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Testing links between river patterns and in-channel characteristics using MRPP and ANOVA

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Abstract

This study tests the assumption that the characteristics of channels within multiple channel rivers are different from those of single channel rivers. Some river restoration approaches propose radical transformation of river patterns, from multiple to single channels, based on the link between river patterns and their in-channel characteristics. Determining the links between river patterns and their in-channel characteristics is complicated by differences in geology, history, climate and discharge among rivers. Furthermore, multiple channel rivers are composed of a mosaic of channel types with a range of in-channel characteristics. This study minimizes these problems by analysing a single river containing neighbouring single and multiple channel patterns with little change in discharge downstream, and by analysing all channel types. The study addressed two objectives: to determine the hydraulic geometry, energy, and sediment mobility characteristics of neighbouring single and multiple channel river patterns, and to test for statistical differences in these characteristics between patterns. The Renous River shows a wandering pattern for 11.5 km, with multiple channels around semipermanent islands and abandoned channels in the flood plain. The river displays a single channel river pattern where channels are confined by their valley walls, upstream and downstream of wandering. The analysis was conducted at three scales. First, the confined single channel and wandering multiple channel patterns were compared (pattern scale). Second, the confined channel pattern was compared to single and multiple channel sections within the wandering pattern (section scale). Third, all channel types were compared (channel type scale). Multi response permutation procedure (MRPP) and analysis of variance (ANOVA) were used to analyze differences between channels. Difference tests found no simple discrimination between the single and multiple channel river patterns of the Renous River. Tests between the single confined and multiple wandering channel patterns found few differences in the in-channel variables. The tests did find differences between multiple channel sections within the wandering pattern and confined single channels; however, a greater number of differences were found between multiple channel and single channel sections within the wandering pattern, highlighting the variability within the wandering pattern. Two groups emerged when all channel types were tested for differences: perennial main-channels containing the thalweg, and ephemeral side-channels. Therefore, side-channels define the in-channel characteristics of wandering rivers because few differences were found among main-channels in either pattern. This analysis suggests that all channel types, not just main-channels, should be investigated to obtain a complete picture of a river pattern prior to any restoration efforts.

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Engineers must exercise caution when applying the link between river patterns and in-channel characteristics to river restoration efforts.

Keywords: Wandering river; Confined river; Gravel-bed river; Side-channel; Multiple channel; River restoration

1. Introduction

Geomorphologists have long recognized that the patterns created by landforms provide information about their physical characteristics and processes (e.g., Davis, 1899). River patterns may be identified on aerial photographs or maps as channels with self-similar morphometric characteristics, different from other patterns. Sinuosity, braid index, number of channels, and location and type of bars may be used to discriminate between river patterns (meandering, braided, wandering, straight, and anastomosed) (e.g., Leopold and Wolman, 1957; Knighton and Nanson, 1993). In-channel characteristics, such as slope and discharge, have also been used to discriminate between river patterns (e.g., Leopold and Wolman, 1957). However, predicting river patterns from in-channel characteristics may be problematic because of difficulties in identifying the controlling variables (Carson, 1984a; Lewin and Brewer, 2001). Also, variability exists within river patterns that allow channels to be further divided into sections (e.g., multiple or single channel sections) or into individual channel types (e.g., individual perennial or ephemeral anabranch channels around an island) (Nanson and Knighton, 1996).

Classically, river pattern types were thought to vary from meandering to braiding (Leopold and Wolman, 1957). Wandering was added to describe a transitional pattern between braided and meandering with ephemeral or perennial anabranches around semi-permanent islands connected by single channel reaches (Neill, 1973; Church, 1983). Wandering rivers are a type of anabranching river with multiple channel sections composed of individual anabranches (Nanson and Knighton, 1996). Wandering rivers commonly transition downstream from braiding (Church, 1983; Carson, 1984b; Brierley, 1989; Brierley and Hickin, 1991), exhibit features of braided multiple channels and meandering single channels (Church, 1983), and have specific stream power values between braided and meandering (Nanson and Knighton, 1996). Many studies of river patterns have focused on end member meandering or braided channels that clearly display a given river pattern. Transitional river patterns are important for testing the links between river patterns and in-channel characteristics because differences are more subtle.

Differences between river patterns may be less apparent when determined on the same river (e.g., Ferguson and Ashworth, 1991) because of common geology, history, climate, and discharge regime. Characteristics of neighbouring braiding, wandering, and meandering sections may show few differences. Facies models developed on braided, wandering, and meandering reaches of the Squamish River were unrepresentative of local sediment organization (Brierley, 1989). Upward facies transitions predicted from the wandering facies model were not unique when compared to the braided and meandering models (Brierley, 1989). Also, planform facies assemblages of braided, wandering and meandering patterns on the Squamish could not be differentiated by river pattern (Brierley and Hickin, 1991). Since braided, wandering, and meandering facies are very similar, in-channel characteristics of these patterns may also be similar.

A continuum of river patterns occurs in nature where patterns grade from one to another with changing channel characteristics (Knighton and Nanson, 1993). Thresholds between patterns have been identified for end member patterns (e.g., Leopold and Wolman, 1957), but different river patterns show overlap in in-channel characteristics like energy and sediment conditions (Lewin and Brewer, 2001). Understanding the links between river patterns and energy and sediment characteristics is becoming increasingly important as engineers apply these relationships to determine channel restoration procedures (Rosgen, 1996). Rosgen (1996) proposed that, where appropriate, unstable river patterns (e.g., D4 or braided gravel-bed channels) may be engineered into stable patterns using the characteristics (width-depth ratio, bed slope, etc.) of a stable pattern (e.g., C4 or meandering gravel-bed channels) located within a region. This approach uses the development of hydraulic and sediment relationships for a given river pattern to extrapolate between reaches with similar characteristics. Reference reaches are used to determine the detailed characteristics (bed slope, width-depth ratio, etc.) of each river pattern (Rosgen, 1996). The relationship between the wandering river pattern and its channel characteristics is needed because wandering was excluded from the Rosgen (1996) classification. Wandering channels may be classed as unstable and be "restored" to a single meandering channel as has happened to braided channels in California (Kondolf et al., 2001).

