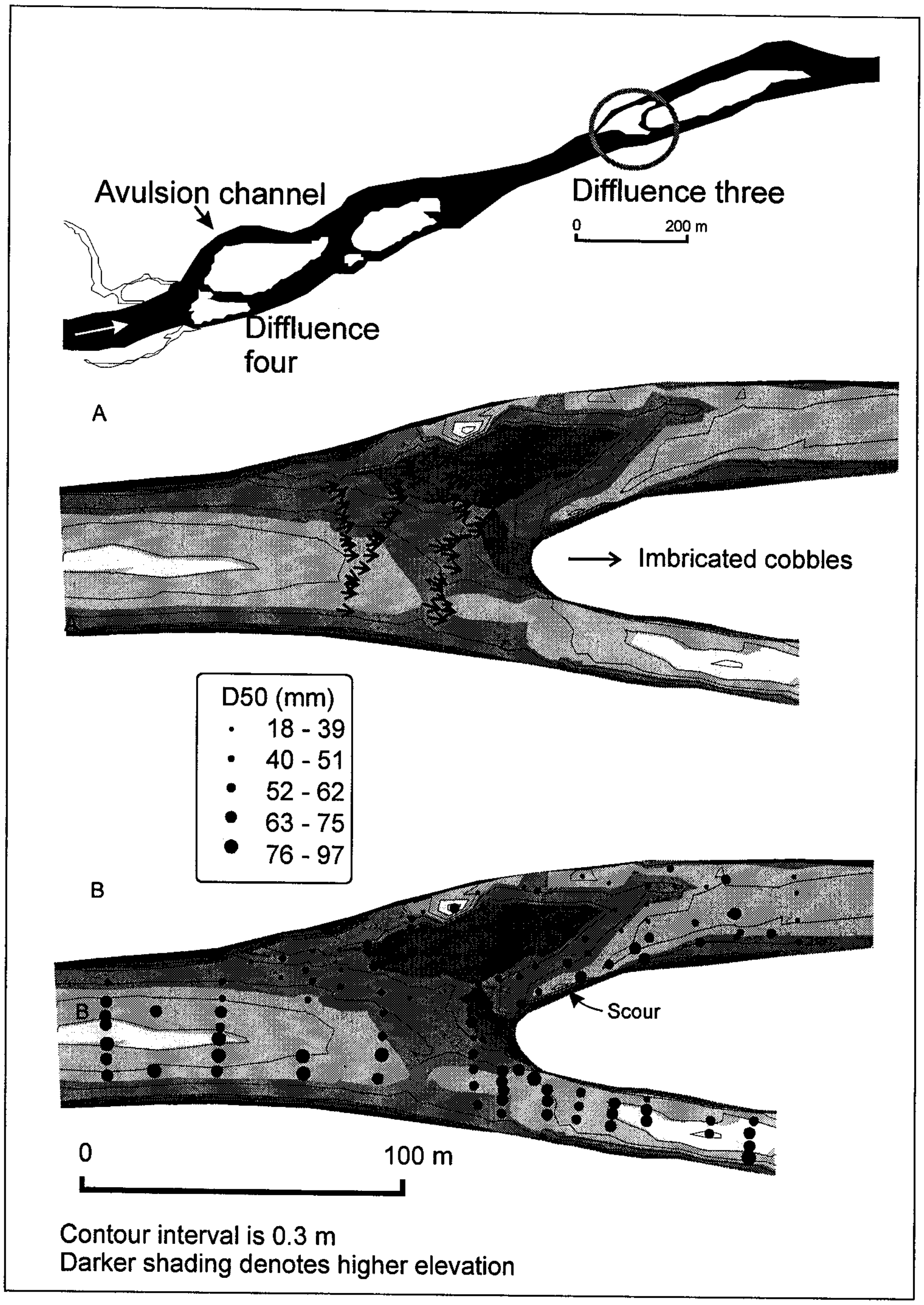


Figure 5-5. (A) Plot of island head accretion rate against accretion surface slope. Plots of (B) accretion surface slope against long profile slope above diffluence and (C) the grain size of the riffles at the diffluence.

Figure 5-6. (A) Morphology of diffluence three showing large tongue shaped bar within the left channel entrance and flow vectors converging into the right channel and diverging over the bar. (B) Map showing finer grain size on the bar within the left channel and coarser grain size in the right channel thalweg. Flow is from left to right.



Avulsion channel
Diffluence three
0
200 m
Diffluence four
A
Imbricated cobbles
D50 (mm)
18 - 39
40 - 51
52 - 62
63 - 75
76 - 97
B
Scour
0
100 m
Contour interval is 0.3 m
Darker shading denotes higher elevation

the left channel entrance. The tongue shaped bar was not present on the 1983 aerial photograph, but was present by 1999. Within the left channel, two smaller sub-channels occurred on either side of the bar tongue at the channel banks. A deep linear scour, at a 10^{o} angle away from the bank, occurred within the sub-channel along the right bank of the left channel. The entrance bar caused the left channel entrance to be higher than the right channel entrance. The right channel contained a deep thalweg with its riffle much lower then the left channel entrance. Imbrication lines converged into the right channel thalweg and diverged around the large tongue shaped bar into the two sub-channels around the left channel entrance bar (Figure 5-6A).

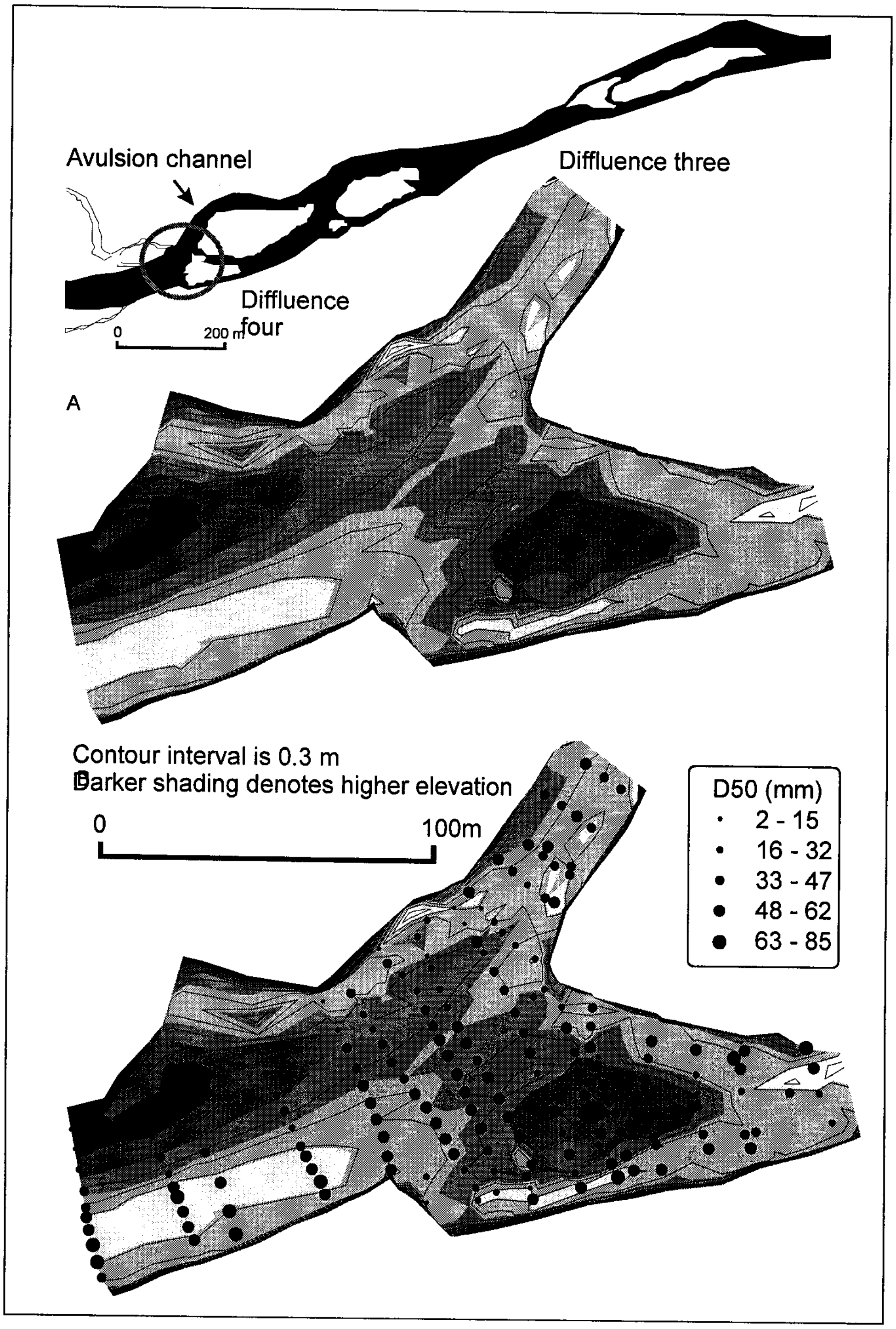
The surface D_{50} of the large bar was finer than the right thalweg, with the coarser sediment following the thalweg downstream into the right channel (Figure 5-6B). Grain size within the sub-channels around the tongue shaped bar were slightly coarser than the bar itself but finer than within the right channel. As seen at diffluence two, diffluence three also accreted upstream (Figure 5-4B).

5.5.2.5. Unstable diffluence following creation

Diffluence four was created between 1976 and 1983 when an avulsion occurred on the left channel bank into an abandoned channel. The avulsion channel increased in size between 1983 and 1999 and is now the left channel. In 2001, the left channel was 27 m wide and 290 m long, while the right channel was 41 m wide and 304 m long.

The morphology of this diffluence was complex. The channels divided at an angle of 53^{o} (Figure 5-7A). A large tongue shaped bar was located at the right channel entrance but did not block the channel entrance. The right and left channel entrances had similar elevations although the right channel carried the flow during summer low flow. A

Figure 5-7. (A) Morphology of diffluence four showing large abandonment bar within the right channel. (B) Map of surface grain size showing coarser grain size on the abandonment bar and coarser in the right channel thalweg. Flow is from left to right.



Avulsion channel
Diffluence three
Diffluence
four
0
200 m
A
Contour interval is 0.3 m
B
Darker shading denotes higher elevation
0
100m
D50 (mm)
2 - 15
16 - 32
33 - 47
48 - 62
63 - 85

large pool occurred just upstream of the bar within the right channel. As with diffluence three, two small channels occurred on each side of the entrance bar near the bank, although the sub-channels were larger at this diffluence. The left channel thalweg occurred mid-channel and was wider than the right channel thalweg that occurred upstream and close to the right bank.

