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Wandering Miramichi rivers, New Brunswick, Canada

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Abstract

Six rivers within the Miramichi basin of New Brunswick display long sections with multiple channels that surround semi-permanent islands, linked by single channels. This type of anabranching river may be termed wandering, displaying a similar planimetric pattern to wandering rivers in western Canada. This research addresses three objectives: (1) to provide a detailed description of the location, pattern characteristics and boundary conditions of wandering Miramichi rivers; (2) to compare the pattern characteristics among wandering rivers within the Miramichi basin and to other wandering, meandering and braided rivers; and (3) to investigate formative processes for wandering Miramichi rivers. Wandering rivers within the Miramichi region occur in larger valleys located downstream of an abrupt change in bedrock from resistive to more erosive bedrock lithology. Larger rivers display greater braid indices than smaller rivers. Wandering Miramichi rivers display more similarities to meandering rivers than braided rivers, exhibit an anabranching pattern, yet have characteristics markedly different from anastomosed rivers. Energy levels, mid-channel bar formation, migration rates and width–depth ratios are all within the meandering range, lower than braided and higher than anastomosed. Once anabranches are created, larger rivers apparently maintain a greater number of anabranches because of greater discharge. Wandering Miramichi rivers may represent another anabranching river pattern type, different from anastomosed and previously described wandering rivers.

Keywords: Anabranching; Wandering river; River pattern; Principal component analysis; Gravel-bedded river

1. Introduction

Classically, river patterns were thought to vary from low-energy meandering to high-energy braiding (Leopold and Wolman, 1957). Wandering was added as a transitional channel form between braiding and meandering that exhibits characteristics of both (Neill, 1973; Church, 1983). Wandering rivers have a complicated channel planform with long sections exhibiting multiple channel anabranches surrounding semi-permanent islands supporting mature forests, separated by single channel sections (Desloges and Church, 1989). Church (1983) indicated that multiple channels of wandering rivers are sedimentation zones that lead to lateral instability, while single channel sections are transportation zones with a stable channel

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form. Carson (1984b) discriminated two types of wandering channels: type I has single channels with high channel migration rates and frequent dissection of point bars, while type II displays high bed sediment supply and low to medium bank erodibility and anabranching. Type II was identified as a separate river class from low energy anastomosed rivers with high, fine-grained suspended sediment concentrations (Carson, 1984b). Anastomosed rivers were identified as anabranching rivers that occur at energy levels lower than meandering (Smith and Putnam, 1980; Knighton and Nanson, 1993). Nanson and Knighton (1996) analysed a wide range of anabranching rivers, identifying anastomosed (their type 1) as low-energy laterally stable and wandering (their type 5) as gravel-dominated, laterally active anabranching rivers.

Wandering rivers occur in many climatic and geologic zones but appear to be most common in mountainous regions with glaciers in their headwaters (Bella Coola River: Church, 1983; Squamish River: Brierley, 1989; Brierley and Hickin, 1991) or downstream of large terraces like those on the Canterbury Plains, New Zealand (Carson, 1984a). In mountain settings, the formation of wandering rivers have been associated with high sediment input from large, easily erodable sources (glacial or alluvial terraces), produced by neoglacial events in British Columbia (Church, 1983; Church and Slaymaker, 1989) and sediment input from tributary rivers. Sediment input from these sources overloads channels, causing the formation of large mid-channel bars that may trigger avulsions due to thalweg shoaling (e.g., Ashmore, 1991). Within channel deposition is also associated with a decrease in channel slope upstream of alluvial fans of tributary rivers that decreases transport capacity (Church, 1983). However, the wandering pattern was first identified on the Athabaska River near Fort Assiniboine, Alberta (Neill, 1973), not a mountain setting; and the mechanisms that create anabranching within rivers are still not as well established as the process of meandering (Nanson and Knighton, 1996).

For decades, plots of slope against discharge have been employed to investigate the differences between river patterns (e.g., Leopold and Wolman, 1957). Wandering rivers plot below braided rivers on these graphs (Desloges and Church, 1989), while anastomosed rivers plot below meandering rivers. Slope and discharge are related to stream power, a form of channel energy, but stream power is generally greater in rivers with larger discharge, thereby limiting the usefulness of this variable. Specific stream power (ω),

$$\omega = \rho g Q_{\mathrm{af}} S / w$$

where ρ is the density of water, g is the acceleration due to gravity, Q_{af} is the mean annual flood discharge, S is channel slope, and w is the bankfull channel width, represents the power expenditure per unit area of the streambed and is a more useful variable for comparing channel energy between rivers (Nanson and Knighton, 1996; Knighton, 1998). Wandering rivers display specific stream powers generally between those for anastomosed and braided rivers. Anastomosed river types (anabranching types 1–4 of Nanson and Knighton, 1996) display specific stream powers between 2 and 40 W m^{-2}, braided rivers display values between 50 and 300 W m^{-2} (Nanson and Croke, 1992), meandering gravel bed rivers display values between 20 and 80 W m^{-2} (data from Van den Berg, 1995), while previously described wandering rivers display values between 30 and 100 W m^{-2} (Nanson and Knighton, 1996).

Along with channel energy, the importance of grain size has also been identified in understanding river patterns (Ferguson, 1987; Desloges and Church, 1989). By comparing potential specific stream power based on valley slope and grain size, Van den Berg (1995) discriminated between braided and meandering rivers. However, the discrimination was based on an estimate of channel width and not actual channel width, a point criticized by Lewin and Brewer (2001, 2003). Nevertheless, stability diagrams of this type reliably discriminate between braided and meandering patterns with few input data and therefore are still useful in investigating general differences between river patterns (Van den Berg and Bledsoe, 2003). Wandering rivers were not included in the analysis of Van den Berg (1995) but are predicted to occur between braided and meandering because wandering rivers are associated with energy conditions transitional between braiding and meandering (Nanson and Knighton, 1996).

Maximum flow efficiency (MFE) has recently been suggested as the underlying mechanism behind anabranching (Nanson and Knighton, 1996; Nanson and Huang, 1999; Jansen and Nanson, 2004). Proponents of MFE argue that multiple channel anabranching reaches convey water and sediment downstream more efficiently than single channel reaches. They argue that, in addition to adjusting slope, bed configuration and channel cross-section, anabranching provides another degree of freedom for a river to maintain the conveyance of water and sediment downstream. Anabranches are hypothesized to form where bed slopes are too low to convey sediment through a single channel, and slope cannot be increased through straightening the channel. Previous research by Nanson and Huang (1999) and Jansen and Nanson (2004) suggest that channel efficiency is related to lower channel cross-sectional area in multiple channel sections than single channel sections. The total cross-sectional area is lower where the total width decreases, which increases the average cross-sectional velocity for a given discharge, and hence increases efficiency. Differences in hydraulic geometry are primarily driven by differences in channel width (Tabata and Hickin, 2003; Burge, 2004). Tabata and Hickin (2003) did not find evidence for MFE as the cause of anabranching on the anastomosed reach of the Columbia River, but Jansen and Nanson (2004) did find evidence for MFE on Magela Creek in northern Australia. The MFE hypothesis has not been tested in wandering rivers.

It is difficult to draw conclusions regarding controls on wandering river channels from regions with varying climate, vegetation, lithology and sedi-