The objective of this study is to test the assumption that the characteristics of channels within multiple channel rivers are different from those of single channel rivers. This paper addressed two objectives: to determine the reach scale hydraulic geometry, energy, and sediment mobility characteristics of neighbouring single and multiple channel patterns and to statistically compare these characteristics. Two opposing hypotheses were examined. Hypothesis one states that in-channel characteristics of neighbouring single channel and multiple channel patterns are different because single channel rivers have meandering characteristics and multiple channel rivers have braided characteristics. Therefore, average in-channel characteristics of neighbouring single channel confined and multiple channel wandering patterns are predicted to be different. Hypothesis two states in-channel characteristics of neighbouring single channel and multiple channel patterns are not different because they have the same discharge regime, sediment discharge, geology and climate. Therefore, in-channel characteristics of neighbouring single channel and multiple channel patterns are predicted to be similar.

2. Study area

Research was conducted on the Renous River located near the centre of the Miramichi drainage basin in New Brunswick, Canada (Fig. 1). The 60-m wide Renous has a mean annual flood of 147 m^3/s and drains 611 km ^{2} of the Miramichi highlands. The forest-covered Miramichi highlands consist of plateaus reaching 600 m (asl) in elevation with 250 m of local relief (Rampton et al., 1984). Forest logging is a major industry in the area but direct impacts on channel geomorphology are minor due to the low relief. The Renous shows a classic wandering pattern for 11.5 km, with multiple channels around semipermanent islands and abandoned channels in the

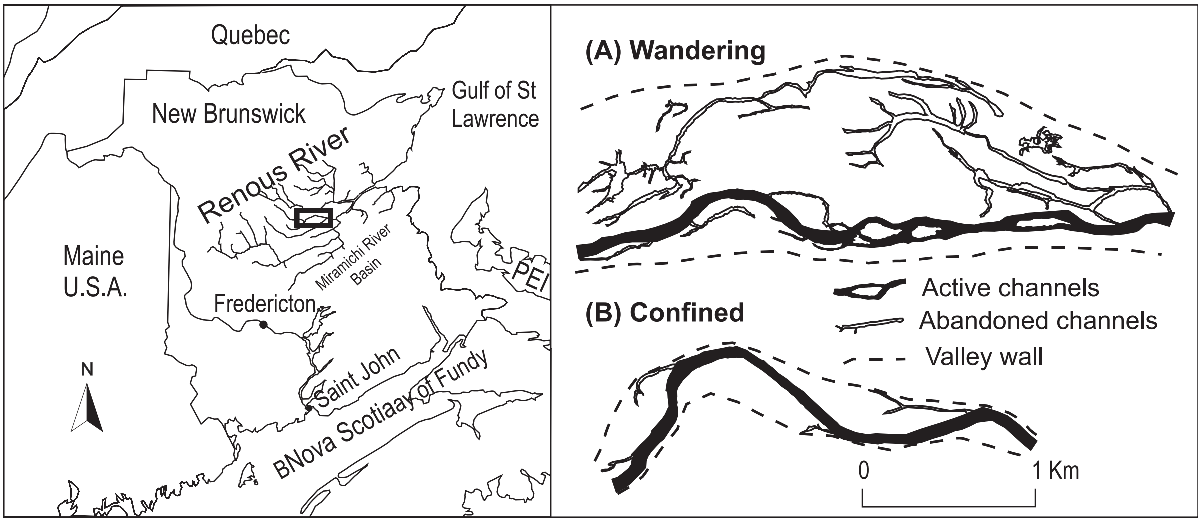

Fig. 1. Location map of the Renous River study reach. Examples of (A) wandering and (B) confined sections of the Renous River showing active channels, abandoned channels, and the location of the valley wall.

flood plain (Fig. 1A). Unlike the wandering Bella Coola (Church, 1983) and Squamish Rivers (Brierley, 1989), the Renous River does not physically have a transition between braiding and meandering. Wandering begins where valley width increases to accommodate multiple wandering channels and ends where valley width decreases downstream. Multiple channel reaches within the wandering section of the Renous are not explained by local perturbations in bedrock or by the entrance of large tributaries or alluvial fans into the valley. Confined sections have single channels with few islands where narrow valley bottoms restrict channel migration and limit space for the production of multiple channels (Fig. 1B). The term confined will be used to describe this channel type even though these channels not fully confined by the valley walls (as described by Brierley et al., 2002) but may be considered partially or semi confined because some channel migration still occurs.

The wandering Renous section displays a generally concave long profile with decreasing slope downstream (Fig. 2). Upstream and downstream of wandering, confined sections show little downstream trend in slope. The long profile of the Renous River displays numerous variations from the mean slope ($0.021\ mm^{-1}$) (Fig. 2). The bed D_{50} also shows much variability, displaying a general fining downstream that coarsens within the downstream confined section.

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 (60–80 cm) ice cover that commonly forms ice jams during spring breakup and occasionally during winter melts (Beltaos et al., 1989). Within the wider neighbouring Southwest Miramichi River, which also displays a wandering pattern, breakup occurs between March 22 and May 2; the average breakup date is April 14 (Allen and Cudbird, 1971). Evidence of ice jams is common on the Renous with frequent scars on trees and ice push marks on channel banks.