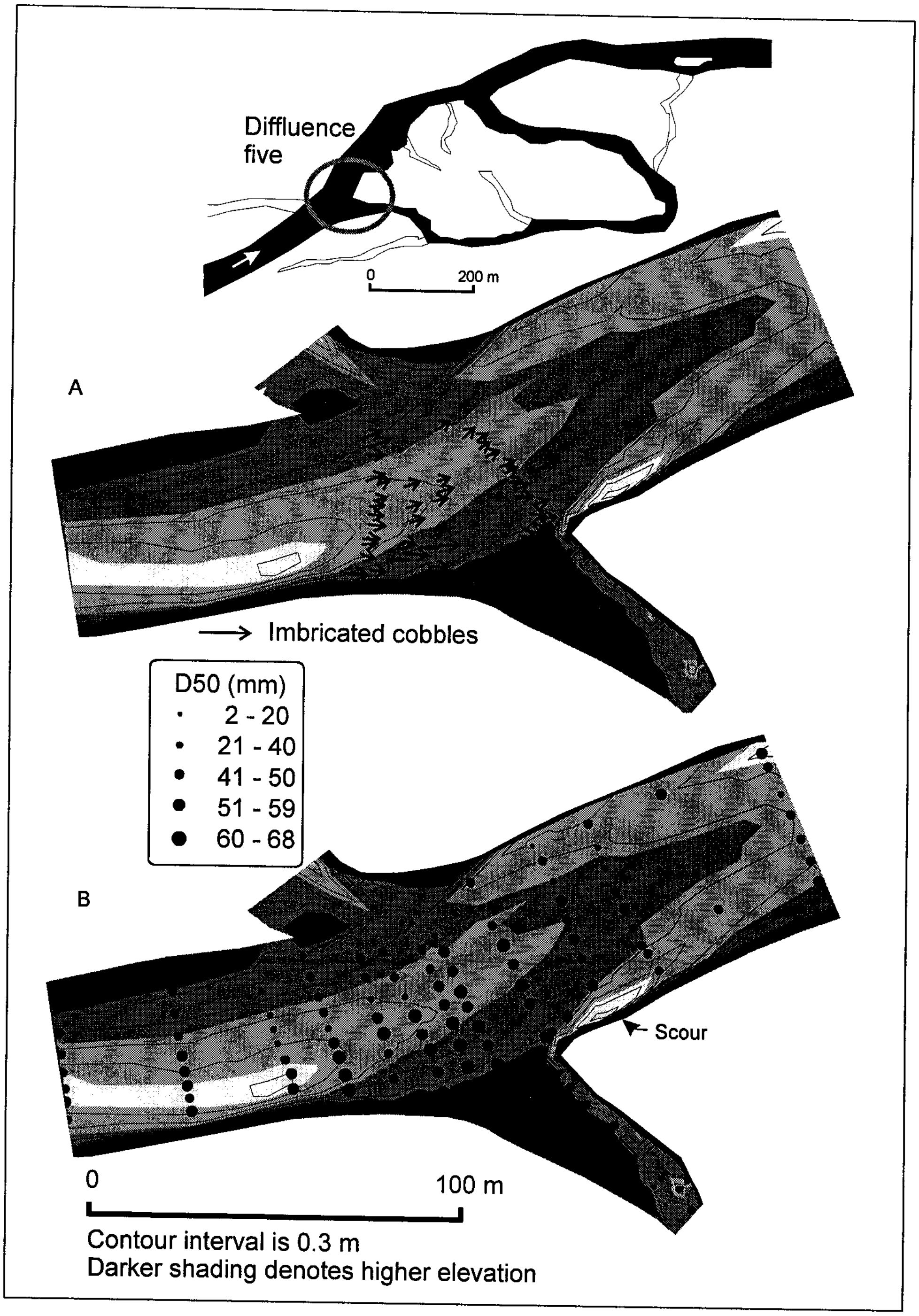
In 2001, the surface D_{50} of the right channel entrance bar was coarse and the coarseness extended upstream of the bar into the pool (Figure 5-7B). Sediment fined downstream onto its tongue and was coarser in the sub-channels around the bar. The grain size was finer at the entrance to the left channel but coarsened downstream of the entrance. Imbrication lines were not surveyed at this diffluence due to high flow conditions.

5.5.2.6. Diffluence abandonment

Diffluence five was created following an avulsion on the outside of a meander bend, now the abandoning channel, into an abandoned channel. The avulsion began before 1945 and remained small until 1965, but became larger than the main-channel by 1983. The former main-channel became quite small by 1999, although still receiving flow during high stages. The right channel was 28 m wide and 831 m long and the left channel was 60 m wide and 319 m long.

The right channel divided from the left channel at an angle of 55° (Figure 5-8A). The morphology of this diffluence was simpler than other diffluences. The entrance to the right channel was perched above the left channel and a small bar occurred at the island head in front of the abandoning channel. A large bar occurred below the diffluence within the left channel. Two small sub-channels occurred at the right and left banks

Figure 5-8. (A) Morphology of diffluence five showing a small island head bar near the entrance to the right channel and a diffuse bar within the left channel downstream of the diffluence. (B) Map showing coarser grain size in the larger channel near the diffluence, and finer grain size within the smaller channel entrance. Flow is from left to right.



Diffluence five
0
200 m
A
Imbricated cobbles
D50 (mm)
2 - 20
21 - 40
41 - 50
51 - 59
60 - 68
B
Scour
0
100 m
Contour interval is 0.3 m
Darker shading denotes higher elevation

around the bar. A linear scour occurred at a 15° angle away from the right bank in the left channel near the diffluence, within one sub-channel. Imbrication lines showed flow directed toward the right channel entrance but most flow remained in the left channel and appeared to diverge over the large bar (Figure 5-8A).

The D_{50} was coarsest just in front of the diffluence within the main-channel and became finer towards the left bank (Figure 5-8B). Finer material also occurred on the large bar downstream of the diffluence and in the entrance to the right channel.

5.6. Discussion

5.6.1 Diffluence angle

My evidence points to a range of diffluence morphology that depends on local site condition and stability. Some variance (adj. $r^2 = 0.23$) in diffluence angle was explained by diffluence order and anabranch length ratio. Diffluence angle may have increased with diffluence order, the location of diffluences in subordinate anabranches, because of the effect of winter ice melting later in smaller secondary channels than main-channels. As order increases, channels become smaller and ice may melt in place instead of breaking up (Smith 1980). When water enters smaller channels of increasing order, flow may be blocked by ice still in place after main-channel break-up and forced into smaller channels at high angles.

Diffluence angle decreases with anabranch length ratio, that is, the diffluence angle decreased as the length of the secondary channels and main-channels became more similar. Longer, inefficient secondary anabranches have higher diffluence angles because they are in the process of being abandoned. Diffluence five (Figure 5-8) displayed a high diffluence angle and is in the process of abandonment. Since local characteristics did not explain a high percent of the variance in diffluence angle, other factors, such as site history, may have a large influence.

5.6.2 Diffluence chronosequence

Reconstructing river dynamics is complicated because the driving processes often occur over decades to centuries, much longer than the duration of one study. One approach to overcome this problem is a chronosequence. A chronosequence differs from a time series in that space replaces time. In this study, diffluences are interpreted in terms of stages of development. Examining the five diffluences as a chronosequence reveals two pathways from diffluence creation to abandonment (Figure 5-9). In the first pathway, diffluences become stable and remain active for long periods after creation, and eventually become unstable and are abandoned (Figure 5-9A). In the second pathway, diffluences become unstable soon after creation and quickly abandon, skipping the stable stage (Figure 5-9B).

The chronosequence approach is prone to two potential sources of error. First, all stages of diffluence development are not represented, and second, variability within each development stage is not represented. Undoubtedly, like missing evolutionary links, diffluence morphologies occur between the ones identified. The selected diffluences are not intended to represent all possible diffluence morphologies or histories but instead are intended to be examples of common morphologies to illuminate diffluence processes. Three summers of field observation on four rivers in the region found no example that did not fit the chronosequence model. Although not observed, it is possible that an unstable diffluence may become stable.

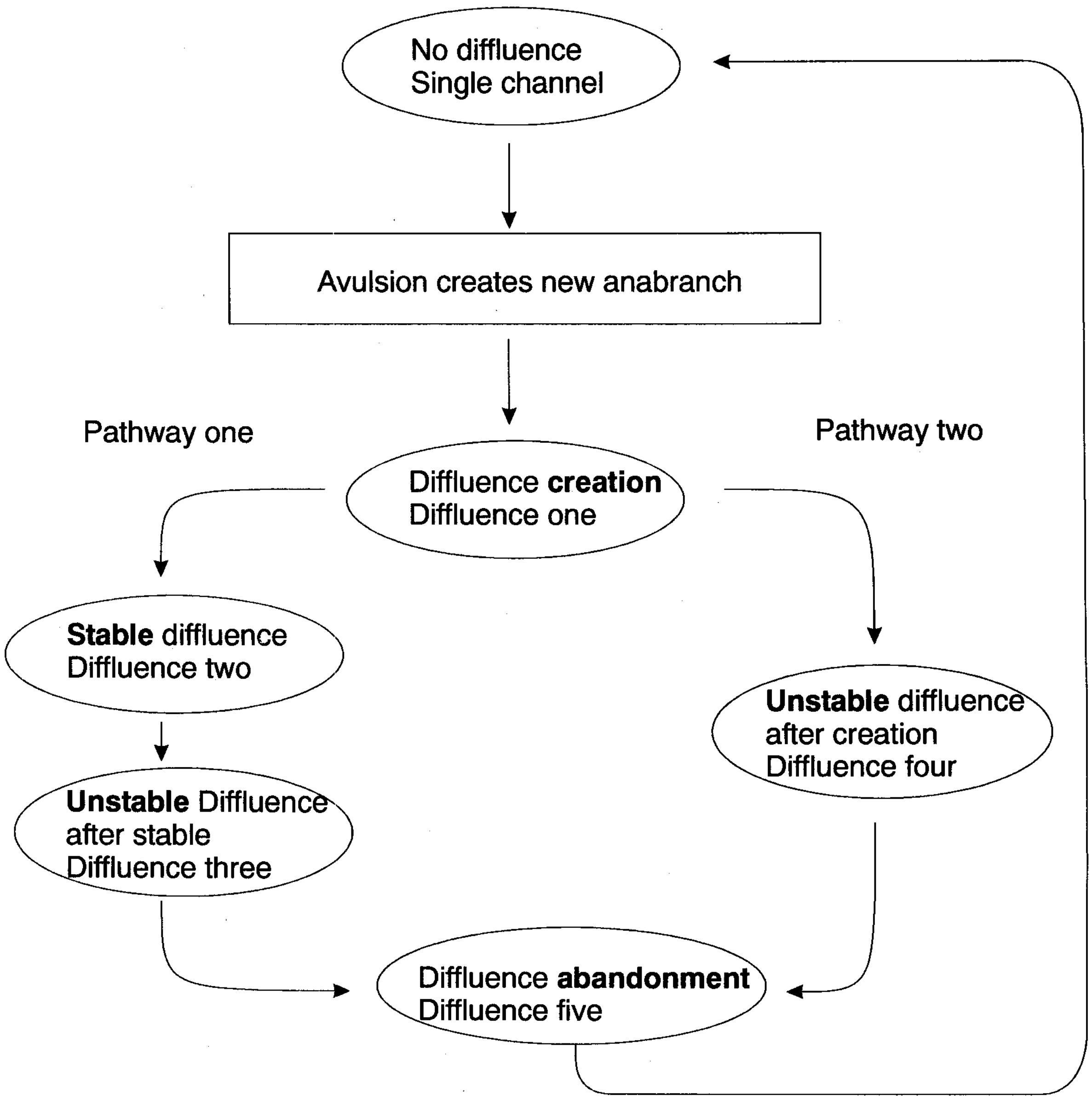


Figure 5-9. Flow-chart displaying two pathways from diffluence creation to abandonment. In pathway one, diffluences are created and then remain stable for long periods before finally becoming unstable and abandoning. In pathway two, diffluences quickly become unstable and abandon following creation and therefore skip the stable stage.