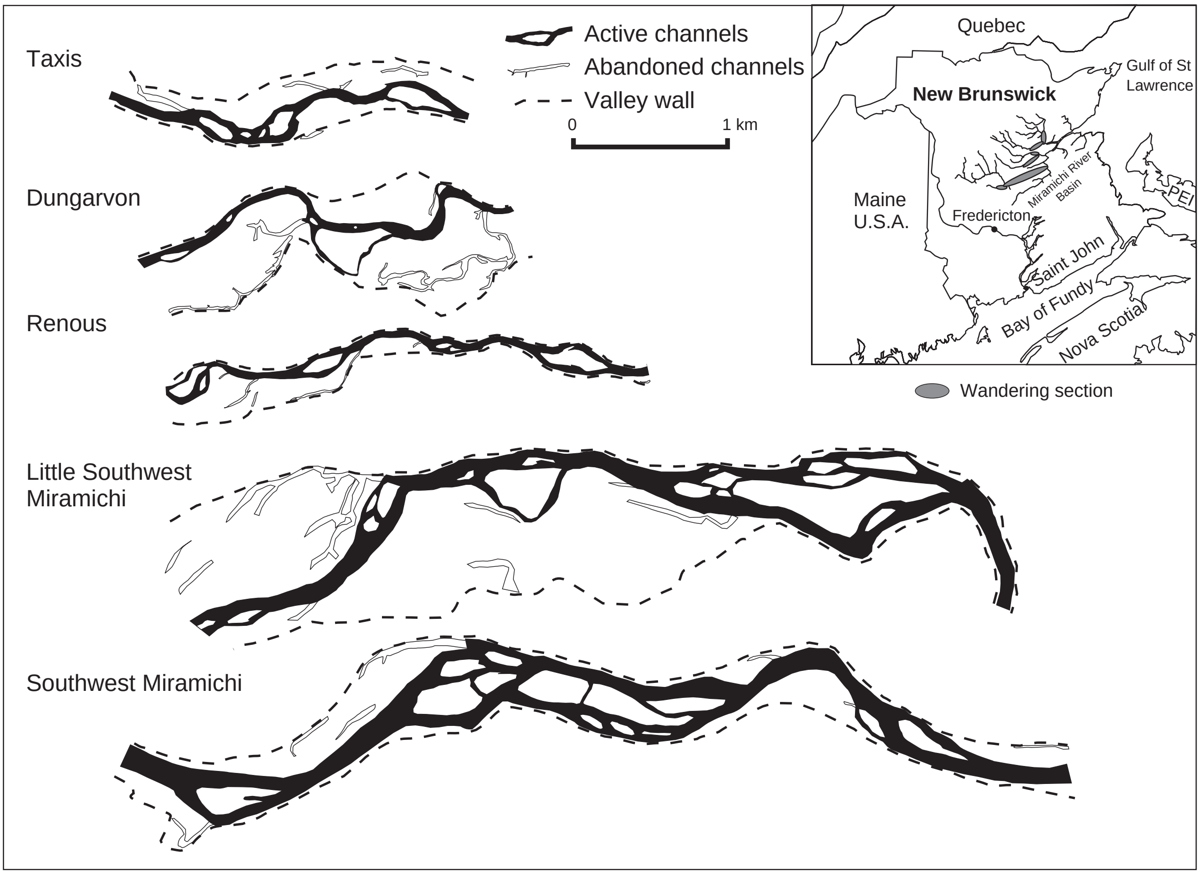

Fig. 1. Location of wandering rivers within the Miramichi basin (inset), showing multiple channel sections from the five wandering rivers analyzed.

ment production. In the current study, the Miramichi region of New Brunswick, Canada, was chosen because a cluster of wandering rivers occurs under similar regional conditions (Fig. 1). The beds of these rivers are commonly gravel but often include cobbles. Rivers within the Miramichi drain the Miramichi highlands, a plateau with 250 m of local relief and a maximum elevation of 600 m a.s.l. (Rampton et al., 1984). Much of the region is overlain by a thin blanket of late Wisconsinan till (Lamothe, 1992), with glaciofluvial deposits scattered throughout the province (Rampton et al., 1984).

Detailed data on the channel pattern characteristics of long sections of rivers within the same region are rare. Several indices describing multiple channel rivers have been used (see Bridge, 1993, for a review), and these indices may quantify different aspects of multiple channel rivers, including the number of channels and the length of channels. Employing a number of indices may therefore be useful to compare between rivers.

This research addresses three objectives: (1) to provide a detailed description of the location, pattern characteristics and boundary conditions of wandering Miramichi rivers; (2) to compare the pattern characteristics among wandering rivers within the Miramichi basin and to other wandering, meandering and braided rivers; and (3) to investigate formative processes for wandering Miramichi rivers.

2. Methods

Scaled river sizes were selected for analysis from the largest (Southwest Miramichi and Little Southwest Miramichi Rivers) to the mid-sized (Renous and Dungarvon Rivers), to the smallest (Taxis River) (Fig. 1, Table 1). Channel pattern characteristics were measured from 1:10,000 orthophotomaps compiled and georectified from aerial photographs taken in 1973, 1974 and 1975 (New Brunswick, 1979). Each river was divided into relatively homogeneous single channel and multiple channel sections of ~100 channel widths in length. For each section, the width of the main channel (the largest channel in a valley cross-section) and valley width were measured at every five channel widths downstream on the orthophotomaps (~20 times per section) and averaged for each section. The locations of wandering sections were identified and compared to regional trends in bedrock lithology. The widths of the valleys and channels were measured and the total channel width (sum of all channels in valley cross-section) was determined. To allow for comparison among rivers and floodplains of different sizes, valley width was normalized by the main channel width and the total channel width was normalized by the average channel width of single channels. The orthophotomaps allowed for the identification of channels greater than 5 m in width (0.5 mm map distance).

The wandering Miramichi river pattern was quantified using six river pattern indices on five rivers (Table 2). Four indices (sinuosity, braid index, average number of channels across valley and channel order) are commonly used in the literature; braid wavelength was modified and an abandoned channel index was created. To allow for comparison between rivers of different sizes, braid wavelength was normalized by main channel width. By definition, braid index will increase with the length of secondary channels and decrease with increasing main channel sinuosity (longer main channels). Braid index can display high values with few channels (diffluences) if the secondary channels are long. Normalized braid wavelength is related to the number of channels and not channel length and therefore provides the best single variable to quantify multiple channel river patterns. The abandoned channel index was created to quantify the length of abandoned channels within each reach because abandoned channels are common in wandering rivers and may be used as avulsion paths during the creation of new channels. A potential error in using the abandoned channel index is the variable visibility of abandoned channels on the orthophotomaps at different river stages because of flooding of abandoned channels.

Lateral migration rates were determined for 26 km on the Southwest Miramichi River by comparing 1:12,000 aerial photographs from 1945 and 1983 using a Bausch and Lomb Zoom Transfer Scope.

To compare to the characteristics of other rivers, the slope and mean annual flood of the five Miramichi rivers were determined. River bed slope (*S*) was measured in the field for each reach using a level or differential GPS or estimated from 1:20,000 ortho-

Table 1

Mean values for channel characteristics (±standard error) for (A) multiple channel wandering sections and (B) single channel sections of the five study rivers

(A) Wandering sections	Southwest Miramichi (n=12)		Little Southwest Miramichi (n=5)		Renous (n=2)		Dungarvon (n=5)		Taxis (n=2)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Basin area (km^2)	3253		1340		611		623		495	
Valley width (m)	396.49	36.26	**494.96**	87.21a	270.45	85.45	**225.24**	26.02b	196.60	56.60
Main channel width (m)	**106.93**	4.33a	**79.90**	5.39b	**42.00**	0.10c	**41.42**	2.17c	**36.90**	1.90c
Main channel depth (m)			2.00		1.75				2.00	
Norm. valley width	3.77	0.33	6.12	0.93	6.43	2.02	5.60	0.91	5.40	1.81
Wandering dist. (km)	61.8		18.0		6.8		30.7		8.4	
Braid index	1.28	0.09	**1.20**	0.04a	1.10	0.05	**1.05**	0.02b	1.14	0.02
Norm. wavelength	12.83	2.91	15.00	4.09	17.90	2.00	29.64	6.76	37.25	1.15
# channels across valley	1.68	0.15	1.48	0.12	1.40	0.10	1.20	0.08	1.30	0.00
Diffluence order	2.75	0.25	2.60	0.40	2.00	0.00	2.40	0.25	2.50	0.50
Sinuosity	**1.02**	0.01c	**1.15**	0.03b	**1.44**	0.09a	**1.12**	0.02b	**1.03**	0.03bc
Abandoned index	0.48	0.12	0.81	0.32	0.93	0.36	0.60	0.09	0.36	0.25
Mean annual flood discharge (m^3 s^{-1})	593		272		148		124		109	
Bed slope (m m^{-1})	0.0018		0.0019		0.0021		0.0027		0.0026	
Valley slope (m m^{-1})	0.00185		0.00219		0.00302		0.00302		0.00268	
Specific stream power (W m^{-2})	98		63		73		80		75	
Width–depth ratio			40		24				18	
D_{50} (mm)			67		70				55	

(B) Single channel sections	Southwest Miramichi (n=2)		Little Southwest Miramichi (n=2)		Renous (n=3)		Dungarvon (n=3)		Taxis (n=4)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Valley width (m)	216.35	48.65	258.05	91.95	289.90	109.58	169.80	90.11	130.88	17.32
Main channel width (m)	125.20	0.29	70.35	10.35	51.40	1.89	40.97	1.62	40.65	2.28
Main channel depth (m)			2.85		1.82				2.01	
Norm. valley width	1.73	0.39	3.95	1.89	5.79	2.40	4.19	2.24	3.26	0.50
Braid index	1.02	0.02	1.00	0.00	1.04	0.01	1.01	0.01	1.04	0.03
Norm. wavelength	119.40		0.00	0.00	143.50	44.98	118.95	3.25	86.95	10.61
# channels across valley	1.00	0.00	1.00	0.00	1.07	0.03	1.00	0.00	1.05	0.03
Diffluence order	1.5	0.50	0.00	0.00	2.00	0.00	1.67	0.33	1.50	0.29
Sinuosity	1.04	0.04	1.30	0.30	1.38	0.17	1.05	0.05	1.03	0.03
Abandoned index	0.00	0.00	0.07	0.07	0.34	0.15	0.43	0.36	0.15	0.12
Bed slope (m m^{-1})	0.0027		0.0031		0.0022		0.0034		0.0024	
Valley slope (m m^{-1})	0.00281		0.00403		0.00304		0.00357		0.00247	
Specific stream power (W m^{-2})	126		118		62		101		63	
Width–depth ratio			25		28				20	
D_{50} (mm)			107		70				89	

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 Bonferroni post hoc tests.