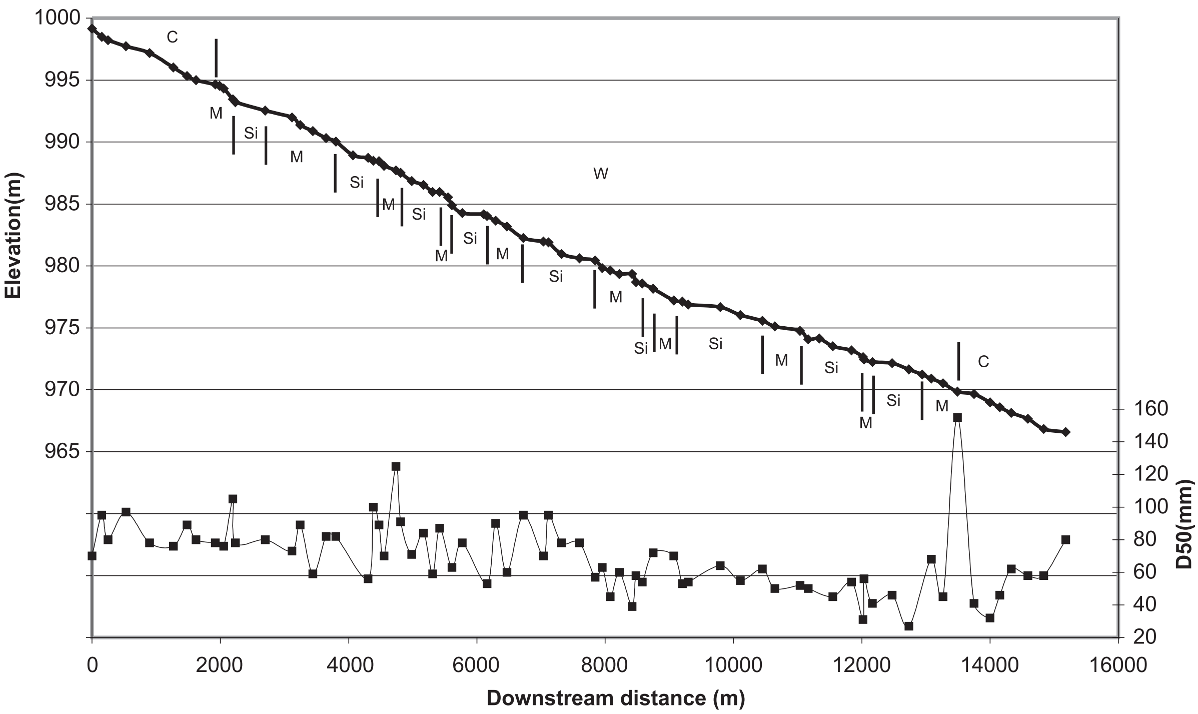

Fig. 2. Long profile and bed D50 for the confined and wandering patterns of the Renous River. Locations of confined (C), wandering (W) single (Si), and multiple (M) are denoted.

3. Methods

Forty-five reaches within 15 km of the Renous River were identified for analysis. Reaches were on average 470 (S.E. 26) m in length, delineated primarily on the basis of channel type, and secondarily on the basis of self-similar bed and water level slope. Detailed descriptions of channel types are given in Table 1. Seven confined, eleven single, twelve primary, seven secondary, four avulsion, and four abandoning reaches were identified within the study area. Single channels within wandering and confined channels were not uniform. To analyze their variability, long sections (>1 km) of confined and single wandering channels were divided into reaches with homogeneous bed and water level slope.

The analysis was conducted at three spatial scales: pattern (>1 km), section (<1 km) and channel type (<1 km). Fig. 3 displays the hierarchy of river patterns, sections and channel types used in the analysis. Fig. 4 provides maps of the locations of the channel types used in each analysis. First, the in-channel characteristics for the channels within the single channel confined and multiple channel wandering patterns were compared (pattern scale; Figs. 3A and 4A). Second, the in-channel characteristics for confined channels were compared to values for single and multiple channels within the wandering pattern (section scale; Figs. 3B and 4B). The classification of multiple and single channel sections within the wandering pattern was suggested by Church (1983) and Desloges and Church (1989). Third, the values of all channel types were compared (channel type scale; Figs. 3C and 4C).

Multi response permutation procedure (MRPP) and analysis of variance (ANOVA) were used to analyze differences between the confined and wandering patterns at the pattern, section, and channel type scales (Figs. 3 and 4). MRPP was conducted using PCORD (McCune and Mefford, 1999) software to determine if the entire suite of in-channel characteristics differed among channel types. Euclidean distance was used as the distance measure. MRPP is a nonparametric procedure that does not depend on assumptions such as normally distributed data or homogeneous variances, but rather depends on the internal variability of the data (Mielke, 1984, 1991; McCune and Grace, 2002). MRPP evaluates the uniqueness of a priori defined groups relative to all other possible permutations among groups of objects within the sample that have the same size structure of the proposed classification (Orlowski et al., 1995). MRPP was used successfully to test reach classifications on the Mississippi River (Orlowski et al., 1995). A complete

Table 1
Channels included in the three scales of analysis along with a detailed description of each channel type

(A) River pattern scale (>1 km)	(B) Sections scale (<1 km)	(C) Channel type scale (<1 km)	Detailed descriptions
Confined: single channel pattern partly confined by the valley walls	Confined	Confined	Perennial single main-channels partially confined by narrow valley walls, located upstream and downstream of wandering
Wandering: containing single and multiple channel sections	Single: single channels within wandering pattern	Single	Perennial single main-channels located within wandering pattern between a confluence upstream and a diffluence downstream
	Multiple: all multiple channels within wandering pattern	Primary	Perennial main-channels with the lower thalweg elevation of the two channels at the diffluence
		Avulsion	Ephemeral recent (<20 years old) side-channels with steep cutbanks on both banks, and commonly contained fallen trees
		Secondary	Ephemeral side-channels containing the higher thalweg elevation at the diffluence
		Abandoning	Ephemeral dying (>50 years old) side-channels that still flow during high stages, infilling with sediment, containing young vegetation (e.g., alder and grass)

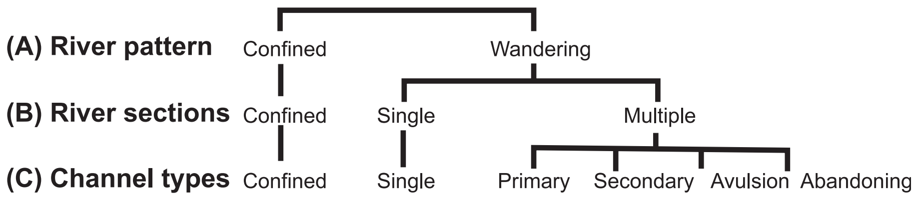

Fig. 3. Schematic diagram of the hierarchy of channels included in the river pattern, river section, and channel type scales of analysis.

description of MRPP is provided by Mielke (1984). Analysis of variance (ANOVA) tested for univariate mean differences between reaches using SYSTAT (1998). Bonferroni post hoc tests were conducted when more than two groups were compared at once. Water level slope, bed slope, shear stress, D_{50}, total stream power, specific stream power, friction factor, and D_{50} bed load showed downstream trends and were detrended using the residuals of statistically significant ($p < 0.05$) linear regressions between each variable and downstream distance. The residuals were then used in statistical tests, and statistical outliers were removed.

