Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **30**, 1227–1250 (2005)
Published online 23 June 2005 in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/esp.1196

Understanding the temporal dynamics of the wandering Renous River, New Brunswick, Canada

Leif M. Burge[1]* and Michel F. Lapointe[2]
[1] *Department of Geography and Program in Planning, University of Toronto, 100 St. George Street, Toronto, Ontario, M5S 3G3, Canada*
[2] *Department of Geography McGill University, 805 Sherbrooke Street West, Montreal, Quebec, H3A 2K6, Canada*

**Correspondence to: L. M. Burge, Department of Geography and Program in Planning, University of Toronto, 100 St. George St., Toronto, M5S 3G3, Canada. E-mail: burge@geog.utoronto.ca*

Abstract

Wandering rivers are composed of individual anabranches surrounding semi-permanent islands, linked by single channel reaches. Wandering rivers are important because they provide habitat complexity for aquatic organisms, including salmonids. An anabranch cycle model was developed from previous literature and field observations to illustrate how anabranches within the wandering pattern change from single to multiple channels and vice versa over a number of decades. The model was used to investigate the temporal dynamics of a wandering river through historical case studies and channel characteristics from field data.

The wandering Renous River, New Brunswick, was mapped from aerial photographs (1945, 1965, 1983 and 1999) to determine river pattern statistics and for historical analysis of case studies. Five case studies consisting of a stable single channel, newly formed anabranches, anabranches gaining stability following creation, stable anabranches, and an abandoning anabranch were investigated in detail. Long profiles, hydraulic geometry, channel energy, grain size and sediment mobility variables were calculated for each channel.

Within the Renous study area, the frequency of channel formation and abandonment were similar over the 54 years of analysis, indicating that the wandering pattern is being maintained. Eight anabranches were formed through avulsions, five were formed through the emergence of islands from channel bars and 11 anabranches were abandoned. The stable anabranch pair displayed similar hydraulic geometry and channel energy characteristics, while unstable anabranch pairs did not. The anabranch pair that gained stability displayed more similar channel energy characteristics than the anabranch pair that was losing stability (abandoning). It appears that anabranch pairs with similar energy characteristics are more stable than anabranches where these characteristics are out of balance. This is consistent with the hypothesis that anabranch pairs of similar length will be more stable than those with dissimilar lengths.

Keywords: river pattern maintenance; wandering river; anabranch; avulsion; channel stability; gravel-cobble river

Received 9 January 2004
Revised 22 September 2004
Accepted 18 November 2004

Introduction

Wandering rivers are composed of multiple channel reaches that divide into individual anabranches around semi-permanent forested islands, connected by single channel reaches (Neill, 1973; Church, 1983). The processes maintaining wandering rivers through time occur at multiple scales. At the reach scale, the location of individual anabranches changes, while at the river scale the wandering river pattern will persist when the long-term rate (over decades or centuries) of anabranch formation equals that of anabranch abandonment. If anabranch formation is greater than abandonment a river may become more anabranching, or if anabranch abandonment is greater than creation a single channel may be formed.

Church (1983) investigated patterns of instability within the wandering Bella Coola River in British Columbia by studying the temporal dynamics of the system over 81 years. Multiple channel sections on the Bella Coola were associated with the expansion of a cross-valley alluvial fan blocking sediment transfer downstream, and the erosion of neoglacial moraines (Church, 1983). New anabranch channels were formed but a greater number of anabranch channels were abandoned during the study period. Therefore, the number of single channel sections on the Bella Coola River increased through time. The increase in channel stability is related to the exhaustion of sediment introduced from neoglacial moraines (Church, 1983).