Table 2
List of the indices describing anabranching that were used in the analysis

Index	Equation	Reference	Emphasis
Sinuosity (PMC)	Main channel length/valley length	Knighton, 1998	Meandering of main channel
Abandoned channel index (AI)	Abandoned channel length/main channel length	This paper	Abandoned channel length
Braid index (BI)	Side channel length+main channel length/main channel length	Mosley, 1981	Channel length
Normalized braid wavelength (N.wave)	(Main channel length/total number of channel nodes)/main channel width (Node=confluence or diffluence)	Modified from Ashmore, 2001	Channel divisions
Average number of channels across valley (Av # Ch)	Number of channels across a valley cross section measured 20 times per reach and averaged	Ashmore, 1991	Number of channels
Channel order (Order)	Greatest number of divisions downstream in a channel within a reach	Bristow, 1987	Hierarchy of channel divisions

photomaps. Mean bankfull channel depth was determined from field surveys. Mean annual flood discharge (Q_{af}) was determined as the mean of the annual maximum daily discharge from gauges on the Southwest Miramichi, Little Southwest Miramichi and Renous Rivers (Environment Canada, 1997). The mean annual flood discharge for the ungauged Dungarvon and Taxis Rivers, and a section of the Southwest Miramichi River, was estimated using a regional relationship developed for the mean annual maximum daily discharge and drainage area for six rivers within the Miramichi drainage basin. Specific stream power was calculated using the mean annual flood discharge, channel slope and the main channel width. Main channel width values may be slightly lower in multiple channel sections due to the inclusion of anabranch channels that are narrower than single channels. This may cause a slight inflation of specific stream power values in multiple channel sections. Grain sizes were determined at the upstream ends of more than 30 riffles in the main channels of the Renous and Taxis Rivers through measuring the B axis of 100 randomly chosen clasts. Grain sizes were determined at the upstream ends of more than 30 riffles on the Little Southwest Miramichi River using a visual grain size estimation technique developed by Latulippe et al. (2001).

Van den Berg (1995) discriminated between braided and meandering channel patterns using two pattern-independent boundary conditions: median grain size of the channel bed sediment and potential specific stream power. The argument against using this analysis is that the regime equations used to estimate the channel width underestimated the channel width in braided rivers and this caused an overestimation of potential specific stream power and the discrimination seen on the diagram (Lewin and Brewer, 2001, 2003). Plots of slope against discharge are also problematic because they use channel slope instead of valley slope. Meandering causes channels to become longer and the channel slope to decrease, thereby causing the discrimination seen on slope-discharge graphs (Carson, 1984a). Acknowledging that these analyses are limited in determining the underlying causes of the differences in river patterns, they are still useful in comparing among river patterns because their discriminations are robust. This study uses multiple analyses with different assumptions to obtain a more complete comparison of Miramichi rivers to other river types.

Data on meandering and braided rivers from Van den Berg (1995) were used to compare to wandering Miramichi rivers. Low sinuosity rivers were excluded from the analysis as suggested by Van den Berg. Rivers with grain sizes <5 mm were also excluded. To estimate the boundary conditions acting on a river channel, potential stream power was calculated using the valley slope and width estimated using a regime equation as suggested by Van den Berg (1995) for gravel-bedded channels. The pattern of the Squamish River grades from braided to wandering to meandering downstream (Brierley, 1989) and was used for an additional comparison. Mean annual flood for the Squamish River was determined from Water Survey of Canada data (Gauge 08GA022). Channel sinuosity, channel slope and bed grain size (D_{50}) data were from Brierley (1989). Wandering and anastomosed river characteristics compiled by Nanson and Knighton (1996) were also compared to wandering Miramichi rivers.

2.1. Statistical analyses

Differences in pattern characteristics among wandering Miramichi rivers were investigated with a Pearson correlation matrix with Bonferroni probabilities using SYSTAT (SPSS, 1998). Differences among pattern variables were further investigated using principal component analysis (PCA) using CANOCO (ter Braak and Smilaur, 1999). PCA allows the analysis of numerous variables from different river sections at once, can be used to determine the most important variables, and provides a visual representation of the multivariate differences among rivers for interpretation. Only multiple channel reaches were used in the analyses. Braid index, main channel sinuosity, average number of channels per cross reach 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.

2.2. Causes of flooding in wandering Miramichi rivers

To investigate the causes of flooding in wandering Miramichi rivers, the maximum daily annual stages were extracted from an Environment Canada gauge on the Little Southwest Miramichi River for the years 1995 to 2001. The available record for analysis is short because Environment Canada only began storing stage data in digital format after 1995. The previously collected chart data was unavailable. Two populations of data emerged: ice-influenced and open-water stages. The peak annual ice-influenced stage was compared to the highest annual stage for open-water conditions, occurring in spring following the breakup of the ice cover. Frequency of high stage events was determined using

$$T = (n + 1)/N$$

where T is the return period (in years), n is the number of years of record and N is the rank of a particular event from largest to smallest (Knighton, 1998). The frequency of ice-influenced stages was compared to those of open-water. Stage frequency analysis is most robust when conducted on large data sets. A small data set was used for the frequency analysis because of difficulty in acquiring more data. This may have resulted in the actual return period for a given stage being in error.

3. Results

Wandering rivers were located in the lower reach of the Miramichi basin, upstream of confluences with larger rivers or near the Miramichi estuary (Fig. 1). Wandering reaches of the Southwest Miramichi and Little Southwest Miramichi Rivers terminated near the Miramichi River estuary. The wandering reaches of the Renous and Dungarvon Rivers ended near their confluence with each other, and the wandering reach of the Taxis ends near its confluence with the Southwest Miramichi River. The distribution of wandering rivers within the Miramichi appeared to be related to a change in bedrock lithology downstream, from more resistant Ordovician–early Devonian volcanic and plutonic to less resistant Devonian–Permian sedimentary bedrock (New Brunswick Department of Natural Resources and Energy, 2000) that has allowed valleys to widen and accommodate multiple channels (Fig. 2).

The relationship between valley width (Vw) and main channel width (w) showed that multiple channels did not occur below the line Vw=0.78w+110 because valley walls were too close together to provide accommodation space for multiple channels to develop (Fig. 3). The discriminant function represented the narrowest valley sections in which multiple channels occurred. Channels that occurred above this line were termed semi-confined because channel migration was limited by contact with the valley walls. Normalized valley width was significantly higher (ANOVA, p=0.003) in multiple channel sections than single channel, generally confined sections (Table 1). Within multiple channel sections, main channel width was correlated with valley width (r=0.50, p=0.009). Six, single-channel sections occurred above the confinement discriminant function. In these sections, wandering did not occur even though valleys were wide enough to accommodate the formation of multiple channels, indicating that factors in addition to wide valleys are important for

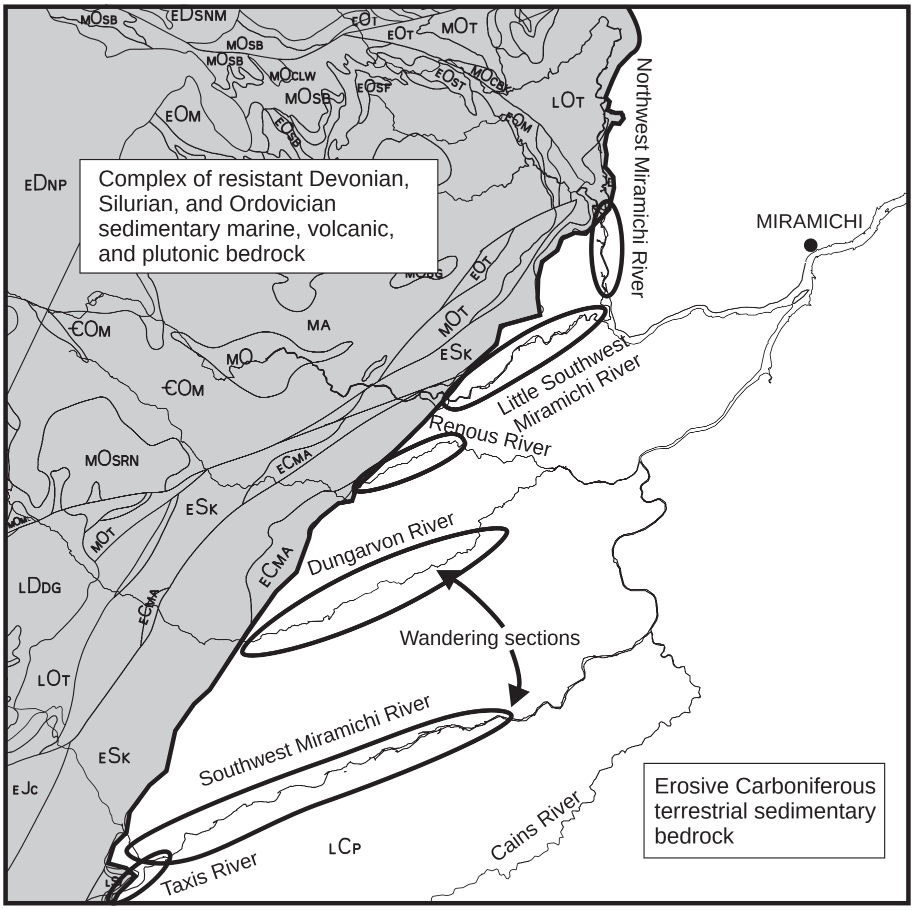

Fig. 2. Bedrock map of New Brunswick showing the location of wandering rivers within the Miramichi basin located with sedimentary bedrock downstream of volcanic and plutonic bedrock (New Brunswick Department of Natural Resources and Energy, 2000).

the development of multiple channels within the region.