For each reach, hydraulic geometry, energy, and grain size and sediment mobility characteristics were determined. Hydraulic geometry characteristics included width, depth, width–depth ratio, normalized length, friction factor, and bed slope. Energy charac-

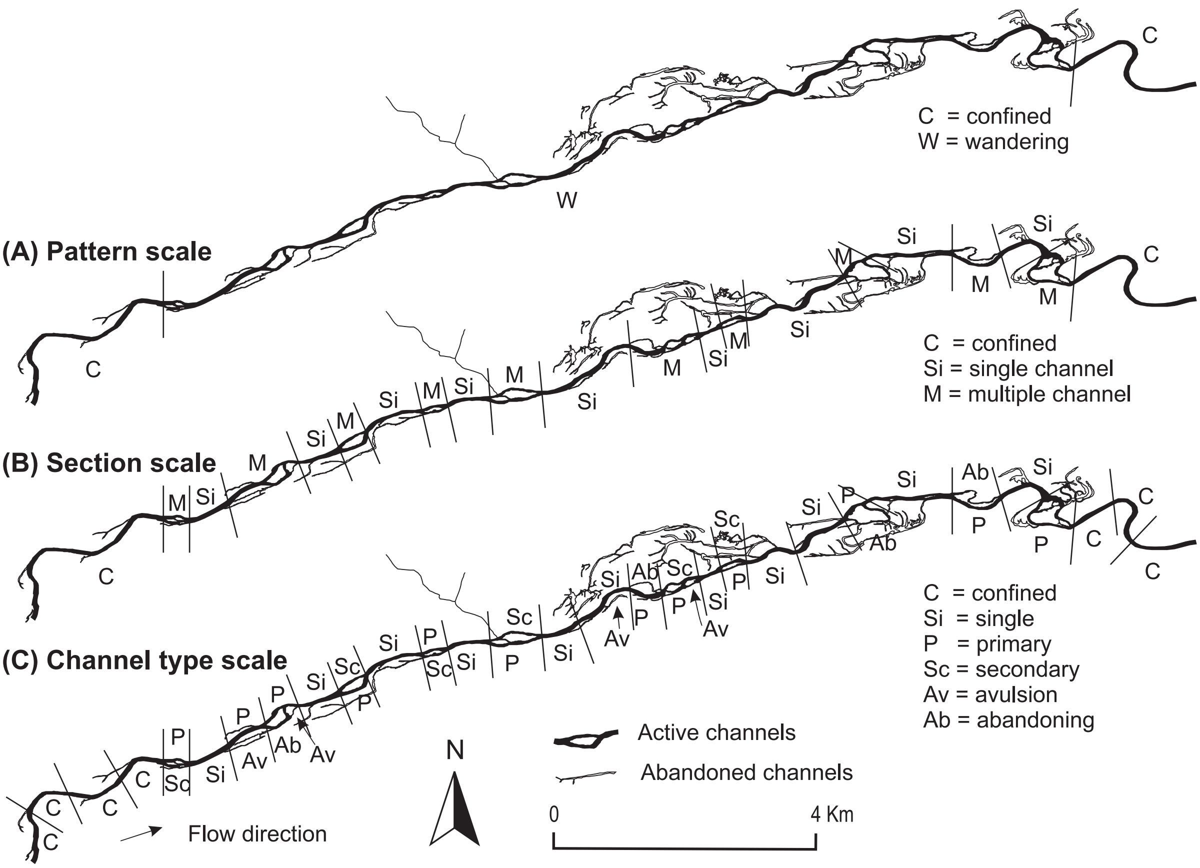

Fig. 4. Maps of classifications of channels at the (A) pattern, (B) section, and (C) channel type scales.

teristics included water level slope, shear stress, discharge, total stream power, and specific stream power. Grain size and sediment mobility characteristics included D_{50}, mobility ratio, sediment discharge, unit sediment transport rate, and bed load D_{50}. Three of the 45 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 level slope were determined.

The Renous River was mapped from 1:12,000 aerial photographs taken in 1999 using Arcview GIS 3.2 (1999) with image analysis. In the field, elevations of riffle thalwegs and bankfull water levels were surveyed with a laser level and downstream distances with a hip-chain during the summers of 2000 and 2001. Bankfull flow levels were surveyed using the highest elevation of organic detritus (leaves and grass) deposited on shrubs or trees during the previous years' high flows and generally followed flood plain elevations. Channel widths were measured in the field at riffles and supplemented with widths measured from the map of the Renous. For each reach, bankfull water level and bed slope were determined using a regression equation of bed or bankfull water level elevation and downstream distance. At least three elevation points were used for each slope calculation. Average bankfull depth was determined at the midpoint of each reach by subtracting bankfull water level elevation from riffle thalweg elevation, calculated using the regression equations. Width–depth ratio was determined using average bankfull width and depth for each reach. For confined and single reaches, length represented the length of homogeneous water level and bed slopes. For multiple channels, length was the distance between upstream diffluences and downstream confluences. Length was then normalized by the average bankfull width of main-channels (average single and confined width = 59.5 m). Bankfull discharge was determined using the mean annual maximum daily discharge from 1966 to 1994 (Environment Canada, 1997) for the McGraw Brook gauge on the Renous River. Discharge within each anabranch channel was estimated using the proportion of the cross-sectional area of each anabranch to the total area of all reaches across the valley.

The energy within each reach was estimated in four ways: water surface slope, total stream power, specific stream power, and shear stress. 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, per unit length, for overcoming friction and transporting sediment (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 ($\tau_o = \rho g R S$, 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 water surface slope as the energy slope and average bankfull depth at riffles as R.

Surface grain size distribution was determined at the heads of riffles by measuring the B axis of 100 randomly chosen clasts. The mobility of the bed was estimated using the mobility ratio ($Mr = \tau_o / \tau_c$, where τ_o is shear stress and τ_c is the critical shear stress, approximated by D_{50} in mm) (Lapointe et al., 2000). Mobility ratio relates shear stress to grain size; high values indicate greater bed mobility than low values. Sediment transport rates were estimated using shear velocity ($U^* = (\tau_o / \rho)^{1/2}$) and the D_{84}, D_{50} and D_{16} values at riffles applied to ACRONYM 1 (Parker, 1990). The ACRONYM set of sediment transport equations give reasonable results when applied consistently (e.g. Talbot and Lapointe, 2002). The ACRONYM output, unit transport rate, bed load D_{50} and calculated sediment discharge, were estimated for each reach. Finally, flow resistance was estimated using friction factor ($1/f^{1/2} = 1.36\ (D/D_{50})^{0.281}$), where f is the channel resistance or friction factor and D is bankfull depth at riffles (Bray, 1979).