5.6.2.1. Newly created diffluence

Diffluence one is a newly created diffluence. Diffluences are created through deposition of mid-channel bars or through avulsion (Gottesfeld and Johnson-Gottesfeld 1990). Avulsions commonly occur into abandoned channels that are lower in elevation than the floodplain. Avulsions may be triggered by logjams (Gottesfeld and Johnson-Gottesfeld 1990), large floods (Nanson and Knighton 1996), sediment waves (Church 1983), or icejams (Hicks 1993). Icejams, common in the Miramichi basin (Beltaos *et al.* 1989), form downstream of avulsion sites to force water over floodplains into abandoned channels and cause avulsions.

Channel morphology changes as the avulsion develops. For example, at diffluence one, avulsions commonly occur on the outside of meander bends, the location of the channel thalweg (Leddy *et al.* 1993). After the avulsion, sediment transport and flow patterns change so that the super elevation on the outside of the bend (Hickin 1974, Smith *et al.* 1989) breaks down as water flows into the new channel. As seen in diffluence one, a bar may develop on the outside of the bend that ramps up to the avulsion channel entrance and extends downstream within the main-channel (Figure 5-2). The bar forces the thalweg from its usual location near the cutbank to the inside of the bend. During this stage of development, most flow remains downstream within the main-channel but some flow is steered into the secondary channel (Figure 5-2A).

The fine bar is deposited at the island head probably due to a slight backwater created by the obstruction of the island head and aggregation within the main-channel. The riffle may become armoured if it degrades. Discharge in the main-channel downstream of the diffluence decreases following avulsion as flow is lost into the avulsion channel. Little or no coarse particles can be transported into the avulsion channel perched above the main-channel. A positive feedback may be generated as aggradation within the main-channel downstream deflects flow into the avulsion channel. As aggradation increases in the main-channel, more flow is forced into the avulsion channel until equilibrium is reached and bedload is transported into the new channel.

The linear scour in the main-channel may be created by energetic secondary flow downstream of the diffluence due to the obstruction of the island head itself, similar to horseshoe scours around bridge piers. Another possible cause is flow constriction during icejams, common at island heads, form jets of high flow near the bed and enhanced erosion (Beltaos *et al.* 1989). Linear scours of various sizes were observed at all diffluences. The grain size is smallest within the scour due to infilling at low flows. Island head bars may not always develop following an avulsion, but instead the diffluence may become unstable and start to abandon the former main-channel following an aggressive avulsion.

5.6.2.2. Stable diffluence

Diffluence two is interpreted as a stable diffluence. Stable diffluences occur at the heads of islands that survive for many decades or centuries. Imbrication lines show relatively uniform flow exiting the upstream pool, directly toward the island head. Super elevation occurs as flow ‘feels’ the obstruction of the island head and slows. Super elevation creates secondary flow that directs flow into each anabranch. Linear scours found at diffluences are probably created by three-dimensional flow immediately downstream of the island head. Complex flow structures are created by the gradient between the super elevation at the island head and the downstream channel. This is consistent with modelled flow vectors found at the heads of mid-channel bars (Lane *et al.* 1995, Lane and Richards 1998, Nicholas and Sambrook Smith 1999).

At stable diffluences, a large island head bar divides flow of sediment and water into downstream anabranches (Figure 5-3A). Upstream island head accretion deposits were imaged at an island head on the Fraser River, British Columbia using ground penetrating radar (Wooldridge 1999). The upstream dip angle of these deposits ($< 1^{o}$) was within the same range (0.5 to 1.44^{o}) as the slope of island head bars at stable diffluences within New Brunswick. The bar may accrete in a process similar to deposition at the head of mid-channel bars within braided rivers (Ashworth 1996). Sediment is transported by the downstream flow up the bar toward the island head. Smaller particles are redirected into downstream anabranches by secondary flow or topographical steering, while particles that are too large to be redirected stall on the bar surface.

I hypothesize that the island head bar performs the critical function of creating stability at these diffluences by buffering the degradation of the entrance to either anabranch. Deposition on the bar surface causes upstream accretion of new floodplain at the island head. A large volume of sediment is stored upstream of the entrance of each channel within the bar. The stable island head bar at diffluence two was 2.53 times larger (Figure 5-3A) in area and 1.57 times larger in volume than the incipient island head bar at diffluence one (Figure 5-3). At a stable diffluence with a large island head bar, if the entrance of an anabranch begins to degrade into the island head bar, sediment is transported into its entrance, partially blocking it, decreasing the flow of water and preventing further degradation. This also increases the flow into the other channel, allowing it to slightly degrade and capture flow. Without the large island head bar to buffer degradation, one channel entrance could more quickly degrade to capture flow, causing the abandonment of the other channel, leaving it perched at a much higher elevation than the degraded channel at the entrance. This feature may maintain diffluences in a dynamic equilibrium that allow islands within wandering rivers to be semi-permanent features, lasting for many decades or centuries.

Island head accretion rate appears to increase with accretion surface slope (Figure 5-5). The slope of accretion surfaces appears to be positively related to the thalweg long profile slope above diffluences and the average grain size of the riffles at diffluences. The slope of the accretion surfaces may increase with the long profile slope above diffluences because channels with greater hydraulic energy may create stronger secondary flow that deflects more sediment into downstream anabranches. Also, higher energy channels are associated with greater transport rates and may transport larger material onto the accretion surface at a greater rate than lower energy channels. The greater availability of coarser material may also increase the island head slope and in turn increase the accretion rate.

5.6.2.3. Unstable diffluence following stability

After many years of stability, stable diffluences may eventually break down. Instability is instigated by an alteration in sediment transport patterns, which may be caused by changes upstream in entrance geometry due to upstream meander migration, avulsion, or terrace erosion. Diffluence three (Figure 5-6) became unstable after a period of stability. At diffluence three, sediment transport probably increased on the left side of the channel due to the avulsion upstream that created diffluence four (Figure 5-6). This caused deposition of the tongue shaped anabranch entrance bar of fine sediment in the left channel. The island head bar decreased in size and may have been displaced into the left channel to form the anabranch entrance bar. The anabranch entrance bar forced flow to converge into the right channel, causing degradation into the right side of the island head bar and increased flow capture. The bed coarsened at the right channel entrance as smaller clasts were selectively transported during degradation, armouring the bed. The anabranch entrance bar in the left channel may break down to recover stability at this diffluence. Judging by the diffluence geometry and the size of the bar it seems likely that the left channel will become abandoned, with the right channel becoming the only channel.

5.6.2.4. Unstable diffluence following creation

Diffluences may become unstable soon after an avulsion, skipping the stable stage. Diffluence four became unstable soon after its creation. Diffluence four appears to retain much of its pre-avulsion geometry upstream of the diffluence. Sediment appeared to flow into the right channel directly out of the upstream pool (Figure 5-6) but water flow into the right channel decreased substantially following the avulsion. This caused deposition of a coarse tongue shaped anabranch entrance bar within the right channel as most sediment discharge continued into this channel. The left channel gained dominance because it degraded into finer material at its entrance, formed by the tail of the upstream point bar. This diffluence may become stable if the diffluence geometry changes so water and sediment flow is split more evenly between the channels and an island head bar develops. However, due to the relatively high angle between the channels and the large bar blocking the right channel entrance, the right channel will probably eventually be abandoned.

5.6.2.5. Diffluence abandonment

Diffluence five is being abandoned. As diffluence stability further breaks down, a tongue shaped anabranch entrance bar may block an abandoning channel as the discharge of water decreases. Although not seen on the Renous, logjams may work in concert with the bar to block side-channels (Gottesfeld and Johnson-Gottesfeld 1990). The main-channel straightens and further degrades into the island head bar, pushing it downstream (Figure 5-8). The remnant of the island head bar may be seen just ahead of the entrance to the abandoning channel. Bed armouring occurs near the diffluence as coarse sediment within the island head bar is exposed during the degradation process. The finer material is transported downstream but complete removal of the bar from the reach may require some time.

5.7. Conclusions

Diffluence morphology and surface grain size are important to the dynamics of multiple channel systems by controlling the flow of sediment and water into downstream anabranches. Some variance in diffluence angle (adj. $r^2 = 0.21$) was explained by their location in subordinate anabranches and the relative length of anabranch pairs. Since local anabranch characteristics did not explain a high percent of the variance in diffluence angle, other factors, such as site history, may have a larger influence.

A chronosequence model displayed two pathways from diffluence creation to abandonment, one with a stable stage lasting for decades to centuries before instability and abandonment and one without a stable stage that becomes unstable following creation and quickly abandons. Diffluences created by avulsions may develop a bar at the island head that may grow to become an island head bar if the diffluence stabilizes. Island head bars divide flow into anabranches and are hypothesized to provide a reservoir of sediment that buffers degradation of either entrance anabranch, thereby maintaining anabranch stability.

At stable diffluences, island head bars accrete upstream between 0.9-2.5 m/yr, as determined through dendrochronology. The bar accretes as larger particles are deposited on the upstream facing accretion surfaces while smaller particles are redirected into anabranches by secondary flow, a process similar to the upstream accretion of mid-channel bars in braided rivers (Ashworth 1996). At unstable diffluences, anabranch entrance bars form to block flow into one anabranch, increasing instability. Similar bars were also seen at the heads of abandoned channels on the wandering Morice River, British Columbia (Gottesfeld and Johnson-Gottesfeld 1990).

The location of a large bar upstream or downstream of diffluences enhances diffluence stability or instability, respectively. Diffluences are dynamic river elements that may remain stable over long periods or they may destabilise resulting in the abandonment of one anabranch. Diffluences are integral components of wandering river systems that control the flow of water and sediment into downstream anabranches.

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6. Chapter six: Summary and conclusions

This dissertation provides a better understanding of wandering river dynamics by investigating the characteristics and regulating mechanisms of wandering rivers at three spatial-temporal scales. This information is critical to manage side-channel habitat vital for salmonid species and for appropriate engineering of multiple channel rivers.

6.1. Answers to research questions

In the introduction of the dissertation two general questions were posed. 1) What are the characteristics of wandering rivers in the Miramichi drainage? 2) What processes influence these characteristics? Figure 6-1 shows the relationship between the scales of investigation and the processes found to influence the characteristics at that scale. The processes occurring at a smaller scale impact the characteristics of the scale above.

At the largest scale of the river pattern, (chapter two, figure 6-1) investigated three questions: (1) what regional factors influence the location of wandering rivers? (2) What determines differences in pattern characteristics among wandering rivers of different sizes? (3) What are the effects of avulsion triggers, specifically icejams on the wandering river pattern?

For a river to become wandering three factors appear to be needed: (1) wide valleys, (2) channel energy levels between braiding and meandering, and (3) avulsion triggers. Principal component analysis showed that larger rivers within the Miramichi displayed greater anabranching intensity than smaller rivers. This appears to be related to higher stages during icejams within the larger rivers than small rivers, creating a greater number of avulsions. This study suggests that river patterns may vary with size.