The Renous River, New Brunswick, was chosen for this research because it displays a wandering pattern, but does not have alluvial fans entering the valley; nor does it have erosion of neoglacial terraces overloading the river with sediment (Burge, in press). Bedload is supplied from the floodplain through channel migration and the channel bed. Therefore, the wandering pattern of the Renous River may be relatively stable over a number of decades or centuries and be maintained by processes other than an over-supply of bedload sediment. The Renous River also sustains a run of Atlantic salmon (*Salmo salar*), and a better understanding of natural river processes may assist in maintaining the ecological integrity of this important salmon river. River managers often consider short spatial scales (channel reaches) and timescales (1–5 years) in making management decisions; a longer-term perspective based on geomorphologic analysis may increase river managers' awareness of the dynamics of river channels (Kondolf *et al*., 2002). Understanding the conditions under which anabranches are formed, maintained and abandoned within wandering rivers over a number of decades is therefore important for successful restoration and effective management of multiple channel rivers.

This research investigates the long-term (54-year) average state of a wandering river and then explores the detailed channel changes. The study had two objectives: (1) to examine the temporal dynamics of a wandering river using a conceptual model and (2) to investigate and test the conceptual model using historical analysis of channel locations and geometry, and field-based channel characteristics of case studies.

Study Area

The Renous River is located near the centre of the Miramichi drainage basin, New Brunswick (Figure 1, inset). The Renous shows a wandering pattern for 11·5 km, with multiple channels around islands, and abandoned channels within the floodplain (Figure 1). The Renous is 60 m wide, has a mean annual flood of 147 $m^3 s^{-1}$, an average bankfull specific stream power of 49·6 W m^{-2} and a mean D_{50} of 63 mm and drains 611 km^2 of the Miramichi plateau (Burge, 2004). Wandering begins where valley width increases to accommodate multiple wandering channels and ends where valley width decreases downstream (Figure 1). Confined sections with single channels and few islands occur where narrow valley bottoms restrict channel migration and limit space for the production of multiple channels (Figure 1). The wandering Renous section shows a concave long profile (from 0·0036 to 0·0019 slope) and downstream fining of sediment (D_{50} from 77 mm to 47 mm) (Burge, 2004). Multiple channel reaches within the Renous are not explained by local perturbations in bedrock or the entrance of large tributaries or alluvial fans into the valley. The wandering section of the Renous is not located between braiding upstream and meandering downstream, unlike the Bella Coola (Church, 1983) and the Squamish (Brierley, 1989) rivers in British Columbia.

At McGraw Brook, in the centre of the study reach, the mean monthly air temperature varies between −11·8 °C in January and 18.8 °C in July, with April to October temperatures above freezing (Caissie and El-Jabi, 1995). During winter, Miramichi rivers form a thick (0·5 m) ice cover that commonly forms ice-jams during spring break-up and occasionally during winter melts (Figure 2(A)) (Beltaos *et al*., 1989). These ice-jams leave large ice blocks on the floodplain and on the channel edge (Figure 2(B)). Within the wandering reach of the larger neighbouring Southwest Miramichi, break-up occurs between March 22 and May 2, with the average break-up date on April 14 (Allen and Cudbird, 1971). Ice-jams may cause avulsions by forcing water over floodplains, initiating scour within the floodplain and creating new channels or may cause the reoccupation of paleochannels (Hicks, 1993; Gay *et al*., 1998; Smith and Pearce, 2002). Evidence of ice-jams is common on the Renous with frequent scars on trees (Figure 3(A)), boulder pavements (Figure 3(B)), and ice push marks on channel banks. Boulder pavements, the most common and stable feature formed by river ice, are composed of a thin veneer of boulders that protect the weaker underlying material (Mackay and Mackay, 1977). Boulders are aligned with their long axis downstream and have many striations caused by overriding ice.

The Anabranch Cycle

The anabranch cycle was developed through literature reviews and field observations. Formation and abandonment processes occurring at the scale of the individual anabranch are hypothesized to maintain the wandering pattern. The model displays five stages represented by numbered boxes that are linked by lettered arrows that indicate the