Wide valleys were also generally longer and allowed rivers to display multiple channels for a greater distance. The length of the multiple channel wandering pattern was related to the main channel width (r=0.78, n=5). However, the Dungarvon River displayed multiple channels for a longer distance than predicted by its width (Table 1). As shown in Fig. 2, the Dungarvon flows over sedimentary bedrock for a greater distance than other rivers of similar size because of its location in relation to the change in bedrock, allowing widening of the valley for a greater distance. The location of wandering suggested that bedrock lithology imposed an overriding control on the location of wandering rivers within the Miramichi basin.

3.1. Wandering Miramichi river pattern characteristics

Few statistically significant differences in pattern characteristics were seen among river sections due to high variance within the characteristics of each river (Table 1). In general, larger river had higher indices of anabranching than smaller rivers (Table 1). Braid index, normalized braid wavelength, number of channels across valley and highest order values were greater in the two larger rivers than the three smaller rivers. The braid index ranged from 1.08 to 1.26 and was lower than wandering sections of the Bella Coola and Peace Rivers (Desloges and Church, 1989; Jiongxin, 1997). The main channels of wandering Miramichi rivers were relatively straight with sinu-

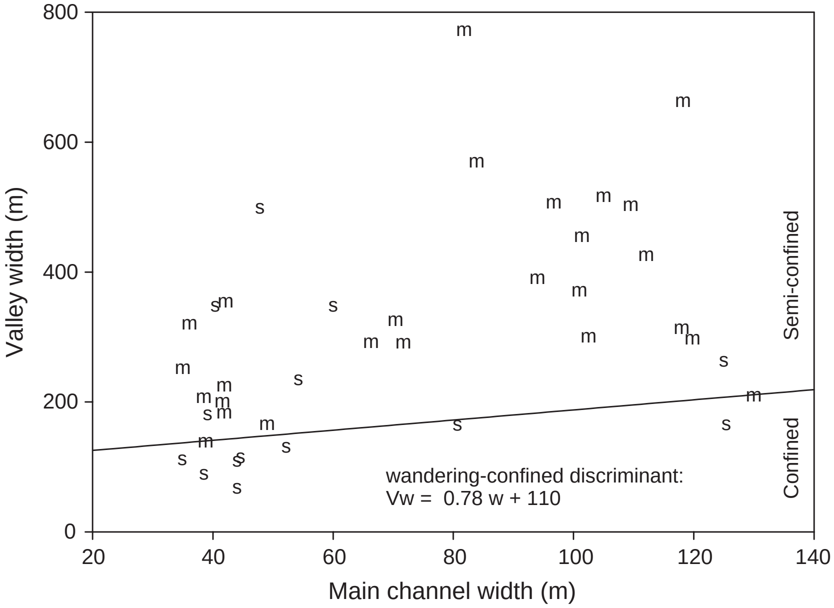

Fig. 3. Scatter plot of main channel width and valley width showing wandering sections above a discriminant function between confined and semi-confined sections. The discriminant function represents the narrowest valley sections in which multiple channels occurred. Note, *s* denotes single and *m* denotes multiple channel wandering sections.

osity values between 1.02 and 1.44 (Table 1). 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 braid index, normalized wavelength, number of channels across valley and highest order (Table 3). Normalized wavelength was negatively correlated with the other variables because it decreased as anabranching increased, due to greater numbers of diffluences per main channel length. Sinuosity and abandoned channel index were not significantly correlated with anabranching indices (Table 3). Abandoned channel index was correlated with normalized valley width.

3.2. Principal component analysis

The first two PCA axes explained 86.1% of the variance in channel characteristics (Fig. 4). PCA 1 explained 77.1% of the variance and was associated

Table 3
Pearson correlation matrix comparing wandering river characteristics is shown in regular font below diagonal

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

The matrix of Bonferroni probabilities that were <1 are italicised above the diagonal and correlations where $p<0.05$ are in bold.

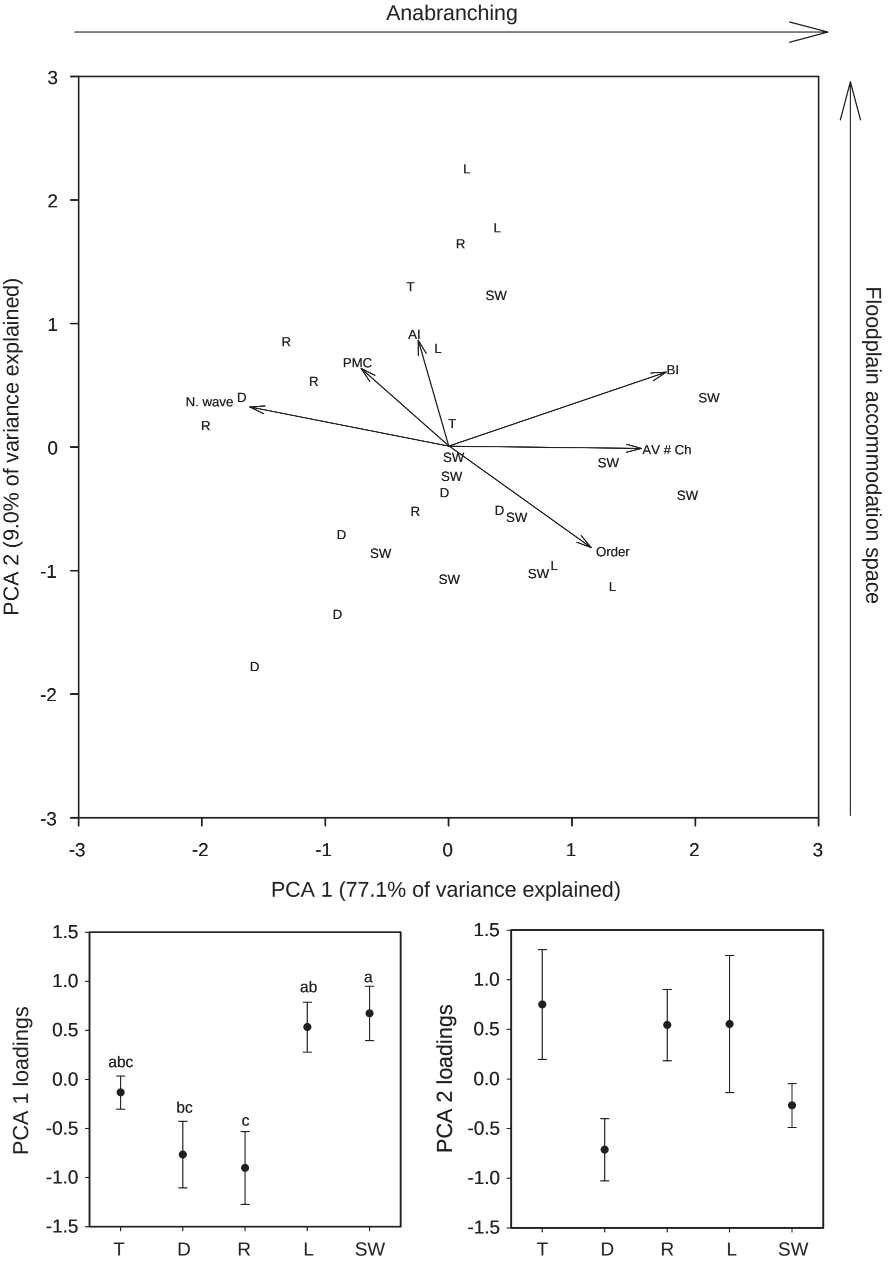

Fig. 4. Principal component analysis (PCA) of six river pattern variables showing 86.1% of the variance explained in the first two axes. The outside of the plot displays the interpretation of the relationship between PCA 1 and anabranching, and PCA 2 and floodplain accommodation space. Below the PCA are plots showing average loadings for each river, standard error bars and differences determined through ANOVA lettered as a>b. (SW=Southwest Miramichi, L=Little Southwest Miramichi, R=Renous, D=Dungarvon, T=Taxis, N.wave=normalized braid wavelength, PMC=main channel sinuosity, AV # Ch=the average number of channels across valley, AI=abandoned channel index, Order=highest channel order and BI=braid index).

with braid index, number of channels across valley, diffluence order and normalized braid wavelength. PCA 2 explained 9.0% of the variance and was associated with abandoned index, main channel sinuosity, braid index and highest order.