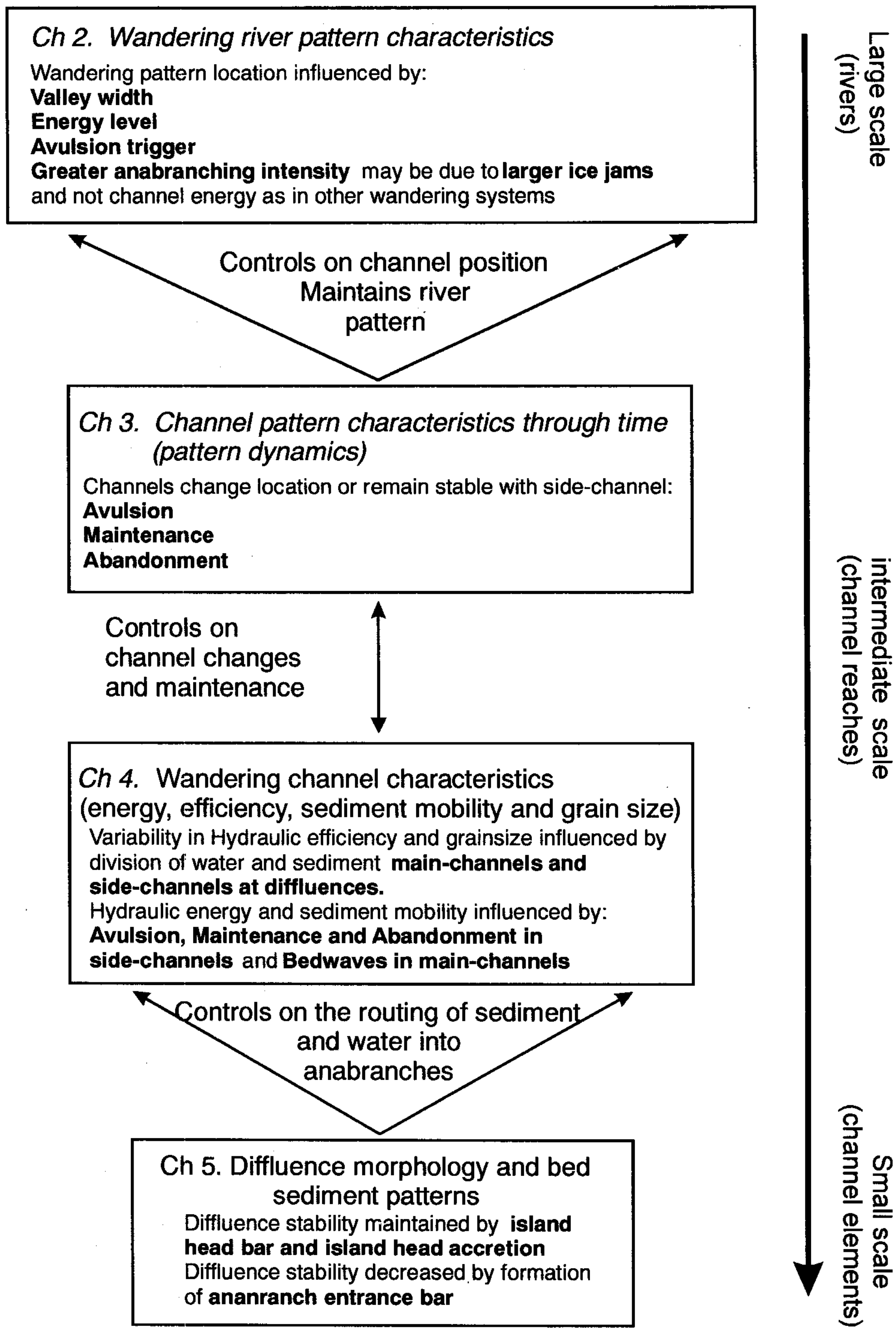


Figure 6-1. Flow chart displaying the nesting of analysis scales. Dissertation chapters decrease in scale from the river pattern, to channels within the pattern, to diffluences that divide flow into anabranches. Processes found to control the dynamics at each scale are presented within the boxes.

At the intermediate scale of the channels themselves (chapter three, Figure 6-1), the changes in individual channels through time within one river were quantified and analyzed. Chapter three investigated two research questions: (1) can the pattern characteristics of wandering rivers be in dynamic equilibrium? (2) If so how is dynamic equilibrium maintained?

Chapter three presented a temporal investigation of the wandering Renous River. Within the Renous River study area, channel creation and abandonment frequencies were similar over the 50 years of analysis, indicating that the wandering pattern is in a state of dynamic equilibrium. How the dynamic equilibrium is maintained was illustrated through the development of a conceptual model called the anabranch cycle showing the conditions necessary for the creation, maintenance and abandonment of side channel.

Also at the intermediate scale of channels (chapter four, Figure 6-1), characteristics among all channels within one river were analyzed. Chapter four investigated two questions: (1) how do bedwaves influence the energy and sediment mobility within wandering river channels? (2) How do the processes of the creation, maintenance and abandonment of side-channels influence energy and sediment mobility within wandering river channels?

Principal component analysis determined that side-channel dynamics and bedwaves in main-channels influence the hydraulic energy and sediment mobility characteristics within wandering river channels. Variability in hydraulic energy and sediment mobility within side-channels depended on their formation, maintenance and abandonment. Variability of energy and sediment mobility within main-channels was influenced by the formation of bedwaves within some main-channels.

Finally, at the smallest scale of individual channel elements (chapter five, Figure 6-1), the range of island head diffluence morphologies and bed grain size distributions were determined and analyzed using a chronosequence. Chapter five answered two questions: (1) how is the stability of diffluences reflected in their morphology and surface grain size? (2) What are the processes that maintain stable diffluences through time?

Diffluences are dynamic river elements that may remain stable over long periods or may destabilise resulting in the abandonment of one anabranch. Diffluence morphology is directly related to their stability. Diffluence stabilization or destabilization is related to a large bar located just upstream or downstream of the diffluence apex, respectively. A large bar located directly upstream of stable diffluences accretes upstream and enhances diffluence stability.

The dissertation illustrates that within wandering rivers, processes occurring at different spatial and temporal scales interact to create and maintain the wandering pattern. Water and sediment is routed into anabranches at diffluences, the amount of which depends on the diffluence geometry and stability. Processes occurring within the anabranches, spatially and temporally, determine whether anabranches will grow, be stable or become abandoned. The pattern itself may differ among rivers depending on the magnitude and frequency of events that create or abandon anabranches. This creates a complex river pattern that varies across rivers (inter-river) and spatially and temporally within a river (intra-river).

6.2. Miramichi type wandering rivers

I propose that the wandering rivers within the Miramichi basin of New Brunswick are a new genetic-type of the wandering river pattern, with a genesis distinct from wandering rivers with high sediment transport rates and avulsions caused by thalweg shoaling. Miramichi wandering rivers appear to be closer to meandering than braiding, with infrequent mid-channel bars, energy levels within the same range as gravel bedded meandering rivers, and with width-depth ratios and channel migration rates lower than other wandering rivers. Wandering Miramichi rivers form where valley width provides space for the formation of multiple channels. Multiple channels form mainly by avulsion caused by large frequent, intense, icejams formed mid-winter or during the spring melt. Miramichi type wandering rivers may be identified by energy levels occurring at the low end of wandering, near meandering, with low width-depth ratios, few mid-channel bars and the presence of icejams.

Multiple channel sections of wandering rivers within the Miramichi are usually formed by avulsions. Within the Miramichi, frequent icejams trigger avulsions by forcing flow over the floodplain and into abandoned channels. However, avulsions may also be triggered by thalweg shoaling from mid-channel bar growth, logjams or infrequent large floods. I suggest that all wandering rivers require triggers to cause avulsions that produce channels around semi-permanent islands with mature forest. Enough energy is needed during an avulsion trigger to strip the floodplain and form a new channel, even if an abandoned channel is utilized. Wandering rivers occur within a band of specific stream power between meandering and braiding (Figure 6-2). I suggest that this band corresponds to the energy levels where avulsion triggers produce enough energy to strip

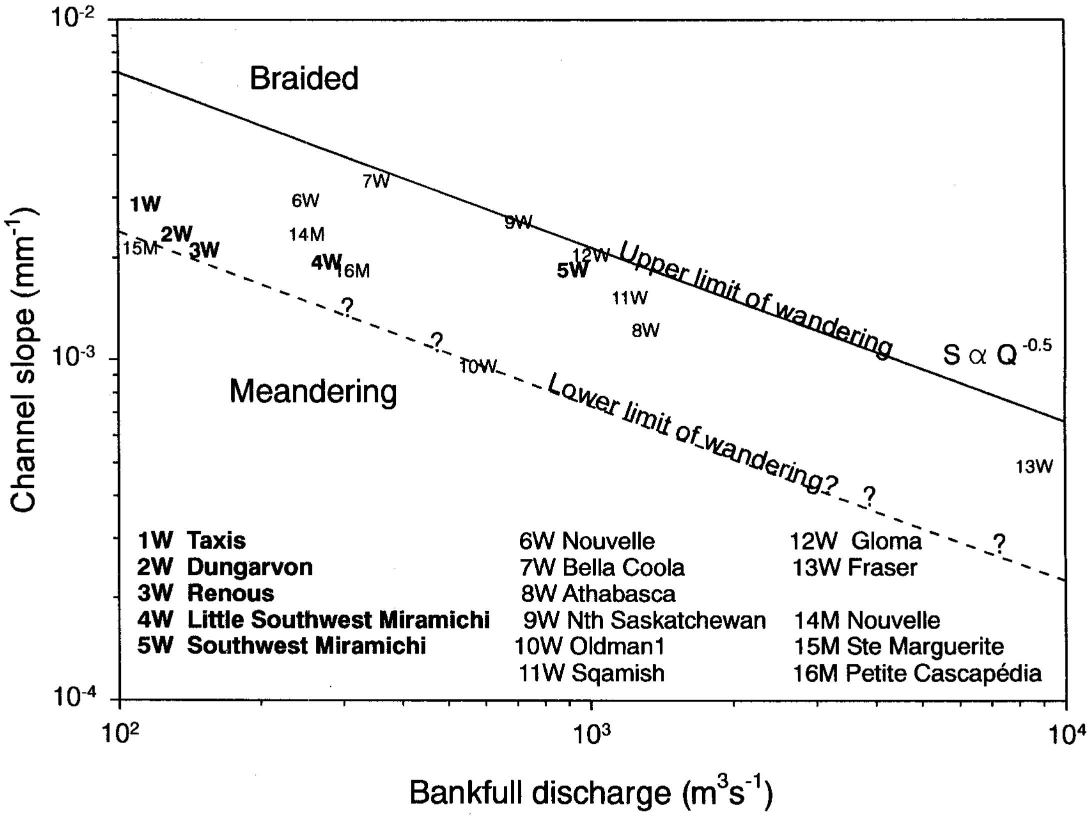


Figure 6-2. Plot of slope and discharge (bankfull or mean annual flood) displaying zones where wandering, meandering and braiding occur. I suggest that wandering occurs in the zone where potential avulsion-triggering events have enough energy to strip the floodplain.

the floodplain. The upper limit of this band is controlled by energy levels large enough to erode channel banks, widening channels and causing braiding. The lower limit of this band is controlled by energy levels too low to cause avulsions, even when an avulsion trigger occurs and overtops the floodplain. If frequent avulsion triggers occur within a river but its energy level is not in the band where wandering rivers occur, a wandering river will not form. Also, if a river is in the band of wandering river energy level but avulsion triggers do not occur, a wandering river will not form. In this way, energy levels and avulsion triggers work in concert to create and maintain wandering rivers. The location of wandering rivers is therefore dictated by the valley slope that creates energy levels between braiding and meandering and the presence of avulsion triggers.

6.3. Management of wandering rivers

The ability of a stream to produce fish depends not only on the amount and accessibility of habitat, but also on the distribution of habitat types. Wandering rivers offer diverse habitat that changes through the seasons. This project has added to the understanding of the temporal changes in wandering rivers as well as furthering the understanding of the organization of channel energy and hydraulic geometry within these rivers. This increased knowledge will aid in conserving these vital habitats.