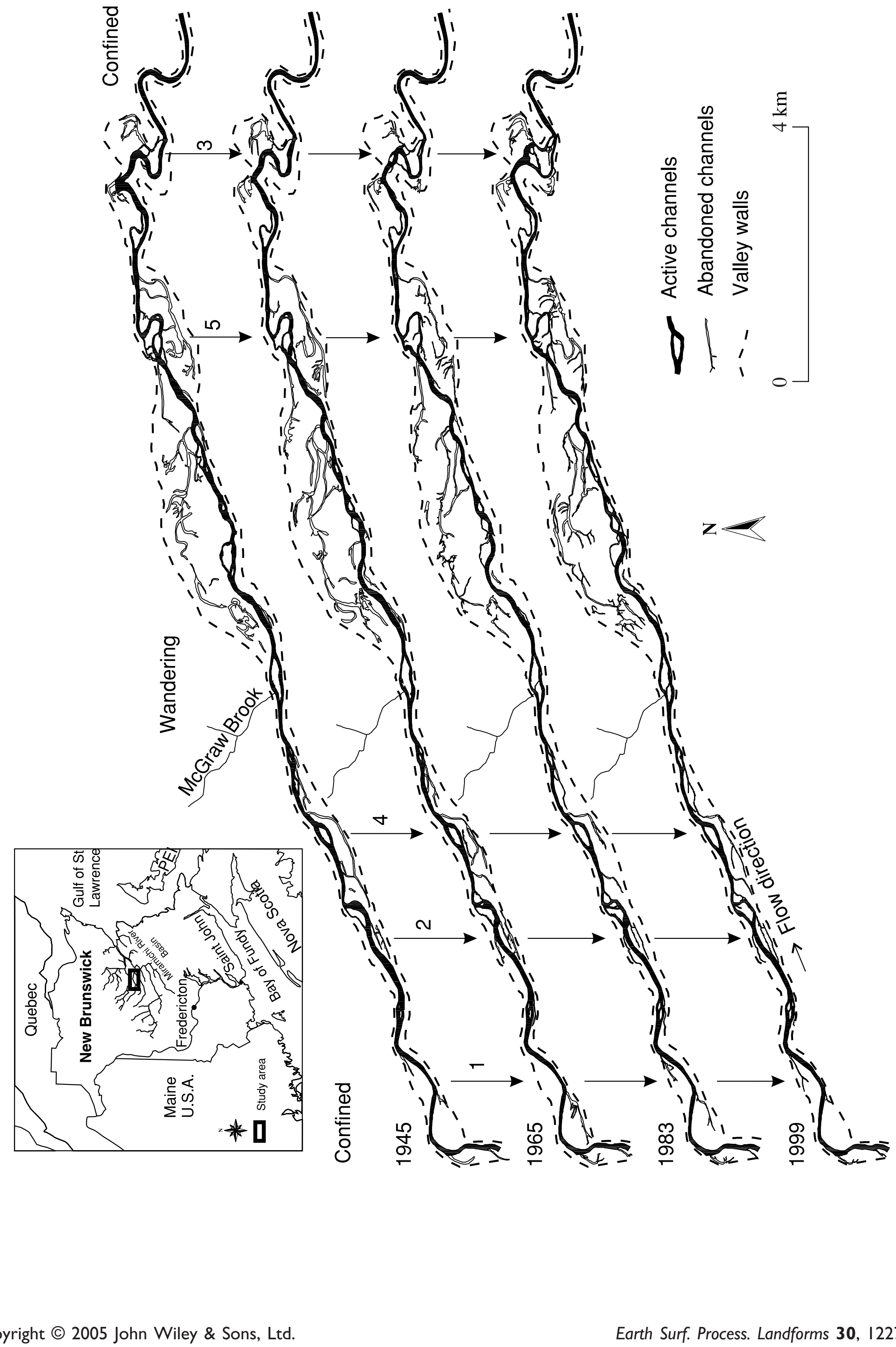

Figure 1. Maps of the wandering section of the Renous River, New Brunswick, for 1945, 1965, 1983 and 1999, redrawn from aerial photographs. Arrows point to specific system stages discussed in the text and enlarged in Figure 7. Inset map and map of 1999 channel after Burge (2003).