4. Results

At the pattern scale, MRPP showed significant differences ($p = 0.04$) between the confined single channel pattern and wandering patterns (Figs. 3A and 4A) based on the entire suite of variables (Table 2). However, ANOVA revealed few univariate differences between the individual characteristics; only discharge ($p = 0.002$) and total stream power ($p = 0.02$) were different. Therefore, hypothesis one (in-channel characteristics of neighbouring single channel confined and multiple channel wandering patterns differ) is supported because differences were

Table 2
Mean values and standard errors for 16 variables used in analysis of the confined and wandering at the pattern scale

	Confined, $n=7$			Wandering, $n=35-38$		
	Mean	Std. Error	[a]	Mean	Std. Error	[a]
MRPP[b]	***X***[c]		a	***X***		b
Depth (m)	1.82	0.08	a	1.66	0.06	a
Width (m)	57.5	2.3	a	44.5	3.0	a
Width–depth ratio	32.0	2.0	a	28.1	1.8	a
Normalized length	8.3	0.9	a	7.9	0.4	a
Friction factor	0.086	0.005	a	0.087	0.003	a
Bed slope (%)	0.22	0.03	a	0.26	0.02	a
Water slope (%)	0.23	0.04	a	0.25	0.02	a
Shear stress (Pa)	41.4	8.6	a	39.8	2.3	a
Discharge (m^3 s^{-1})	**147.6**	0.0	a	**91.0**	7.3	b
Total stream power (W m^{-1})	**3326.6**	587.1	a	**2104.3**	200.6	b
Specific stream power (W m^{-2})	56.9	9.6	a	49.6	3.8	a
D_{50} (mm)	70	7	a	63	3	a
Mobility ratio	0.58	0.09	a	0.65	0.04	a
D_{50} bedload (mm)	62	6	a	56	2	a
Sediment discharge (g s^{-1})	59.35	43.36	a	32.60	6.61	a
Unit sediment trans. (g s^{-1} m^{-1})	1.00	0.72	a	0.96	0.22	a

[a] Means followed by a different letter are significantly different (ANOVA, $p<0.05$), and ranking of means is indicated by: a>b>c.
[b] MRPP tested for multivariate differences between groups.
[c] Bold values or X's denote at least one significant difference ($p<0.05$) from other variables.

found at the pattern scale. However, the differences do not appear to be due to meandering or braiding processes because no differences were seen in hydraulic geometry, sediment mobility, and only water level slope was greater in wandering. The wandering pattern was not homogeneous, but instead contained multiple and single sections (a classification suggested by Church, 1983); thus further analysis was required to determine more subtle differences not apparent at the pattern scale.

At the section scale, when the wandering pattern was dissected into single and multiple channel sections for the comparison with confined single channels (Figs. 3B and 4B), multiple channel sections showed multivariate differences (MRPP, $p=0.04$) from both single channel confined and single channel wandering sections (Table 3). Interestingly, confined single channels and single channel sections within the wandering pattern were indistinguishable, with no significant differences in any channel variable. Nine variables showed univariate differences between multiple and single channels within the wandering pattern, while only three differences were seen between multiple channels within the wandering pattern and confined single channels (Table 3), suggesting that there is higher variability within the wandering pattern than between the wandering and confined patterns. ANOVA showed many significant differences in hydraulic geometry among channel types. Confined and single sections had greater discharge ($p<0.0001$) and width ($p<0.007$) than multiple sections. Multiple sections were shorter ($p=0.05$), had greater bed slope ($p=0.002$), and smaller width–depth ratio ($p=0.02$) than single sections. Water level slope was steeper in multiple than single sections ($p=0.04$). Confined and single sections had greater total stream power than multiple sections ($p<0.02$). Multiple sections had greater mobility ratios and unit sediment transport rate than single sections ($p=0.006$ and $p=0.035$, respectively).

Apparently, hypothesis one is again supported because multiple wandering sections were different from confined single channel sections. In addition, hypothesis two is apparently supported because single and confined sections were not different. Multiple channel wandering sections contained different hydraulic geometry (lower width–depth ratio and higher bed slope), higher energy characteristics (water level slope), smaller grain size, and higher sediment mobility (mobility ratio and unit transport rate) than single wandering sections. Multiple channel sections were treated as homogenous at the section scale. To determine why multiple sections differ from other sections, all multiple channel types were investigated. Multiple channel sections are composed of four channel types: primary, secondary, avulsion and abandoning (Table 1; Fig. 3), allowing a further analysis based on channel type be conducted without knowledge of river pattern.

At the channel type scale, when confined single channels and each wandering channel type were considered separately, MRPP revealed two groups:

Table 3
Mean values and standard errors for 16 variables used in analysis at the section scale

	Confined, $n=7$			Multiple, $n=25-27$			Single, $n=10-11$		
	Mean	Std. Error	[a]	Mean	Std. Error		Mean	Std. Error	[a]
MRPP[b]	***X***[c]		b	***X***		a	***X***		b
Depth (m)	1.82	0.08	a	1.60	0.07	a	1.82	0.11	a
Width (m)	**57.5**	2.3	a	**37.9**	3.4	b	**60.8**	2.1	a
Width-depth ratio	32.0	2.0	ab	**25.3**	2.1	b	**35.1**	2.2	a
Normalized length	8.3	0.9	ab	**7.0**	0.5	b	**9.9**	0.8	a
Friction factor	0.086	0.005	a	0.087	0.003	a	0.087	0.004	a
Bed slope (%)	0.22	0.03	ab	**0.30**	0.02	a	**0.17**	0.03	b
Water slope (%)	0.23	0.04	ab	**0.28**	0.02	a	**0.19**	0.02	b
Shear stress (Pa)	41.4	8.6	a	42.9	2.8	a	32.2	3.4	a
Discharge (m^3 s^{-1})	**147.6**	0.0	a	**68.6**	6.2	b	**145.9**	1.7	a
Total stream power (W m^{-1})	**3326.6**	587.1	a	**1860.0**	245.8	b	**2703.9**	279.8	a
Specific stream power (W m^{-2})	56.9	9.6	a	51.00	4.9	a	46.0	5.8	a
D_{50} (mm)	**70**	7	a	**60**	3	b	**69**	5	a
Mobility ratio	0.58	0.09	ab	**0.73**	0.04	a	**0.47**	0.005	b
D_{50} bedload (mm)	62	6	a	55	2	a	59	4	a
Sediment discharge (g s^{-1})	59.35	43.36	a	40.81	8.62	a	13.18	6.04	a
Unit sediment trans. (g s^{-1} m^{-1})	1.00	0.72	ab	**1.25**	0.29	a	**0.24**	0.11	b

[a] Means followed by a different letter are significantly different (ANOVA, $p<0.05$), and ranking of means is indicated by: a>b>c.
[b] MRPP tested for multivariate differences between groups.
[c] Bold values or **X**'s denote at least one significant difference ($p<0.05$) from other variables.

main-channels and side-channels (Figs. 5 and 6; Table 4). Main-channels are ephemeral channels containing the thalweg that carry most of the flow and include, confined, single wandering and primary wandering channels. Side-channels are ephemeral channels that have higher elevations at channel diffluences, causing flow to stop at lower stages, and include secondary, avulsion, and abandoning channels. MRPP showed confined, single, and primary channels were indistinguishable (p>0.3); however each of these channel types differed from secondary, avulsion and abandoning channels ($p<0.05$). Secondary channels differed from all other types ($p<0.05$), while avulsion and abandoning channels were different from all other types ($p<0.04$) except from each other.