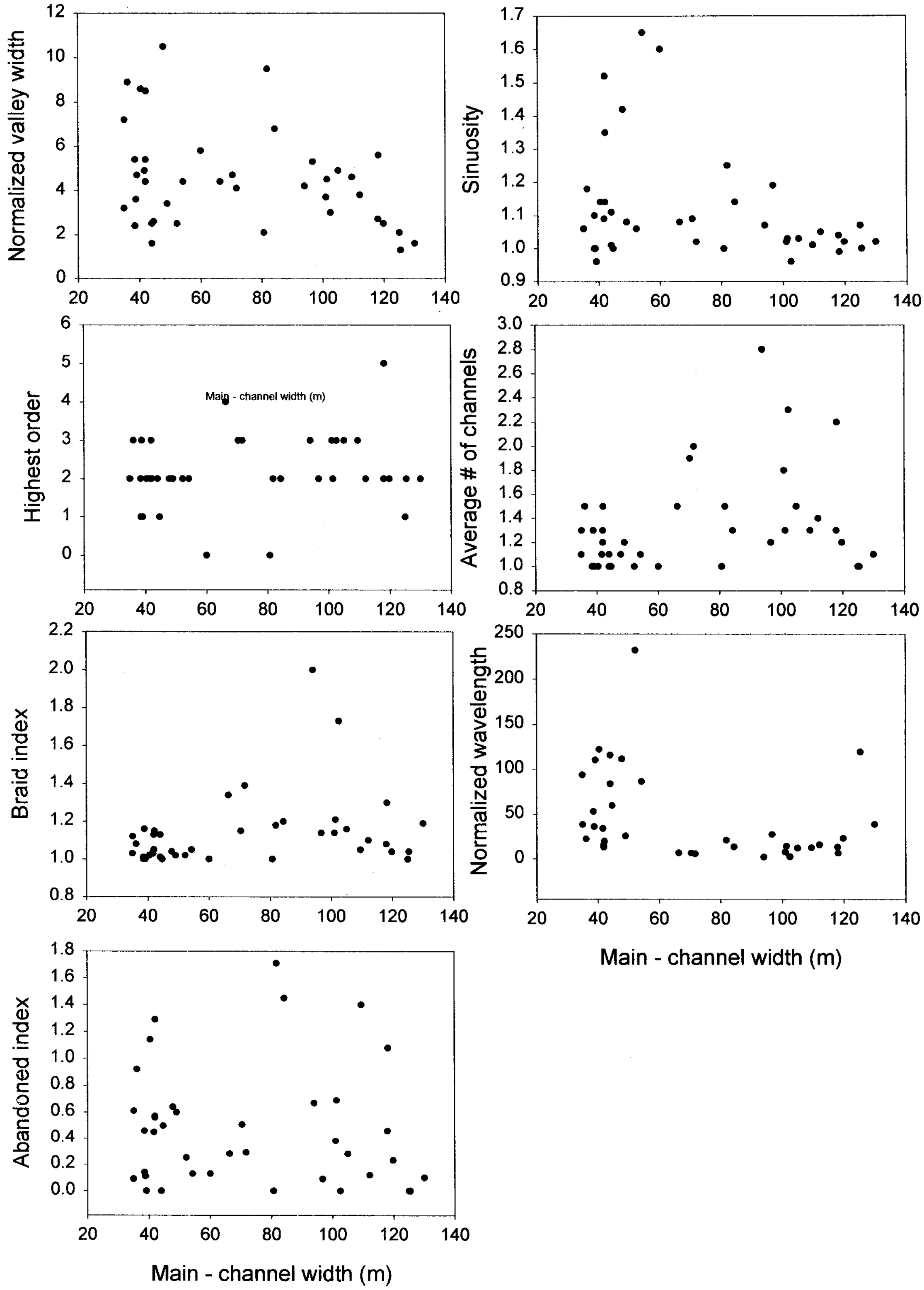
To maintain wandering systems, avulsion triggers should be allowed to occur. This may mean creating artificial floods from dams or allowing icejams to occur. Avulsions should be allowed to happen when they initiate. To limit flood damage during the natural maintenance of multiple channels by high stages, construction should be limited on these floodplains. Also, where possible, roads should be built on high ground to limit interference with natural river processes and prevent flooding. Abandoned channels should not be infilled so that they may provide future avulsion sites and back channel habitat.

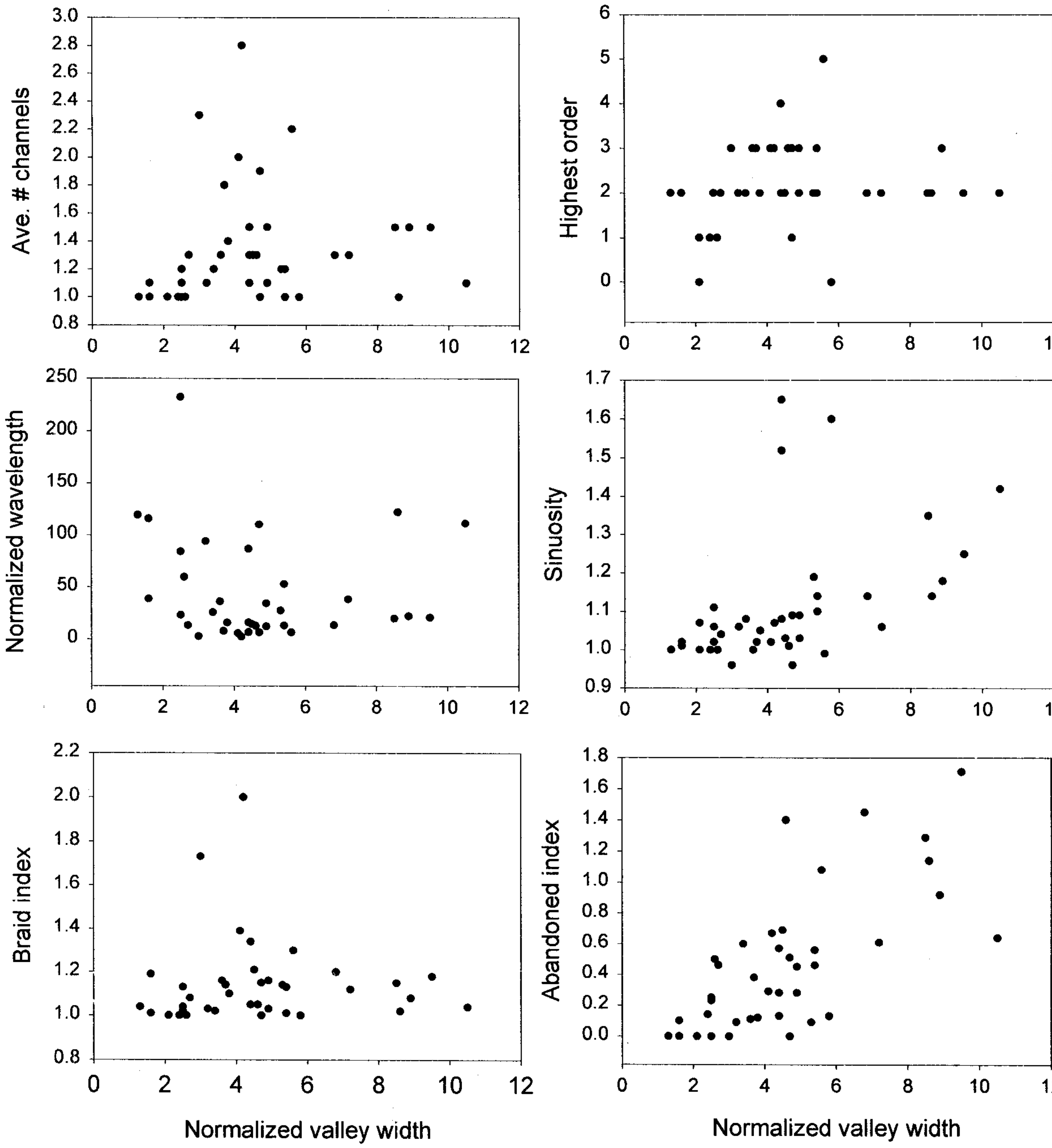
Where side-channels are created to enhance habitat for fish, care should be taken to construct stable diffluences. Diffluences may be stable when built with an angle of approximately 40°. An island head bar should be constructed from coarse material that slopes upstream at 0.0025 mm^{-1}. Upstream of the diffluence, the channel should be deep and straight, with the thalweg gently turning into the main-channel.

Although still poorly understood, bedwaves are an important aspect of the long profile of wandering rivers. The creation of side-channels may also create bedwaves under certain conditions yet to be fully defined. Bedwaves occurring in association with a diffluence will cause the slope of the bed upstream of a diffluence to decrease, while causing an increase in bed slope downstream of the diffluence. The decrease in bed slope above the diffluence may enhance flooding because of channel aggradation and enhanced icejams and logjams. Rivers near the transition between wandering and braiding, where sediment mobility is high and numerous mid-channel bars occur, the increase in slope downstream of the diffluence may cause the channel to widen and increase its width-depth ratio and become less stable. Where rivers are not near the transition, where the channel bed is armoured and few mid-channel bars occur, the channel downstream of the diffluence may decrease in width and width-depth ratio and become more stable. More research is needed into the processes creating bedwaves so that rivers may be managed more effectively.

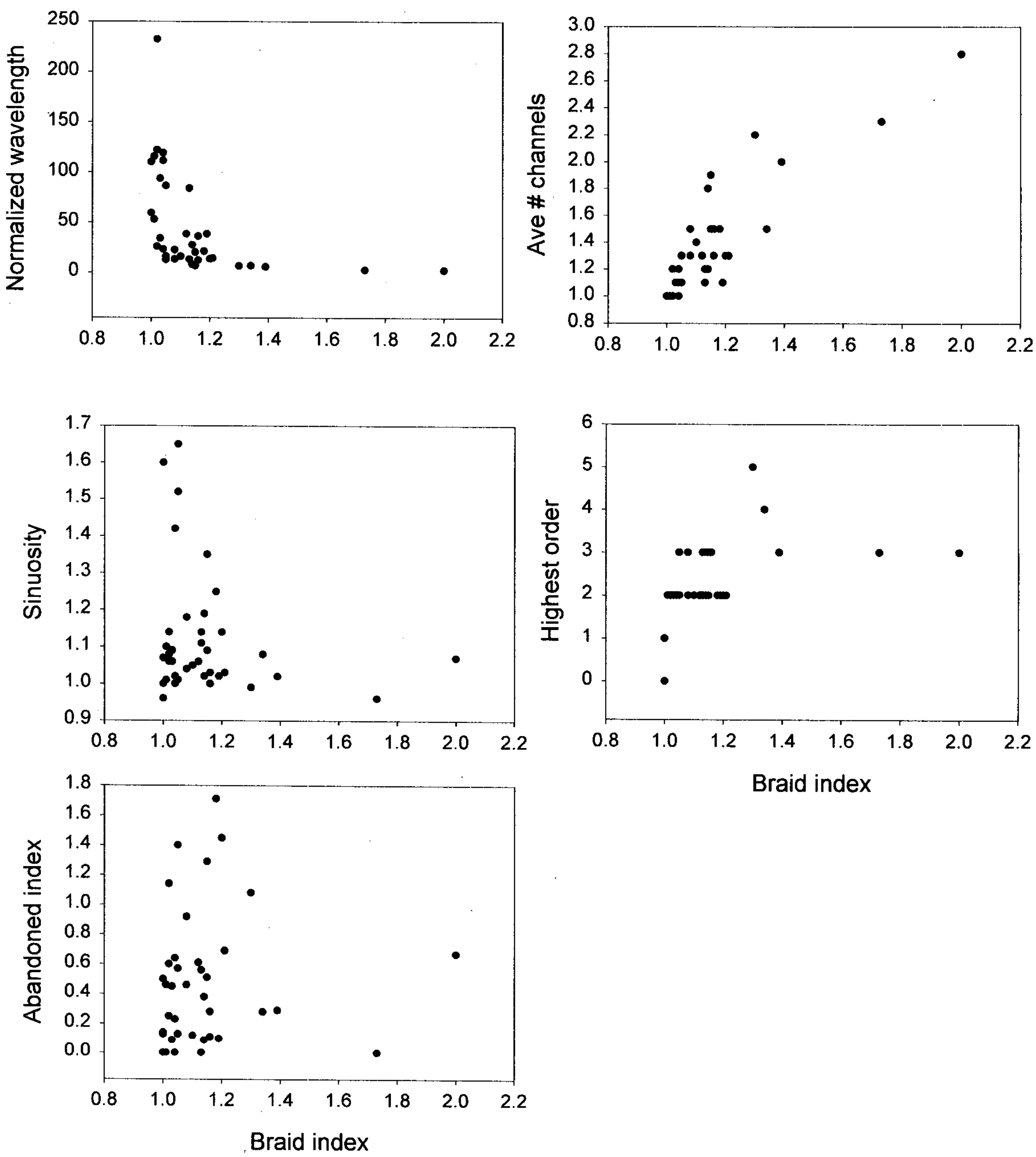
7. Appendix

Appendix 1. Scatter plots of variables correlated in chapter 2.