River sections that displayed greater anabranching plotted high on PCA 1 (Fig. 4). The larger Southwest and Little Southwest Miramichi had significantly higher PCA 1 loadings than the smaller Renous, and the Southwest Miramichi had higher loadings than the Dungarvon (ANOVA, $p<0.05$). Main channel width was positively correlated with PCA 1 ($r=0.46$), also indicating that anabranching was greater in larger rivers. However, the smallest river displayed intermediate values. Specific stream power and mean annual flood were correlated with the PCA 1 loadings and channel characteristics averaged for each river. This resulted in only five sample points for this analysis; therefore, these results may be viewed as preliminary. Only correlations >0.75 were examined because of the small sample size (Fig. 5). Only PCA 1 loadings, average braid index and average number of channels across the valley had correlation coefficients >0.75. Anabranching characteristics of wandering

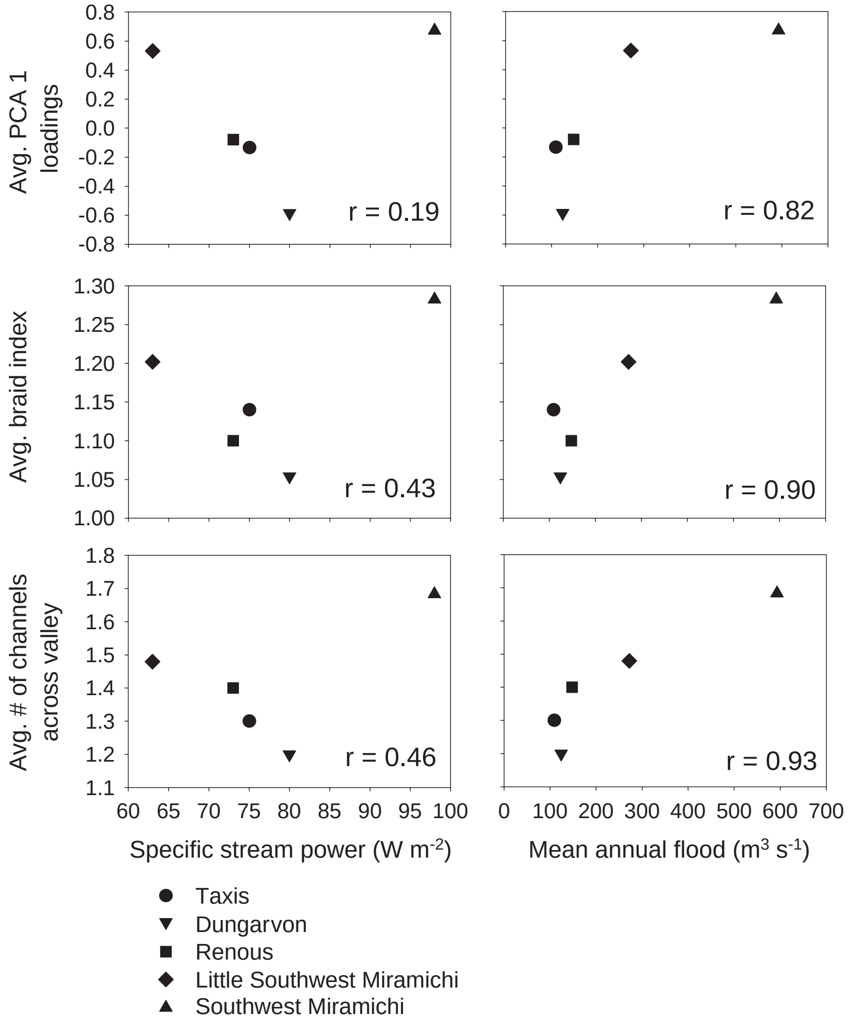

Fig. 5. Correlations between average specific stream power and mean annual flood discharge, and PCA 1 loadings, braid index and average number of channels across valley averaged for all multiple channel sections in each river ($n=5$).

Miramichi rivers displayed greater correlations with mean annual flood than with specific stream power.

Much variability occurred on PCA 2 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 PCA 2. PCA 2 was positively correlated with normalized valley width (r=0.55). PCA 2 is interpreted as being influenced by accommodation space that allows greater sinuosity and abandoned channels within the floodplain. The greater accommodation space allowed for greater room for channel meandering, more abandoned channels on floodplains and additional secondary channels.

3.3. Channel energy, channel migration and sediment input within wandering Miramichi rivers

Wandering Miramichi rivers displayed energy levels well below the transition between braiding and meandering. All wandering rivers within the Miramichi occurred below the slope-discharge discriminant function ($S \propto Q^{-0.5}$) between braided and wandering suggested by Desloges and Church (1989) (Fig. 6). The slope and discharge data from wandering Miramichi rivers suggested a discriminant function

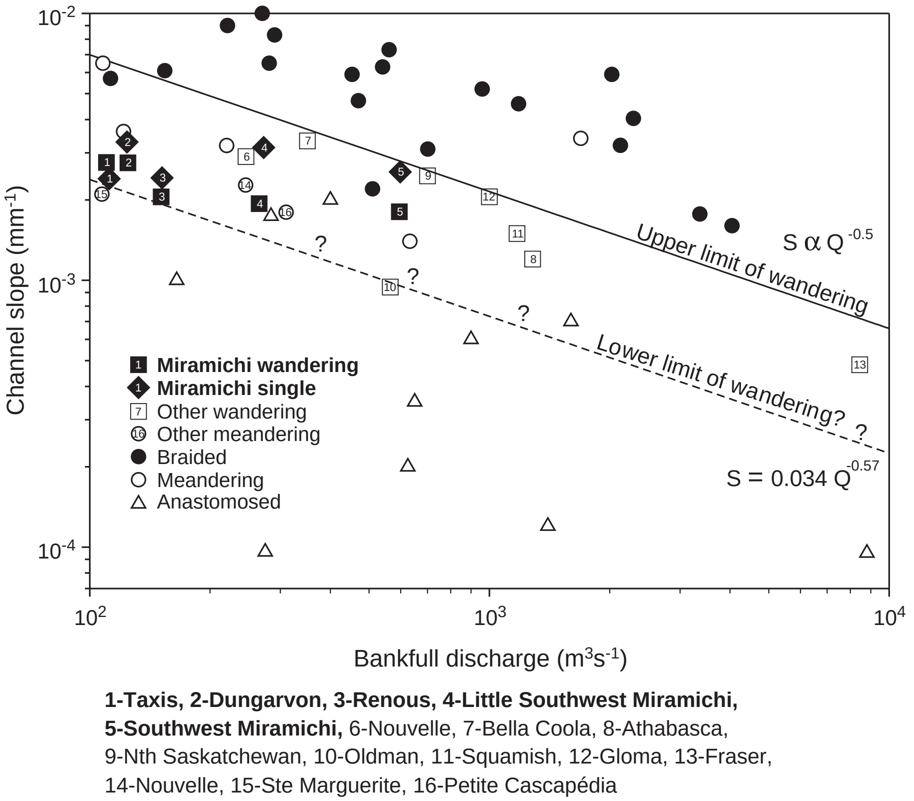

Fig. 6. Slope–discharge plot for the Miramichi gravel-cobble bedded study rivers and eight other gravel-cobble wandering systems (from Desloges and Church, 1989; Payne, 1995; Nanson and Knighton, 1996), and three neighbouring gravel-bedded meandering rivers in Quebec (from Payne, 1995; Eaton, 1998; Coulombe-Pontbriand, 2001). 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. Mean annual flood or bankfull discharge values are from Nanson and Knighton (1996), Payne (1995), Eaton (1998) and Coulombe-Pontbriand (2001). Data for additional meandering rivers and braided rivers are from Van den Berg (1995). Data for anastomosed rivers are from Nanson and Knighton (1996).

(S=0.034$Q^{-0.57}$) as the lower limit of wandering. Wandering Miramichi rivers occurred within meandering, close to the lower discriminant function, that suggested conditions more similar to meandering than braiding. Smaller wandering Miramichi rivers (Taxis, Dungarvon and Renous) had smaller discharge values than previously reported for wandering rivers (Nanson and Knighton, 1996). Anastomosed rivers generally plotted below wandering Miramichi rivers. Single channel Miramichi rivers plotted with greater slopes and the same discharges as the wandering sections on the same rivers. Single channel Miramichi rivers also plotted within the meandering zone (Fig. 6).