ANOVA displayed many significant differences among reaches (Table 4). 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

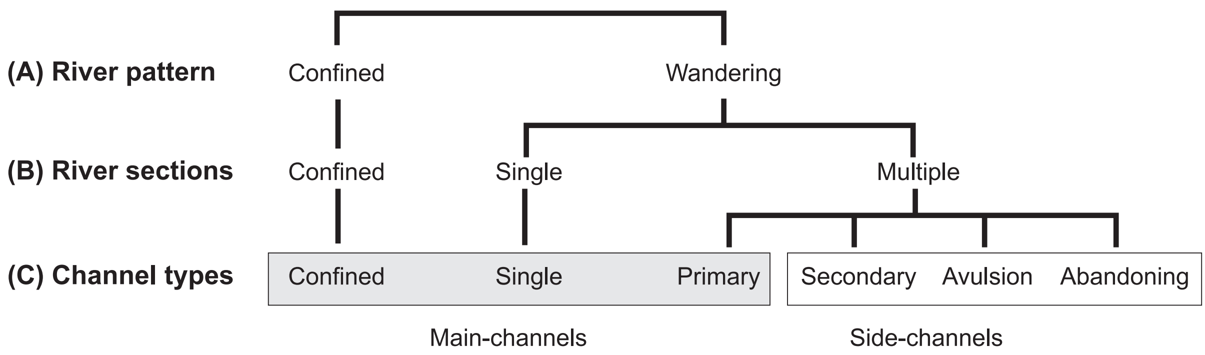

Fig. 5. Schematic diagram showing the classification of main-channels and side-channels found in the analysis.

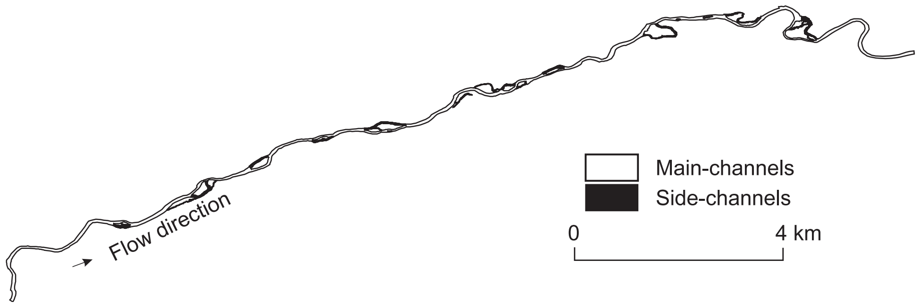

Fig. 6. Map of reclassification of the Renous River into main-channels and side-channels as suggested by the analysis.

were longer than primary, secondary, and avulsions ($p < 0.04$). Discharge showed differences at the reach scale ($p < 0.001$); however, confined and primary, and avulsion and abandoning reaches were not different. Specific stream power was greater in avulsions than abandoning reaches ($p < 0.04$). Single and primary reaches were greater than avulsion and 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 ($p < 0.02$).

Anabranches fundamentally define the planform patterns of multiple channel rivers (Nanson and Knighton, 1996). But, primary anabranch channels were more similar to single wandering channels and confined single channels than secondary, abandoning or avulsion anabranch channels. Therefore, all anabranch channels do not define the in-channel characteristics of the wandering Renous River; rather side-channels, off main-channels, define the in-channel characteristics.

5. Discussion

This study lends support for both hypotheses because some sections of neighbouring single channel confined and multiple channel wandering patterns were similar while other sections were different. Initially, the single channel pattern appeared to be similar to meandering and multiple channel patterns appeared to be similar to braiding as hypothesized. However, primary reaches within multiple channel sections that were predicted to show braided characteristics showed few differences from single channel wandering or confined reaches. Also, confined and single wandering sections were indistinguishable because similar processes maintain both single channel types regardless of where they occurred. These results are constant with those of Brierley (1989) and Brierley and Hickin (1991) who found no association between river pattern and facies models or river pattern and planform facies assemblages. Nanson and Knighton (1996) also found that anabranching rivers were not distinguishable on the basis of slope and discharge from their single channel counterpart. This suggests that similarities in discharge regime, sediment discharge, geology, and climate have produced similar channels regardless of channel pattern.

In-channel characteristics were best differentiated by channel type. Based on the in-channel characteristics the channel types of the Renous River may be differentiated based on main-channels and side-channels. This is not the pattern-based differentiation of multiple and single channels within the wandering pattern, suggested by Church (1983) or Desloges and Church (1989) for the wandering Bella Coola River. However, because of regional differences between the Bella Coola and Renous Rivers, the classification suggested by Church (1983) and Desloges and Church (1989) for Bella Coola River may still be appropriate but requires testing. The greatest number of differences between the wandering and confined single channel patterns was due to of side-channels occurring within multiple sections. Therefore, differences between the confined and wandering patterns are probably not associated with meandering or braiding processes but depend on side-channel processes revealed at the smallest scale of investigation. Side-channels also

Table 4
Mean values and standard errors for 16 variables used in analysis at the channel type scale