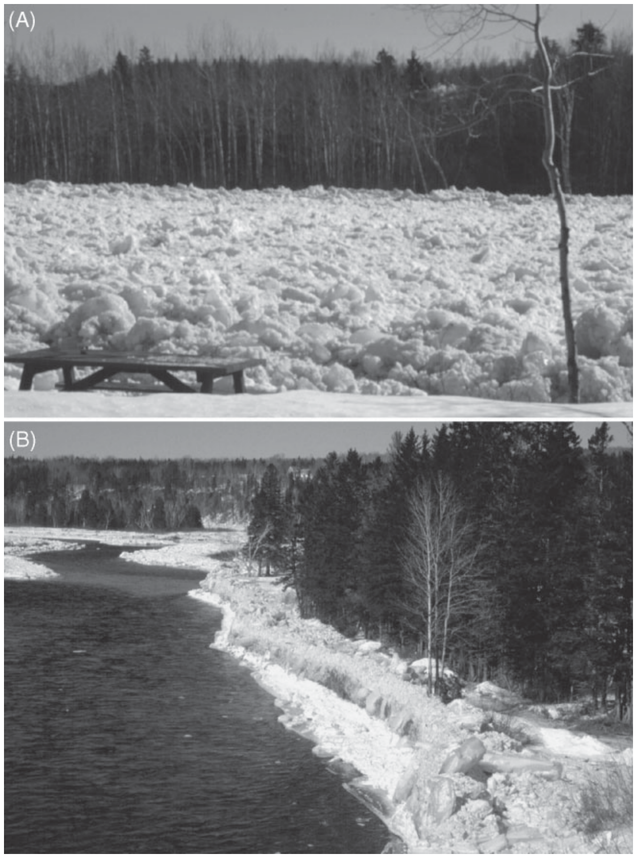

Figure 2. (A) Ice-jam on Southwest Miramichi during the spring of 1998. (B) Wall of ice on the channel bank following ice-jam on the Southwest Miramichi River in the spring of 1998.

processes that shift channels between stages (Figure 4). The system stages include stable single channels (Figure 4 box 1), unstable single channels (Figure 4 box 2), anabranch geometries that gain stability (Figure 4 box 3), stable anabranches (Figure 4 box 4) and anabranch geometries that lose stability (Figure 4 box 5). Stability refers to the potential of a channel section to change system stages, from a single channel to multiple channels or vice versa, or may also be thought of as the longevity of the channel geometry. Unstable stages are short-lived channel geometries that have the potential to adjust relatively quickly to stable stages. Stable stages are long-lived channel geometries that may adjust to unstable stages following a long period of stability. Central to the anabranch cycle model are avulsion triggers, represented by an oval in the model, that displace flow onto the floodplain during high stages to generate new channels. This type of avulsion does not cause a large-scale relocation of the river channel to another location in the valley (first-order avulsion of Nanson and Knighton, 1996), but instead causes a local reorganization of flow when a short channel is formed (second-order avulsion of Nanson and Knighton, 1996).

Jones and Schumm (1999) noted the importance of avulsion triggers in forming avulsions and discussed theoretical stable and unstable states where avulsions may or may not occur. They suggest that avulsion frequency is controlled by the interaction between the rate of the various processes (e.g. channel migration) that move a river toward unstable channel geometry and the frequency of triggering events (Jones and Schumm, 1999). River sections may be stable where the length of an avulsion path is longer than the length of the main channel and unstable where the length of an avulsion path is much shorter than the main-channel length (Jones and Schumm, 1999).

Ice-jams appear to be important in Miramichi wandering rivers (Burge, in press) while other avulsion triggers may be important in other wandering systems. Ice-jam stages are much greater than open water stages for a given discharge because increased roughness within the ice-jam decreases velocity, thereby increasing the stage for a given discharge (Beltaos, 1995). Ice-jams also physically block channels, decreasing their cross-sectional area and increasing the stage. Ice-jams occur at tight bends, shallow cross-sections, island heads and constrictions, and are common in many northern rivers (Beltaos *et al.*, 1989). Flow restriction from ice accumulation in the main channel during break-up