On a plot of specific stream power and width–depth ratio, braided, meandering and anastomosed rivers displayed separation on the plot, previously studied wandering rivers generally plotted in a transition zone between braided and meandering, while wandering Miramichi rivers occurred well within the meandering zone (Fig. 7). Discrimination lines were plotted by eye and were not meant to represent threshold transitions. Braided rivers displayed the highest width–depth ratios and specific stream powers, followed by meandering, and then anastomosed. Width–depth ratios of wandering Miramichi rivers were within the range of meandering rivers, lower than braided rivers and other wandering rivers, and greater than anastomosed rivers. Specific stream powers for wandering Miramichi rivers displayed an average of 86 W m^{-2} and ranged from 63 to 147 W m^{-2} (Table 1). These values were within the lower range of other wandering rivers (from Carson, 1984a; Nanson and Knighton, 1996) and overlapped with meandering values but were higher than values for anastomosed rivers. Single channel Miramichi rivers generally plotted within the same range as wandering Miramichi rivers (Fig. 7).

Using the analysis suggested by Van den Berg (1995), wandering Miramichi rivers were compared to braided and meandering rivers (Fig. 8). The median bed material grain size of wandering Miramichi rivers was between 55 and 70 mm, within the range of both braided and meandering rivers, but potential specific stream power values were much lower than braided rivers (Fig. 8), indicating that wandering Miramichi rivers had similar potential sediment transport rates to meandering rivers. The median bed grain size of single channel Miramichi rivers was between 70 and

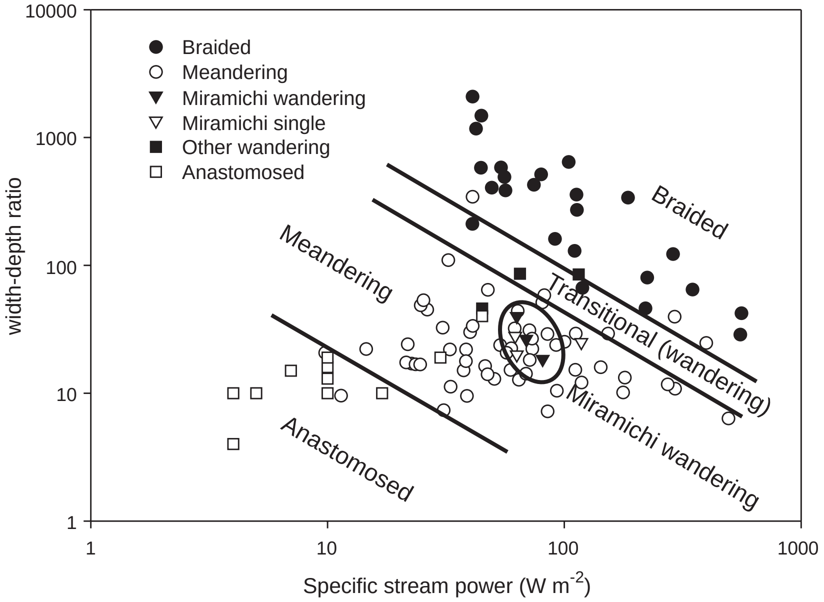

Fig. 7. Plot of width–depth ratio and specific stream power showing the discrimination between braided, meandering and anastomosed rivers. Other wandering rivers generally plot in the transition between braided and meandering. Wandering Miramichi rivers plot well within the meandering zone. The data was compiled from Van den Berg (1995) and Nanson and Knighton (1996).

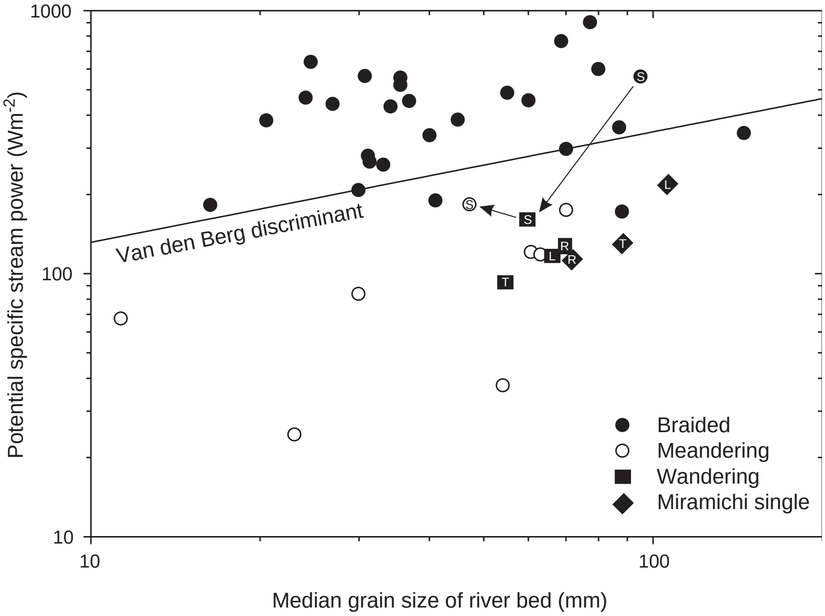

Fig. 8. Analysis suggested by Van den Berg (1995) plotting potential specific stream power and median grain size of river bed. Arrows connect the Squamish River downstream. Data for analysis are from Van den Berg (1995) and Brierley (1989) (L=Little Southwest Miramichi, R=Renous, T=Taxis, S=Squamish).

107 mm, larger than the grain size of wandering Miramichi rivers. Potential stream power values for single channel Miramichi rivers were similar to those of wandering Miramichi rivers, with the exception of the Little Southwest Miramichi River, which displayed a larger value.

The pattern of the Squamish River graded from braided, to wandering, to meandering downstream and occurred in a mountainous basin (Brierley, 1989). The grain size and potential specific stream power for the Squamish River generally decreased downstream (Brierley, 1989). The threshold between braided and meandering suggested by Van den Berg (1995) was crossed downstream, with wandering and meandering occurring below the line. However, all three patterns of the Squamish River plotted above wandering Miramichi rivers, indicating that every pattern of the Squamish River had greater potential for sediment transport than all Miramichi rivers.

Wandering Miramichi rivers displayed low lateral migration rates. The average maximum lateral migration rate at the outside of bends was only 0.9±S.E. 0.1 m year^{-1} or 1.0±S.E. 0.2% of the channel width per year for 26 km on the Southwest Miramichi between 1945 and 1983. These rates were lower than lateral migration rates based on dendrochronology for the Bella Coola River (3.0 to 3.5 m year^{-1} or 2% of the average channel width per year) (Desloges and Church, 1987), a wandering reach of the Feshie River, Scotland (7 m year^{-1} or 18% of the channel width per year) (Ferguson and Werritty, 1983) and a wandering reach of the Nouvelle River in Quebec (7 m year^{-1} or 11% of the channel width per year) (Payne and Lapointe, 1997). These rates were in the same range or lower than many single channel rivers, including the Beatton River in British Columbia (0.2 to 0.7 m year^{-1} or 0.3 to 1.0% of the average channel width per year) (Hickin and Nanson, 1975), the Petite Cascapedia River (1.8 m year^{-1} or 2.6% of the channel width per year) (Coulombe-Pontbriand, 2001), the Bonaventure River (0.2 m year^{-1} or 0.3% of the channel width per year) (Coulombe-Pontbriand, 2001) and the Nouvelle River in Quebec (2 m year^{-1} or 4.5% of the channel width per year) (Payne and Lapointe, 1997). Low rates of channel migration within the Miramichi also suggested a lower energy and sediment mobility regime than other wandering rivers.

Long, multiple channel sections within wandering Miramichi rivers were not associated with extensive erosion of large terraces or the entrance of large tributaries into valleys as described in previous literature (Church, 1983; Carson, 1984b). Extensive field reconnaissance discovered few sediment inputs from eroding valley walls. Local erosion of relatively small (3–6 m in height) terraces was found, but only caused local (hundreds of meters downstream) deposition of single mid-channel bars. On aerial photographs, mid-channel bars were less common within Miramichi rivers than other wandering rivers that had large sediment inputs from neoglacial moraines. Fig. 9 displays six examples of wandering Miramichi channels where point bars and riffles are evident but mid-channel bars are uncommon. Wandering Miramichi rivers also displayed low width–depth ratios, also indicating few mid-channel bars. These observations were inconsistent with channels overloaded with sediment. The low sediment input to river channels