	Confined, $n=7$			Single, $n=11$			Primary, $n=12$			Secondary, $n=7$			Avulsion, $n=4$			Abandon, $n=2-4$		
	Mean	Std. Error	[a]	Mean	Std. Error	[a]	Mean	Std. Error	[a]	Mean	Std. Error	[a]	Mean	Std. Error	[a]	Mean	Std. Error	[a]
MRPP[b]	***X***[c]		b	***X***		bc	***X***		bc	***X***		d	***X***		a	***X***		a
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	abc
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	0.00	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
Discharge ($m^3 s^{-1}$)	**147.6**	0.0	a	**145.9**	1.7	a	**96.8**	5.5	b	**62.5**	2.2	c	**26.5**	3.2	d	**36.4**	11.0	d
Total stream power ($W m^{-1}$)	**3326.6**	587.1	a	**2703.9**	279.8	ab	**2632.6**	419.8	ab	**1772.7**	195.4	bc	**1015.8**	116.2	c	**538.8**	172.1	c
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	abc
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
Sediment discharge ($g s^{-1}$)	59.35	43.36	a	13.18	6.04	a	52.90	14.85	a	44.77	15.64	a	27.47	1162	a	1.02	0.69	a
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

[a] Means followed by a different letter are significantly different (ANOVA, $p<0.05$), and ranking of means is indicated by: a>b>c.
[b] MRPP tested for multivariate differences between groups.
[c] Bold values or **X**'s denote at least one significant difference ($p<0.05$) from other variables.

differentiate multiple channel river patterns from single channel patterns on maps and aerial photographs because, without side-channels, only single channels exist (Knighton and Nanson, 1993).

5.1. Main-channels

Main-channels were similar; primary channels contained only smaller discharge, normalized length, and greater bed slope than single reaches. Discharge in primary reaches was lower because flow divides between two channels. Within main-channels, discriminating multiple from single channels may be possible using bed slope in primary and single channels. Bed slope often increases downstream of channel diffluences (Leopold and Wolman, 1957), and higher bed slope may also be associated with short channels that may have lower sinuosity than single channels. Bed slope in primary channels increases due to aggradation near the channel entrance, degradation at the channel confluence, or a decrease in the sinuosity of the channel. Slope may be higher in primary channels to increase sediment transport through multiple channel reaches by the development of bedwaves (described by Church and Jones, 1982). Primary channels were not similar to braided channels because stream power (total and specific) was not significantly higher in primary channels; width–depth ratios were relatively low; and mid-channel bars, associated with braided rivers, were absent.

Single channel sections within the Bella Coola have been categorized as transportation zones, and multiple channel sections as sedimentation zones (Church, 1983). This analysis reveals no reason to classify single channel reaches within the Renous River as transportation zones because single channels within confined and wandering patterns were indistinguishable and no significant difference was seen in sediment discharge between confined and single reaches. In fact, single channels had lower sediment discharge than primary channels, making it difficult to justify that sediment transport is enhanced in single channels. Moreover, single channels within wandering had lower sediment discharge than any other channel type except abandoning, which may indicate that they may be a depositional location (perhaps the depositional side of bedwaves). Primary and secondary channels within multiple channel sections displayed high sediment discharge and therefore may be the erosional side of bedwaves. This is contrary to Church (1983) who found that sedimentation occurred in multiple channel sections. Differences between the Renous and Bella Coola Rivers may be due to large differences in regional setting and do not preclude the existence of depositional and erosional zones within wandering rivers. This analysis suggests that the zone of sedimentation may occur within single channels upstream of multiple channel sections and that sediment transport may be enhanced in multiple channel sections. The differences between depositional western wandering rivers (Church, 1983; Desloges and Church, 1989; Brierley, 1989; Brierley and Hickin, 1991) and more erosional eastern wandering rivers (Renous River) suggest that the wandering river pattern may be a product of convergence or equifinality where multiple processes produce similar patterns.

5.2. Side-channels

The in-channel characteristics of smaller side-channels, off main-channels, define the wandering river pattern. Side-channels include smaller ephemeral and variable secondary, avulsion, and abandoning anabranches. Differences seen in in-channel characteristics were created by smaller discharge in side-channels, sediment routing of fine sediment into side-channels, and side-channel dynamics. Side-channel reaches contained less than half of the discharge and a higher entrance elevation at diffluences than main-channels. Finer sediment is probably routed into side-channels that do not contain the thalweg, while larger sediment is routed down the thalweg into main-channels. This causes the grain size within side-channels to be smaller than main-channels.

Side-channels showed high variability and ranged from the short, high slope, high energy, and high mobility avulsion channels to the long, low slope, low energy and low sediment mobility abandoning channels. Abandoning reaches were less active with lower bed slope and discharge and were longer than secondary, while avulsions had smaller width and discharge than secondary reaches. Abandoning channels are dying secondary channels, while avulsion channels are growing to become secondary channels. Therefore, abandoning and avulsion channels contained similar characteristics to secondary channels. Secondary channels had greater discharge than avulsion or abandoning channels and greater width than avulsion channels (abandoning had variable width depending on infill rate). However, secondary reaches showed multivariate differences from all other reach types, and avulsion and abandoning reaches were different from all reach types except each other.

Surprisingly, avulsions and abandoning reaches were very similar. These differences could be due to insufficient data because only four avulsion channels and two to four abandoning channels were analysed. Even so, avulsion and abandoning reaches showed differences in energy characteristics, with the greatest differences in water level slope and specific stream power. Despite these differences, hydraulic geometry characteristics (except length and bed slope) and grain size and sediment mobility characteristics were not different between avulsion and abandoning reaches. One would expect bed mobility of abandoning to be lower than avulsion channels. The mean mobility ratio was lower in abandoning; however, it was not significantly different because of the high variance in abandoning reaches.

Growing avulsion channels have higher energy characteristics than abandoning channels; and one might assume that hydraulic geometry and grain size and sediment mobility might also be different. Hydraulic geometry and grain size characteristics were similar because avulsion channels normally occur into abandoned channels (Gottesfeld and Johnson-Gottesfeld, 1990), and therefore avulsions inherit abandoned channel characteristics. Where flood plains become disconnected from the channel this process no longer occurs (Brizga and Finlayson, 1990; Brooks et al., 2003). Abandoning channels receive fine gravel and sand from the main-channel at their heads, while organic material and fine sediment is deposited within lower portions of the channel. When the channel becomes completely abandoned, it no longer receives gravel and sand from upstream and slowly infills with fine sediment and organic material. When an avulsion occurs into an abandoned channel from the main-channel, the avulsion channel cuts into a flood plain composed of coarse material at its entrance. The downstream end of the new avulsion was an abandoned channel, and therefore the avulsion inherits abandoned channel characteristics. As the avulsion continues, sediment is transported down the avulsion into the former abandoned channel and if the avulsion grows to become a secondary channel, gravel is transported through the reach and it loses semblance of its heritage. Therefore, because high-energy avulsions preferentially use abandoned channels, they inherit the characteristics of low-energy abandoning reaches.