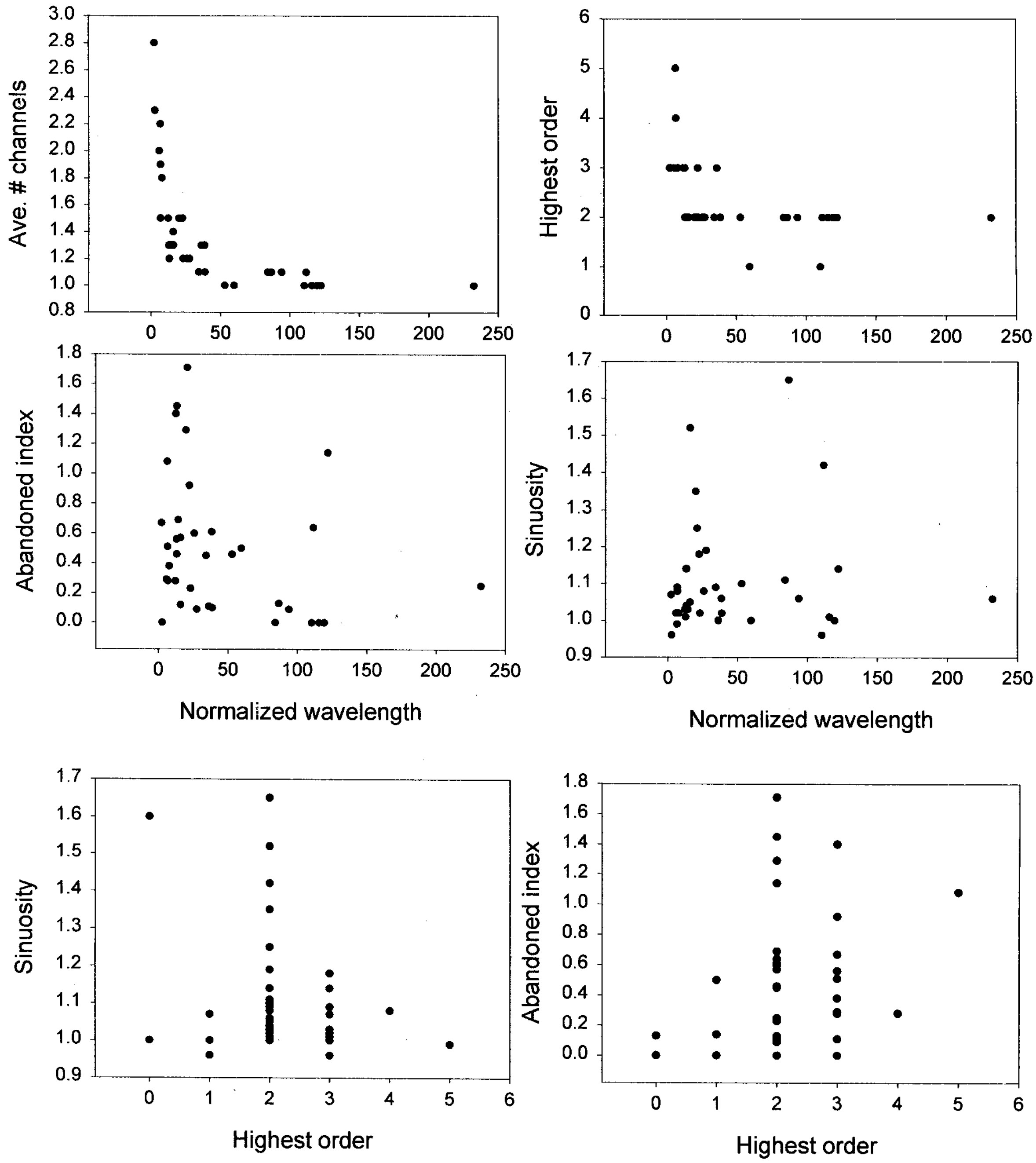

Normalized valley width
Sinuosity
Highest order
Main - channel width (m)
Average # of channels
Braid index
Normalized wavelength
Main - channel width (m)
Abandoned index
Main - channel width (m)



Ave. # channels
Highest order
Normalized wavelength
Sinuosity
Braid index
Abandoned index
Normalized valley width
Normalized valley width



Normalized wavelength
Ave # channels
Sinuosity
Highest order
Abandoned index
Braid index
Braid index


Ave. # channels
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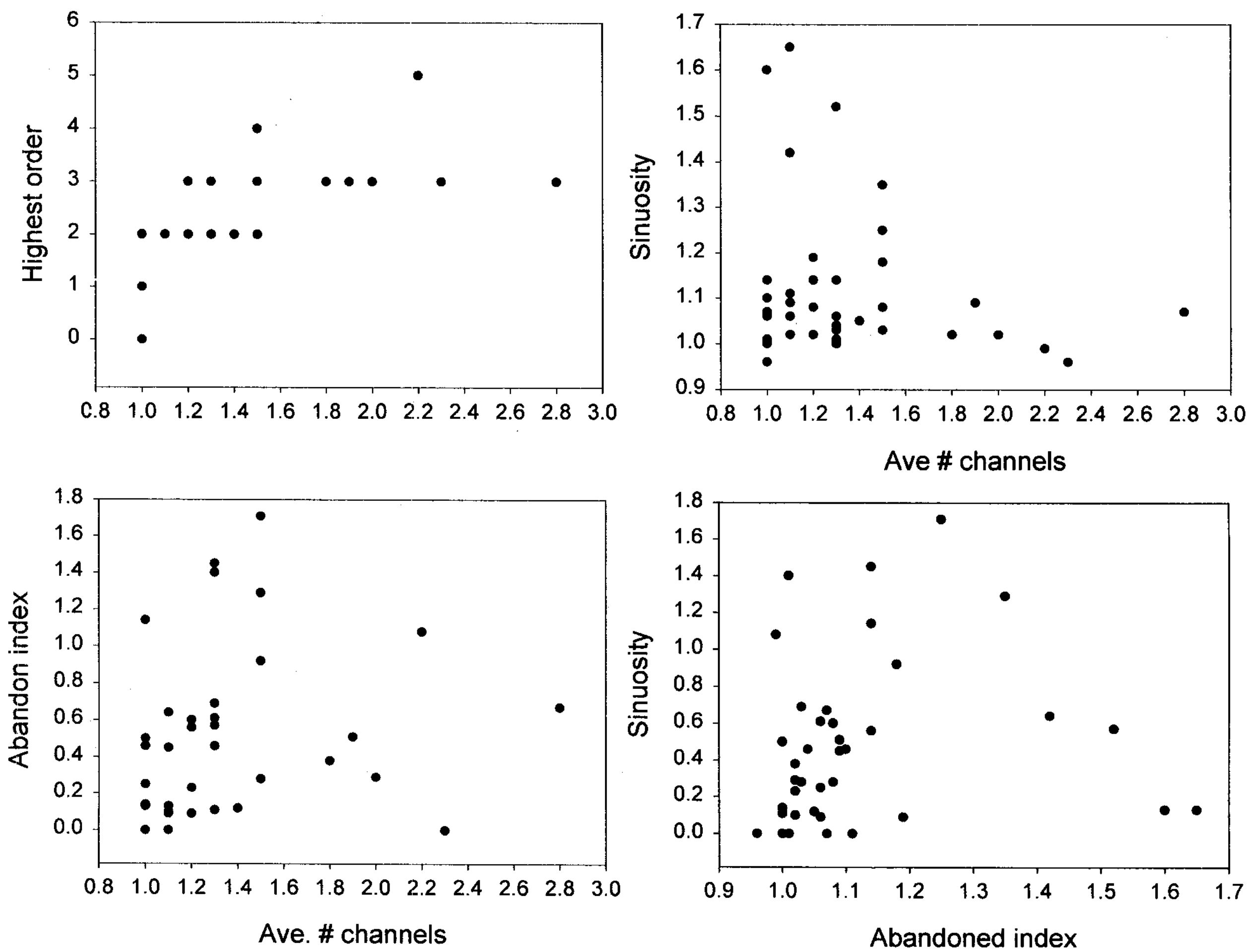
Normalized wavelength
Sinuosity
Abandoned index
Highest order
Highest order