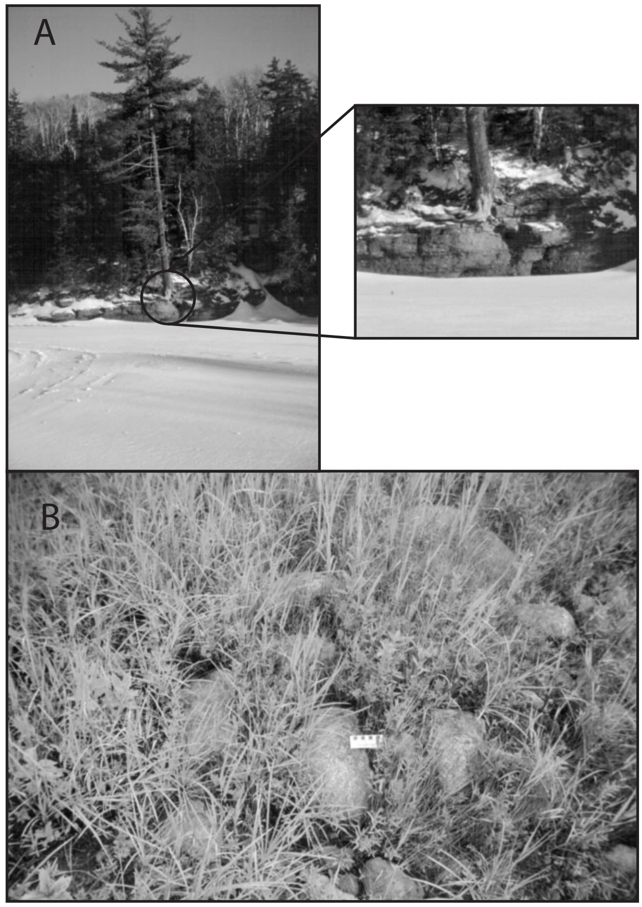

Figure 3. (A) Pine tree on the Taxis River with large scar facing channel. Scar is thought to be formed as ice-jams pass and scrape away bark and wood. (B) Boulder pavement on the Renous River channel edge. Boulder pavements are formed as ice moves past the channel edge and the weight of the ice forces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

often forces flow across floodplains (Smith, 1980; Hicks, 1993; Gay *et al*., 1998; Smith and Pearce, 2002). The overbank flow may erode gullies that elongate upvalley through headcut migration or utilize abandoned channels, which also expand through headcut erosion (Hicks, 1993; Gay *et al*., 1998; Smith and Pearce, 2002). Flow is then reorganized into the new channel following the avulsion (Hooke, 1995; Gay *et al*., 2000; Fuller *et al*., 2003).

The mean annual flood discharges between 1966 and 1994 (Environment Canada, 1997) for the Renous River are presented in Figure 5. Eight large floods greater than 147 $m^3 s^{-1}$ occurred between 1966 and 1994 (Figure 5) that may have caused flooding and triggered avulsions. Large discharges occurred more frequently in the 1970s than in the 1990s, which may have increased channel migration rates and avulsion frequency in the 1970s. Six of the 28 mean annual flood flows were associated with river ice conditions. The largest flood occurred in 1970 and was associated with river ice. However, discharge may not reliably predict flooding in these systems because river ice may cause high stages under relatively low discharges (Beltaos, 1995; Burge, in press). Stage data was not available for the Renous River but was available for the Little Southwest Miramichi River, a neighbouring river to the Renous. Based on a very small dataset of only 6 years, the stages of ice-jam events with a 2·33 year recurrence were 0·96 m above the mean annual flood level on the Little Southwest Miramichi River (Burge, 2003). If mean annual flood is used to estimate floodplain height, then almost 1 m of flooding of the floodplain occurs approximately every second year on the Little Southwest Miramichi. Ice-jams are common in the Miramichi Basin (Beltaos *et al*., 1989), and therefore frequent high-magnitude flooding of the floodplain caused by ice-jams is thought to trigger many of the avulsions on the Renous River.