5.3. Implications

This research has implications for the application of river restoration procedures based on river pattern classification and the effect of reach variability on fish habitat.

5.3.1. River restoration based on river pattern classification

Caution should be exercised when "restoring" rivers by changing the river pattern. In California, braided rivers have been "restored" to a single meandering channel that was quickly abandoned, reverting the river back to a braided state (Kondolf et al., 2001). The Renous is undisturbed, supports an Atlantic salmon (*Salmo salar*) run, and requires no restoration, even though it displays a multiple channel pattern. High width–depth ratio channels may provide poor fish habitat and have been used to discriminate between channels that need restoration and those that do not (Rosgen, 1996). It is important to note that a width–depth ratio may be calculated in one of two ways: for each individual channel or for all channels in a valley cross-section. Width–depth ratios for this study were calculated for each individual channel and were found to be lower generally lower in multiple channels (primary, secondary, avulsion and abandoning) than single channels (confined and single) (Table 4). However, if all the channels across the valley were used to calculate the width–depth ratio, the average width–depth ratio is much higher (54) than for confined and wandering single channels (32 and 35, respectively). The width–depth ratio for the Renous River calculated using all the channels across the valley is above the width–depth ratio of D4 streams described by Rosgen (1996). Since the width–depth ratio for multiple channels within the Renous is greater than the width–depth ratio of neighbouring single channels that may be used as reference reaches, the Rosgen (1996) approach may indicate that the Renous River is in need of restoration.

Analysis of historical aerial photographs showed that the wandering pattern of the Renous has been sustained for at least 50 years. If the multiple channel section was engineered into a single channel, it would probably revert back to multiple channels because of frequent high-stage events caused by ice jams, common in the region (Beltaos et al., 1989). These high stage events cause avulsions that create the multiple channels. If the slope was lowered by increasing sinuosity, bed load transport would decrease, causing the channel to aggrade and also enhancing the formation of multiple channels through avulsions. Therefore, understanding the avulsion mechanisms that create multiple channels is paramount before restoration of multiple channel systems begins.

In-channel characteristics within wandering rivers are highly variable, and therefore reference reaches should be long enough to accurately represent the river pattern. However, the single and multiple channel patterns on the Renous River had very similar characteristics. Within the wandering pattern, primary channels had significantly higher bed slope than single channels; however, the average of wandering primary and single channels displayed the same slope as single confined channels. Also, the technique used to calculate width–depth ratio, identified as a critical value in assessing river stability, is very important. As this analysis has shown, a highly variable pattern such as wandering is best described by analysis of many different types of channels. River engineers need to be very careful when deciding on radical transformations of multiple channel rivers to single channel patterns. In fact, the variability created by multiple channels has been shown to enhance fish habitat.

5.3.2. Reach variability and habitat heterogeneity

Wandering river channels were more variable than confined single channels. Variability within rivers creates habitat heterogeneity important for different life stages of various species of fish on the east and west coasts (Peterson, 1982; Tschaplinski and Hartman, 1983; Brown and Hartman, 1988; Swales and Levings, 1989; Nickelson et al., 1992; Komadina-Douthwright et al., 1997). 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, both spatially and temporally (Dolloff, 1987). Side-channels within east coast wandering rivers provide over-wintering habitat for kelt, adult Atlantic salmon (*S. salar*) (Komadina-Douthwright et al., 1997) and thermal refuge for juveniles (Burge, unpublished data). Much data exists for west coast secondary channels that provide habitat for rearing juvenile coho salmon (*Oncorhynchus kisutch*) (Peterson, 1982; Tschaplinski and Hartman, 1983; Brown and Hartman, 1988; Swales and Levings, 1989; Nickelson et al., 1992), a species whose population is in decline. Production of wild coho salmon smolt in most salmon spawning streams may be limited by the availability of adequate winter habitat (including side-channels) where they emigrate to seek shelter in low-velocity water away from the main-channel, thus increasing the survival rate (Peterson, 1982; Brown and Hartman, 1988; Tschaplinski and Hartman, 1983; Nickelson et al., 1992). Sockeye (*Oncorhynchus nerka*) and steelhead (*Salmo gairdneri*) also use side-channels (Hartman and Brown, 1987). Experiments showed that when steelhead juveniles were transplanted into side-channels, smolt were 31 times more abundant and had 10 times more biomass than those raised in main-channels (Mundie and Traber, 1983). Knowledge of the processes that create and maintain side-channels is needed because of their importance in maintaining habitat heterogeneity (Thorp, 1992).

6. Conclusions

Determining the links between river patterns and their in-channel characteristics is complicated. This is particularly true for multiple channel rivers because they have a mosaic of channel types and characteristics. Channels within neighbouring single channel confined and multiple channel wandering patterns were similar. Smaller side-channels off main-channels define the wandering river pattern. Side-channels (including secondary, avulsion, and abandoning reaches) drive differences in hydraulic geometry, energy, and sediment mobility characteristics between the wandering and confined patterns. Although multivariate differences between confined and wandering patterns were found, these differences were due to smaller discharge and total stream power driven by smaller multiple channels included in the wandering pattern. More detailed multivariate analysis revealed that multiple sections differed from confined and single sections, but confined and single sections were indistinguishable. Univariate analysis showed that multiple sections were more different from single than confined sections because of greater variability within confined than single section variables. Multiple sections had different hydraulic geometry, higher energy characteristics (water level slope), smaller grain size, and higher sediment mobility than single sections. At the channel type scale, two groups emerged: main-channels and side-channels. Main-channels include reaches that contain the thalweg; have perennial flow; and consist of confined, single and primary channels.

Side-channels include ephemeral channels that do not contain the thalweg and consist of secondary, avulsion, and abandoning channels. The in-channel characteristics of multiple channels do not define the wandering Renous River. Side-channels, off main-channels, define the in-channel characteristics of this wandering pattern.

When analysing differences between neighbouring river patterns, all channel types, not just main-channels, must be investigated to obtain a complete picture of a pattern and the links between the channel types and their in-channel characteristics. Care must be taken to determine what the differences between channel patterns represent, particularly when being applied to restoring disturbed systems. Side-channels increase habitat heterogeneity within wandering rivers, providing important habitat for different life stages of aquatic organisms.

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