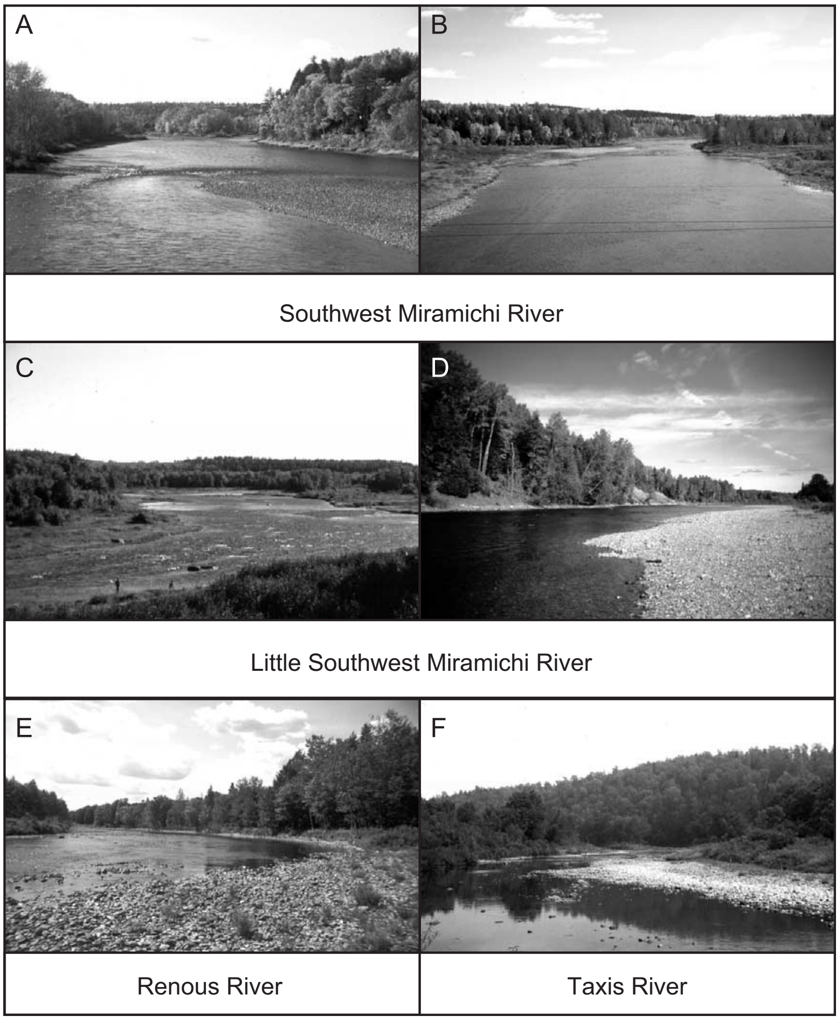

Fig. 9. Photographs of channels within the wandering sections of four wandering rivers. Mid-channel bars within these river channels are rare. A and B show riffles on the largest Southwest Miramichi. C displays the uppermost reach of wandering within the Little Southwest Miramichi where the greatest 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.

from valley sides was also consistent with the low relief in the region and the limited production of sediment since the end of the Wisconsinan glaciation.

3.4. Channel efficiency and flooding characteristics within wandering Miramichi rivers

The MFE hypothesis was not supported in anabranching sections of the Miramichi rivers. Multiple channels are more efficient than single channels where the total channel width of all channels across a valley is less than the width of single channels. However, the average total channel width increased with the number of channels in a valley cross-section (Fig. 10), indicating lower efficiency in multiple channel sections. Some anabranching sections displayed total channel widths less than the average single channel width, indicating that some multiple channel sections may be more efficient than the average single channel (Fig. 10). However, the greatest variability in channel width was seen in single channels, indicating great variability in the efficiency of single channels as well. This analysis was limited by the lack of bankfull channel depth and velocity data for each cross-section to fully assess channel efficiency.

Floodplains within Miramichi rivers were frequently flooded. The Little Southwest Miramichi River had a mean annual flood of 272 $m^3 s^{-1}$ based on 1952–1997 discharge data (Environment Canada, 1997), relating to a stage of 2.47 m above gauge datum. Ice-influenced events displayed higher stages at lower discharges than open-water events (Fig. 11A). In fact, the lowest ice-influenced annual high stage event was approximately equal to the highest open-water stage for the study period. The stage of the mean annual flood had a recurrence interval of 2.33 years based on these data (Fig. 11B). The stage of the 2.33-year recurrence from ice-influenced events was 3.55 m above the datum or 1.08 m above the mean annual flood stage. During winter, Miramichi rivers form a thick (>50 cm) ice cover that commonly leads to ice-jams (Fig. 12) during spring break-up and occasionally during winter melts (Beltaos et al., 1989).

4. Discussion

4.1. Valley width and wandering Miramichi rivers

In the Miramichi basin, wider valleys are associated with less resistant bedrock and valley width is the primary control on the location of wandering reaches (Fig. 2). Other studies have also shown valley

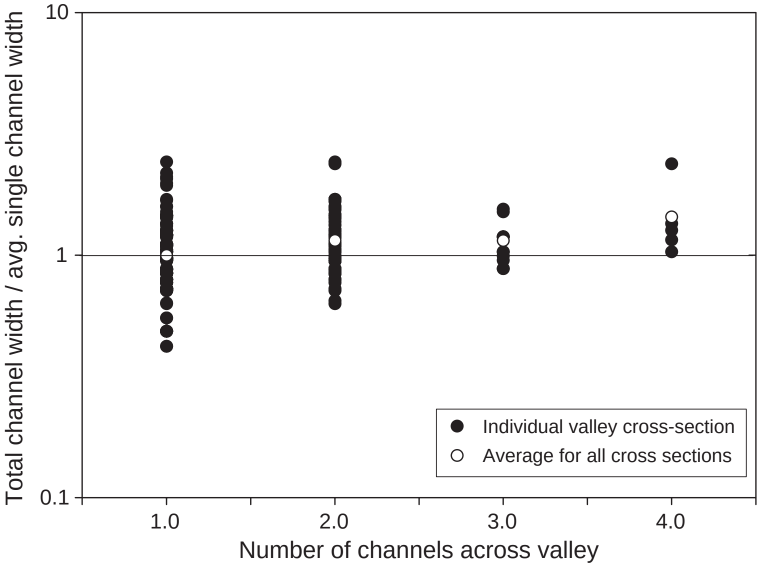

Fig. 10. Total channel width per valley cross-section normalized for the average single channel width plotted against the number of channels across a valley for the five study rivers (n=467).

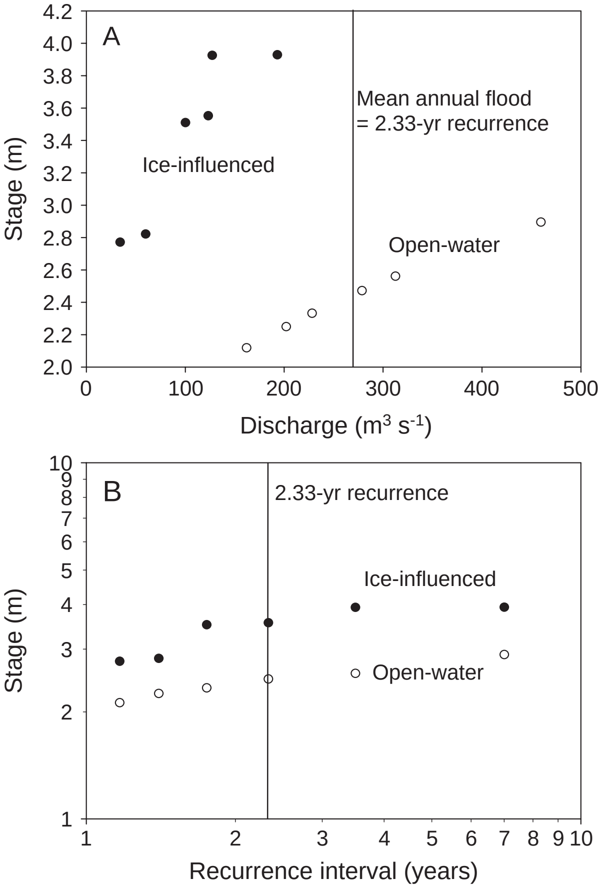

Fig. 11. (A) Stage-discharge plot for highest ice-influenced and open water stages per year, for 1995–2001 on the Little Southwest Miramichi at Lyttleton, New Brunswick. Ice-influenced stages are greater for the same discharge than open-water stages. (B) Stage-frequency plot for ice-influenced and open-water stages for 1995–2001. The 2.33-year recurrence ice-influenced stage is 1.08 m higher than the open-water stage of the same recurrence and is probably an avulsion trigger.

Fig. 12. Ice-jam on the Southwest Miramichi River in April 1998.

confinement to influence floodplain morphology (Ferguson and Brierley, 1999; Burge and Smith, 1999). 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). This relationship was also seen in the principal component analysis (Fig. 4, PCA 2) that was related to the accommodation space in valley bottoms. The greatest length of abandoned channels occurred in wide valleys that provided sufficient accommodation space. Sinuosity and braid index also increased with valley width because large valleys were necessary for meandering and long secondary channels to occur.

4.2. Wandering and single channel Miramichi rivers

Single channel Miramichi sections displayed energy characteristics similar to wandering Miramichi sections (Table 1, Fig. 7). Slope values in single channel sections were generally greater than in wandering sections (Fig. 6), but the specific stream power and width–depth ratio values similar (Fig. 7). Potential sediment mobility within single channel rivers seemed to be in a similar range or lower than in wandering Miramichi rivers because of greater median bed grain sizes and similar potential specific stream powers (Fig. 8). In a more detailed analysis, Burge (2004) determined that the in-channel characteristics (e.g. width–depth ratio, friction factor, bed slope, shear stress, D_{50}) of neighbouring single channel and wandering reaches of the Renous River were very similar. In fact, within main channels of the single channel and multiple channel patterns, only bed slope was found to be significantly greater in the main anabranch channels containing the thalweg.