Highest order
0
1
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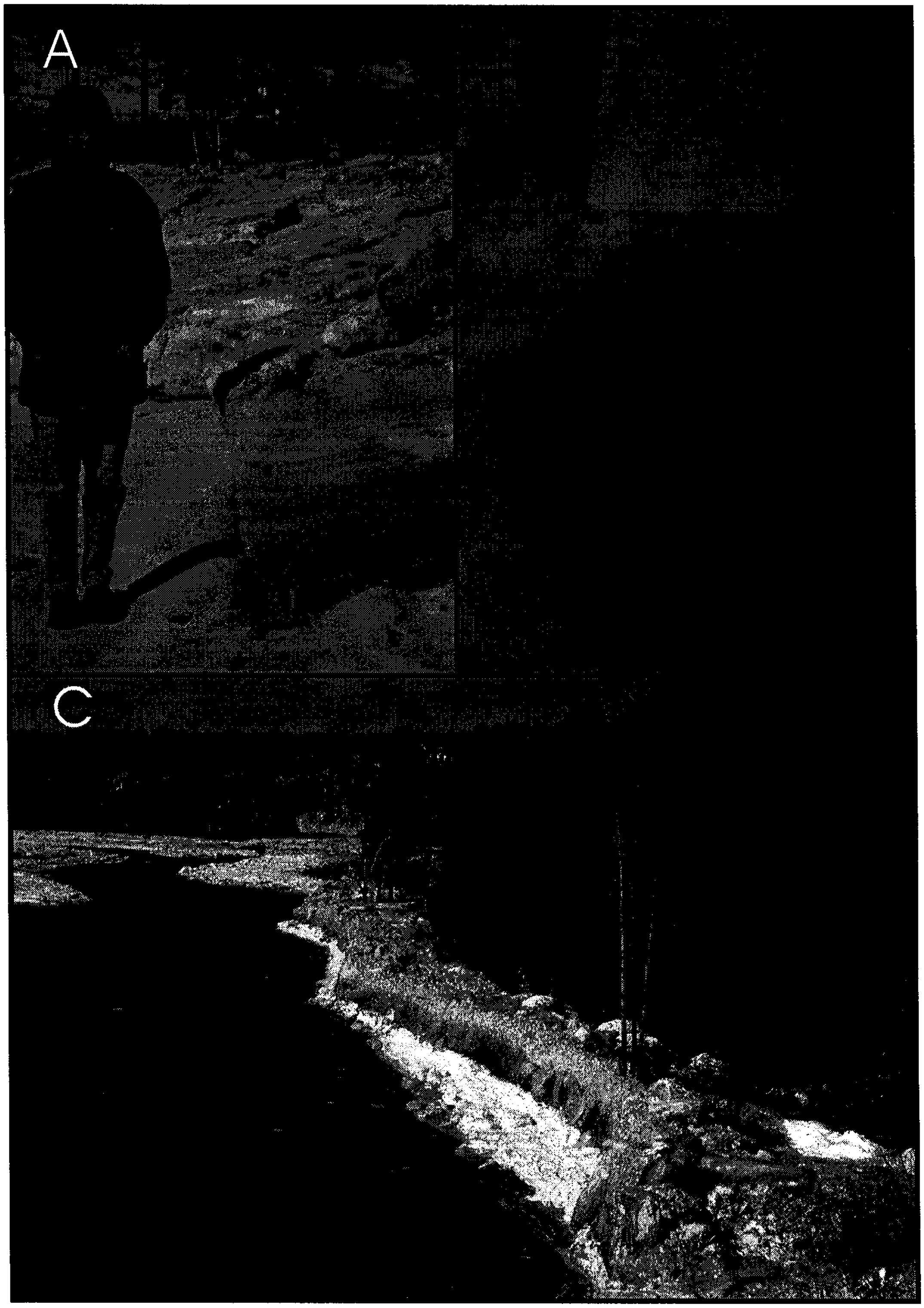
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
Sinuosity
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
Ave # channels
Abandon index
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
Ave. # channels
Sinuosity
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
Abandoned index

Appendix 2. Raw data from Renous River used in principal component analysis.

Downstream distance	Reach type	Depth (m)	Water slope (%)	Bed slope (%)	Bankfull width (m)	Width-depth ratio	D50 (mm)	ff
125	Confined	2.15	0.4	0.38	60	28	82	0.09
573	Confined	1.75	0.15	0.16	65	37	88	0.10
1190	Confined	1.76	0.29	0.32	62	35	77	0.09
1703	Confined	1.76	0.26	0.15	59	33	85	0.10
2059	Secondary	1.67	0.42	0.54	29	17	64	0.09
2059	Primary	1.24	0.58	0.5	58	47	84	0.12
2567	Single	1.99	0.19	0.06	70	35	77	0.09
3044	Avulsion	0.93	0.38	0.38	15	16	56	0.11
3072	Primary	1.48	0.48	0.45	44	30	73	0.10
3446	Abandoned	1.61	0.16	0.18	43	27	72	0.09
3446	Primary	1.82	0.2	0.36	47	26	77	0.09
3649	Avulsion	1.00	0.47	0.49	16	16	59	0.11
3975	Single	1.68	0.25	0.26	58	34	75	0.09
4520	Primary	1.73	0.29	0.23	45	26	79	0.10
4520	Secondary	1.40	0.37	0.37	39	27	65	0.10
5023	Single	1.61	0.27	0.3	55	34	93	0.11
5408	Secondary	1.56	0.28	0.54	30	19	58	0.09
5408	Primary	1.53	0.21	0.18	48	31	73	0.10
5884	Single	1.37	0.23	0.17	59	43	71	0.10
6441	Primary	1.46	0.23	0.31	43	30	69	0.10
6441	Secondary	1.25	0.31	0.32	50	40	73	0.11
6920	Single	2.02	0.13	0.09	64	32	83	0.09
7479	Single	1.91	0.19	0.19	63	33	84	0.09
7684	Avulsion	1.62	0.4	0.48	11	7	50	0.08
8033	Abandoned	N/A	0.24	0.23	7	N/A	N/A	N/A
8033	Primary	1.49	0.3	0.27	64	43	55	0.08
8351	Secondary	1.67	0.2	0.27	33	19	53	0.08
8351	Primary	1.69	0.2	0.19	41	24	52	0.08
8712	Avulsion	1.52	0.33	0.22	14	9	54	0.08
8748	Single	N/A	0.24	N/A	47	N/A	N/A	N/A
8932	Secondary	2.07	0.19	0.25	27	13	38	0.06
8932	Primary	2.26	0.23	0.29	40	18	72	0.08
9070	Single	2.21	0.08	0.07	60	27	59	0.07
10123	Single	2.39	0.19	0.17	62	26	60	0.07
10611	Abandoned	1.31	0.13	0.11	28	21	32	0.07
10611	Primary	1.81	0.23	0.23	60	33	56	0.08
11402	Single	1.45	0.09	0.2	72	49	45	0.08
11791	Primary	1.74	0.2	0.21	68	39	47	0.07
11791	Abandoned	N/A	0.11	0.13	15	N/A	N/A	N/A
12254	Single	1.60	0.22	0.06	60	37	49	0.08
12761	Primary	1.81	0.19	0.19	67	37	47	0.07
12761	Secondary	2.34	0.17	0.25	42	18	45	0.06
13744	Confined	1.96	0.06	0.17	47	24	37	0.06
14371	Confined	1.44	0.24	0.21	54	38	55	0.09
14884	Confined	1.94	0.21	0.17	57	29	65	0.08

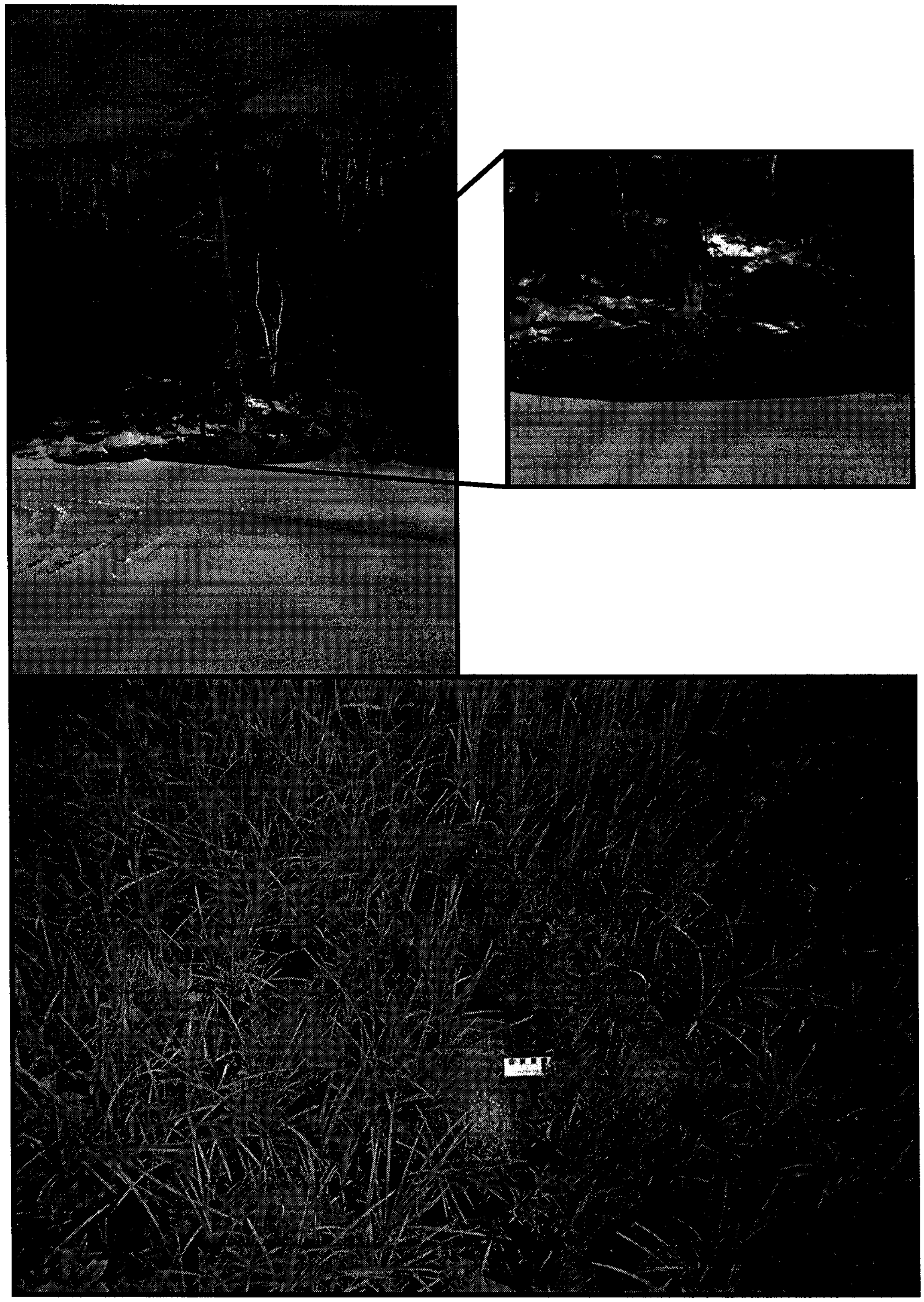
Downstream distance	Reach type	Shear stress (N m^{-2})	Mobility ratio	Est. reach discharge (m^3 s^{-1})	Sp. stream power (W m^{-2})	Est. unit sed. transport (gs m^{-1})	Est. D50 of bedload (mm)
125	Confined	84	1.0	148	97	5.300	79
573	Confined	26	0.3	148	33	0.005	76
1190	Confined	50	0.6	148	68	0.644	70
1703	Confined	45	0.5	148	64	0.382	72
2059	Secondary	69	1.1	60	84	4.532	62
2059	Primary	70	0.8	88	86	2.586	79
2567	Single	37	0.5	148	39	0.140	65
3044	Avulsion	35	0.6	26	65	0.371	51
3072	Primary	70	1.0	121	131	3.551	69
3446	Abandoned	25	0.3	66	24	0.017	58
3446	Primary	36	0.5	81	34	0.099	68
3649	Avulsion	46	0.8	28	79	1.195	56
3975	Single	41	0.6	148	63	0.270	67
4520	Primary	49	0.6	87	55	1.232	60
4520	Secondary	51	0.8	60	57	0.922	73
5023	Single	43	0.5	148	71	0.135	74
5408	Secondary	43	0.7	57	53	0.914	55
5408	Primary	32	0.4	90	39	0.059	61
5884	Single	31	0.4	148	56	0.059	61
6441	Primary	33	0.5	75	39	0.138	55
6441	Secondary	38	0.5	73	45	0.229	63
6920	Single	26	0.3	148	29	0.009	64
7479	Single	36	0.4	129	38	0.091	70
7684	Avulsion	64	1.3	18	68	5.698	48
8033	Abandoned	N/A	N/A	15	49	N/A	N/A
8033	Primary	44	0.8	132	61	1.057	52
8351	Secondary	33	0.6	65	39	0.374	49
8351	Primary	33	0.6	83	40	0.416	48
8712	Avulsion	49	0.9	34	80	1.821	52
8748	Single	N/A	N/A	148	74	N/A	N/A
8932	Secondary	39	1.0	57	39	1.770	35
8932	Primary	51	0.7	91	51	1.007	69
9070	Single	17	0.3	148	19	0.003	49
10123	Single	44	0.7	148	44	1.004	57
10611	Abandoned	17	0.5	37	17	0.085	25
10611	Primary	41	0.7	111	42	0.877	53
11402	Single	13	0.3	148	18	0.002	38
11791	Primary	34	0.7	120	35	0.615	44
11791	Abandoned	N/A	N/A	27	18	N/A	N/A
12254	Single	35	0.7	148	53	0.663	46
12761	Primary	34	0.7	82	23	0.604	44
12761	Secondary	39	0.9	66	26	1.113	43
13744	Confined	12	0.3	148	19	0.002	33
14371	Confined	34	0.6	148	64	0.297	50
14884	Confined	40	0.6	148	54	0.339	55

Appendix 3. Photographs of Miramichi wandering river characteristics.