4.3. River scales and anabranching

The analysis of indices of multiple channel rivers showed that the characteristics of anabranching rivers within the same region scale with river size. Larger rivers produced greater anabranching than smaller rivers. Anabranching characteristics within wandering Miramichi rivers were positively correlated to mean annual flood (Fig. 5). Rivers with a larger mean annual flood appear to be able to maintain a greater number of channels. Each anabranch diverts discharge away from the main channel and, with increasing number of anabranches, less discharge is available to maintain or create additional anabranches. Individual anabranches are formed by avulsions, or the deposition of mid-channel bars that become islands, but the maximum number of anabranches is limited by the supply of discharge that can be divided into individual anabranches. This analysis only explains how a greater number of anabranches can be maintained in a wandering river and not the mechanism for anabranch formation.

4.4. Causes of anabranching in wandering Miramichi rivers

The characteristics of wandering Miramichi rivers have little in common with the wandering rivers previously described in the literature; yet, they still exhibited a planform pattern similar to other wandering rivers. Wandering Miramichi rivers plotted lower than braided rivers on a slope–discharge plot, occurred well below the discriminant function between braided and meandering suggested by Van den Berg (1995), had migration rates similar to meandering, displayed width–depth ratios and specific stream powers within the range of meandering, and did not display evidence of high sediment input. In addition, anabranching did not increase with increasing specific stream power, also indicating a factor other than channel energy in the formation of multiple channels. The presence of mid-channel bars that form vegetated islands, a characteristic common on other wandering rivers, was also uncommon within wandering Miramichi rivers. Wandering Miramichi rivers displayed characteristics more similar to meandering than other wandering, braided or anastomosed rivers, indicating that the formation of anabranches was not due to a process related to high channel energy or sediment mobility, as in other wandering and braided rivers, or low channel energy and sediment mobility, as with anastomosed rivers.

The MFE hypothesis attempts to provide a unifying theory of anabranching in rivers. It states that anabranching forms channels that are more efficient in conveying water and sediment than single channels (Nanson and Huang, 1999; Jansen and Nanson, 2004). The MFE hypothesis for the formation of anabranches could explain the formation of multiple channels within Miramichi rivers if anabranches are more efficient than single channels. Anabranching channels within wandering Miramichi rivers did not appear to be more efficient than single channels. Multiple channel sections within wandering Miramichi rivers displayed greater total channel width than single channel sections (Fig. 10), indicating greater cross-sectional areas and lower velocities within multiple channels than single channels. Burge (2004) found that some individual anabranch channels displayed lower width–depth ratios than single channels, indicating some individual anabranch channels were more efficient than single channels. However, for the sum of all channels across a valley to be more efficient than single channels, the efficiency gain by the individual channels would have to be greater than the efficiency loss due to the addition of channel banks created by the additional channels. The MFE hypothesis was not supported on the anastomosed section of the Columbia River in British Columbia (Tabata and Hickin, 2003) but was supported on Magela Creek in northern Australia (Jansen and Nanson, 2004). Further research is needed to determine the efficiency characteristics of channels downstream of bifurcations.

By eliminating other processes, the remaining evidence for the formation of anabranching channels within the Miramichi suggests that a highly variable flow regime that causes frequent inundation of floodplains is responsible for the creation of anabranch channels. Floodwaters concentrate their erosive energy in low depressions and abandoned channels on floodplains, causing avulsions. High stages caused during ice-jams force flow onto floodplains, perhaps to a depth of 1 m above the floodplain approximately every 2 years (Fig. 11). Avulsions were observed on aerial photographs from 1945 to 1999 of the Little Southwest Miramichi and Renous Rivers. Avulsions commonly occur at the outside of a bend apex where channels have migrated to contact abandoned channels, as documented by other authors (Leddy et al., 1993; Smith et al., 1989). The outsides of bends are common avulsion sites because the water surface super elevation and higher velocities at the outer bank directs flow overbank onto floodplains. Burge and Lapointe (in press) present a model showing the formation of an avulsion into an abandoned channel in a wandering section of the Renous River. The overbank flow that caused the avulsion was attributed to an ice-jam, occurring at a downstream channel bifurcation. Sites were ice-jams occur are common in wandering rivers, including tight bends, shallow cross-sections, island heads and channel constrictions (Beltaos et al., 1989).

Avulsions due to flooding caused by ice-jams have been documented in other rivers (Hicks, 1993; Gay et al., 1998; Smith and Pearce, 2002). The Mackenzie River at Fort Providence, Northwest Territories experiences avulsions because of the frequent, high stages caused by ice-jams (Hicks, 1993). In other rivers, avulsions begin as gullies that form on floodplains during floods (Smith and Pearce, 2002; Gay et al., 1998). The flow that erodes gullies is displaced onto floodplains by ice-jams, blocking main channels in meander loops. These gullies migrate up valley through nick point recession until they encounter a main channel to form an avulsion.

Proving that an individual ice-jam produced an individual avulsion is difficult because the evidence for the process (ice) melts away and even though ice may be the primary cause for an avulsion, the new channel is eroded by water. While ice-jams provide a likely explanation for the formation of channel anabranching within the Miramichi basin, processes related to high sediment input, high channel energy or MFE may form a wandering pattern in other locations.

The channel characteristics of wandering Miramichi rivers are similar to meandering and therefore these rivers would normally be expected to produce single channels, yet they display a distinctively multiple channel character. This makes wandering Miramichi rivers different from the six types of anabranching rivers described by Nanson and Knighton (1996), including previously described wandering rivers. Wandering Miramichi rivers may represent another anabranching river type, defined by semi-permanent forested islands, moderate width–depth ratios, moderate specific stream powers, low migration rates, few mid-channel bars, coarse bed sediment and moderately frequent avulsions triggered by floods. Since avulsions are formed due to overbank flooding often produced by ice-jams, the regional climate that creates ice-jams, along with the location of wide river valleys, is responsible for the distribution of anabranching rivers in the region. Without the occurrence of overbank flood due to ice-jams, rivers within this region may produce only single channels.

4.5. Wandering Miramichi rivers and the river continuum of anabranching channel patterns

Nanson and Knighton (1996) show that rivers can anabranch under a very wide range of stream powers and have suggested a continuum of anabranching patterns from low energy anastomosed to high energy wandering rivers. Anabranch channels in wandering rivers with coarse sediment form due to high stream powers and high sediment input which leads to thalweg shoaling and avulsions, while anabranch channels in some anastomosed rivers form due to low stream power that causes in-channel aggredation, raising the channel above the floodplain and leading to avulsions (Smith, 1983; Smith and Putnam, 1980; Tabata and Hickin, 2003). Wandering Miramichi rivers may be seen as filling out this continuum with intermediate energy levels within the meandering zone. Therefore, the term wandering, and also anastomosing, could be replaced by the more general term anabranching. Anabranching is a common river feature, with the world's five largest rivers anabranching over 90% of their lengths (Jansen and Nanson, 2004). Many meandering rivers produce anabranch channels that last for short periods during neck cutoffs, prior to the formation of oxbow lakes. The terms wandering and anastomosing convey information about the planform pattern, energy levels and grain sizes of the rivers they describe and therefore these terms should be retained.

5. Conclusions

Valley width is the primary control on the location of wandering rivers within the Miramichi basin. Wider valleys form in less resistant bedrock and these larger valleys allow accommodation space for the formation of multiple channels.

Wandering Miramichi rivers are more similar to meandering rivers than other wandering, braided, or anastomosed rivers; yet, these rivers display an anabranching pattern. Energy levels, mid-channel bar formation, migration rates and width–depth ratios for wandering Miramichi rivers are all within the meandering range, lower than braided and higher than anastomosed. Given the evidence that meandering river characteristics dominate within wandering Miramichi rivers, a mechanism for anabranch formation that is not related to braiding (e.g. thalweg shoaling) or anastomosing (e.g. in-channel aggredation) is needed. Within wandering Miramichi rivers, frequent overbank flooding often concentrates flows into abandoned channels that erode upstream to contact main channels. These avulsion channels form new anabranches. The overbank flows within Miramichi rivers are associated with ice jamming within main channels. Once created, a greater number of anabranches may be maintained by greater discharge in larger rivers.

Wandering Miramichi rivers represent an anabranching river type different from the six types of anabranching rivers described by Nanson and Knighton (1996), including previously described wandering rivers. Although anabranching Miramichi rivers appear similar on aerial photographs and maps to previously described wandering rivers that display characteristics more similar to braided rivers (Nanson and Knighton, 1996), anabranching Miramichi rivers display many characteristics similar to meandering rivers. Therefore, Miramichi wandering rivers may represent a different anabranching river type, defined by semi-permanent forested islands, moderate width–depth ratios, moderate specific stream powers, low migration rates, few mid-channel bars, coarse bed sediment and moderately frequent avulsions that are triggered by floods, often related to ice-jams.

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