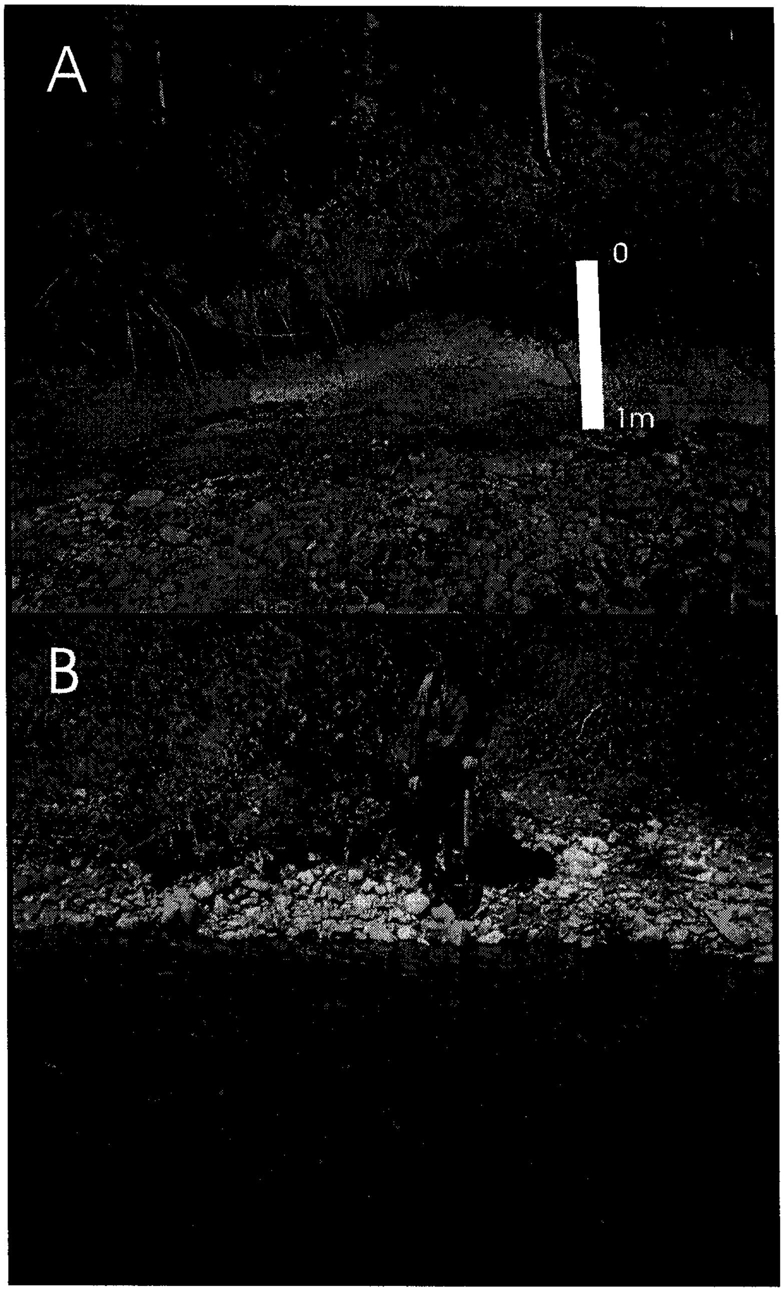


Appendix 3 (A). A. Ice on floodplain following icejam on the Southwest Miramichi river in the spring of 1998. B. Core hole through ice on the Little Southwest Miramichi River in February 2000. Average ice thickness was found to be 0.62 m. C. Wall of ice at the channel bank following icejam on the Southwest Miramichi River in the spring of 1998.

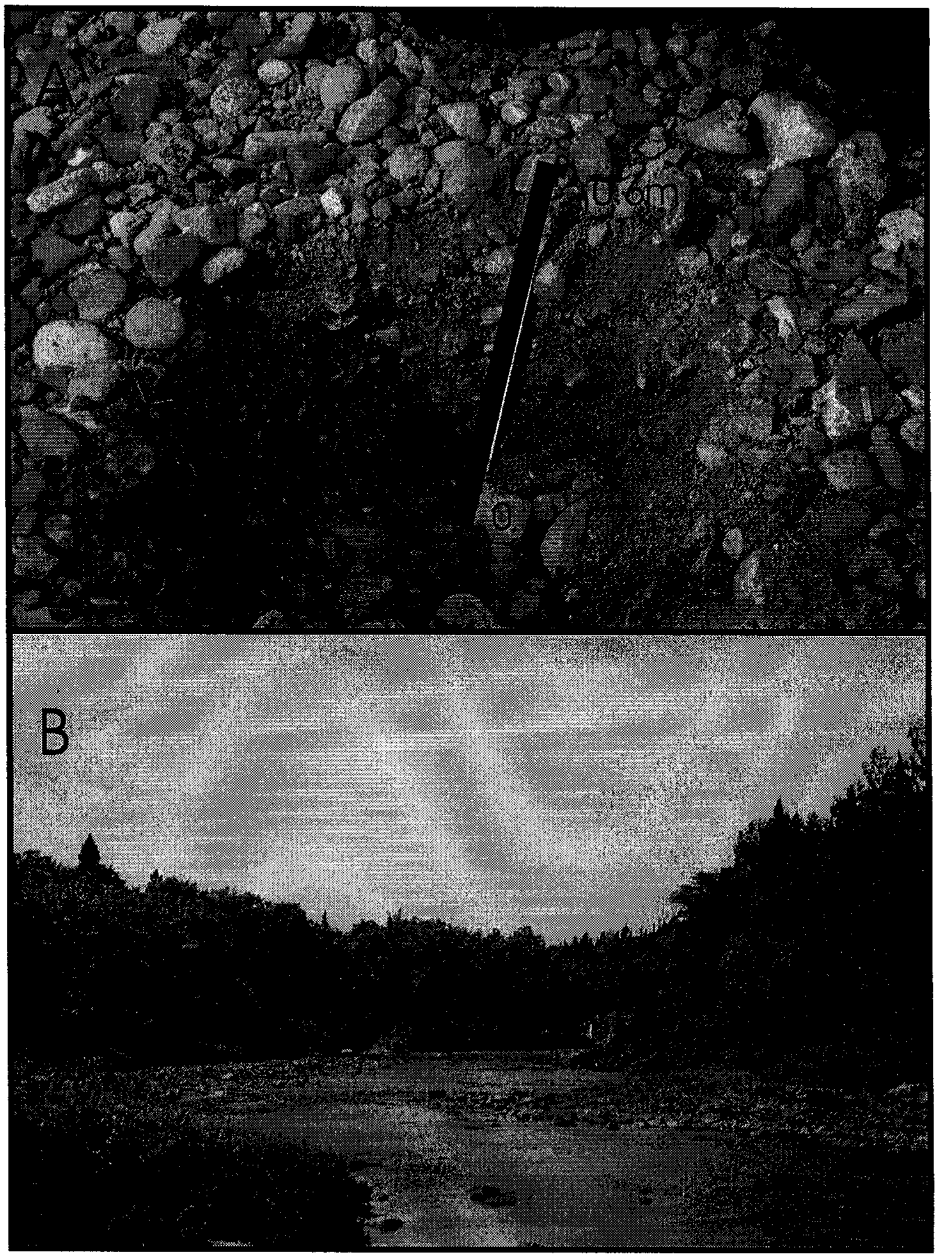
Appendix 3 (B). A. Icejam on the Southwest Miramichi in the spring of 1998.



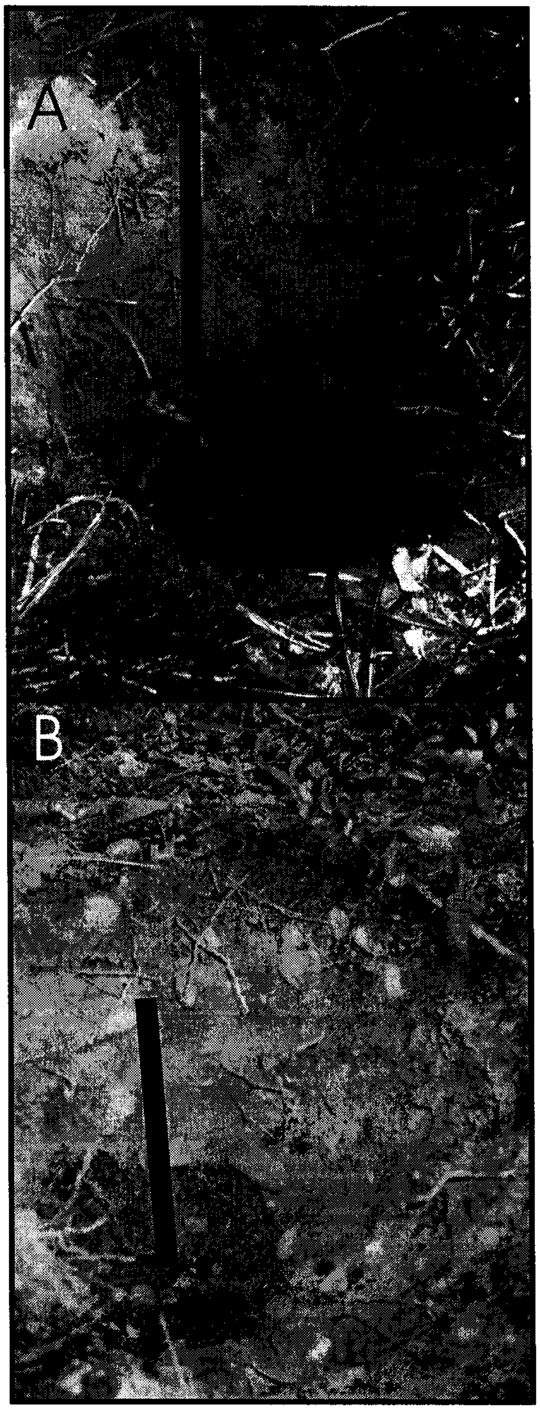
Appendix 3 (C). A. Pine tree on the Taxis River with large scar facing channel. Scar is thought to be formed as icejams pass and scrape away bark and wood. B. Boulder pavement on the Renous River channel edge. Boulder pavements are formed as ice moves past the channel edge and the weight of the ice forces the boulders into the ground.



Appendix 3 (D). A. Channel fill observed on a cutbank of the Renous River. B. Island head accretion deposit on the Renous River. Note deposit continues under water.



Appendix 3 (E). A. Pit exposing an island head accretion deposit in the Renous River channel. B. Riffle on the Renous River. Note the exposed large boulders and the lack of gravel bars.



Appendix 3 (F). A. Pit exposing the Renous River floodplain overbank deposits of sand overlying channel gravels. B. Pit exposing an island head accretion deposit in the Renous River floodplain. (Black bars are approximately 0.6 m long).