Ice-jams have been sited as a process causing multiple channels and avulsions in other rivers (Hicks, 1993; Gay *et al*., 1998; Smith and Pearce, 2002). The Mackenzie River at Fort Providence, Northwest Territories, is thought to experience ice-jam initiated avulsions because of the frequent high stages caused by ice-jams (Hicks, 1993). Smith

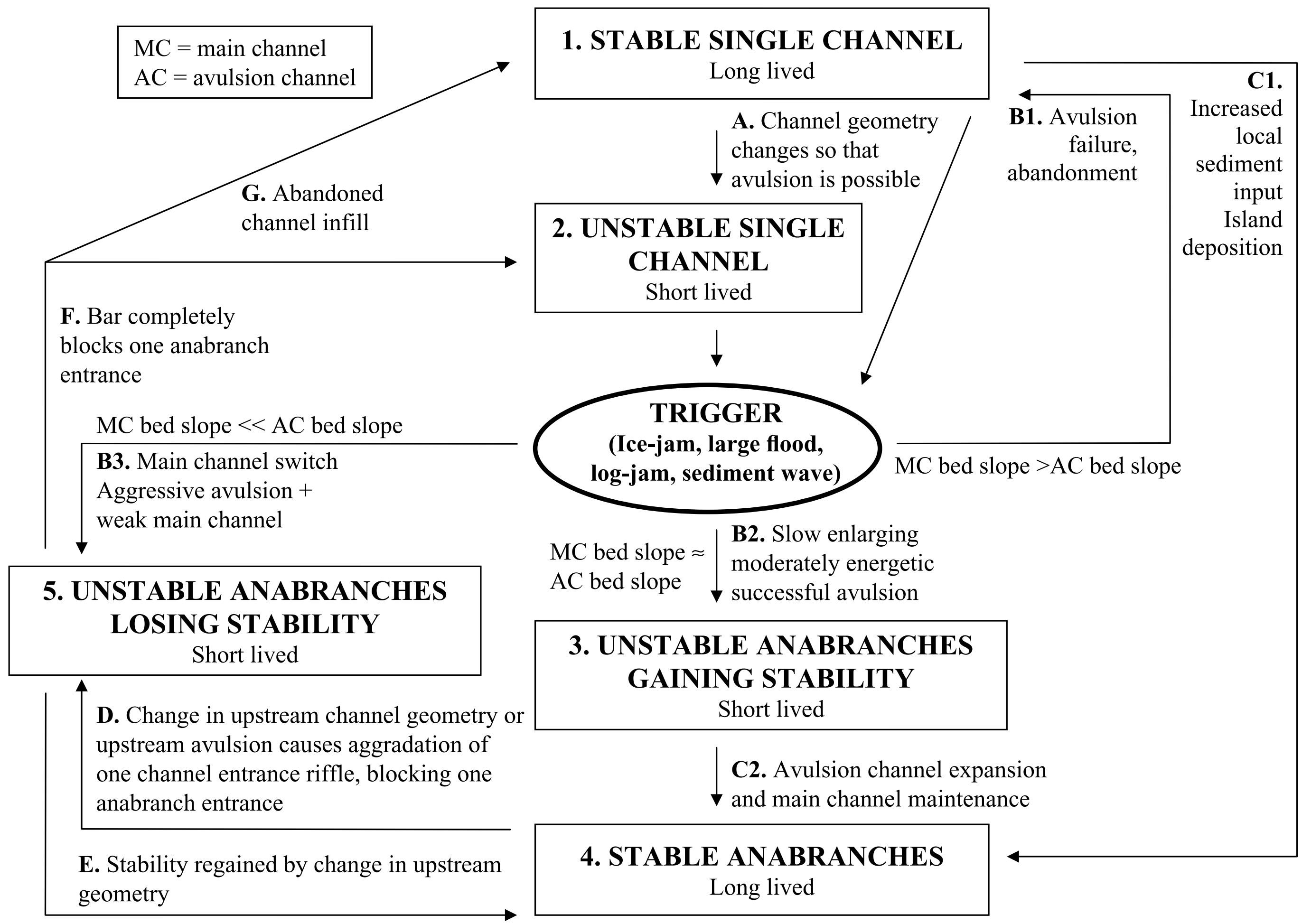

Figure 4. Anabranch cycle conceptual model illustrating how anabranch channels are formed, maintained and abandoned through time. Boxes indicate channel stages and arrows indicate processes moving channel sections between stages. Details of the model are discussed in the text.

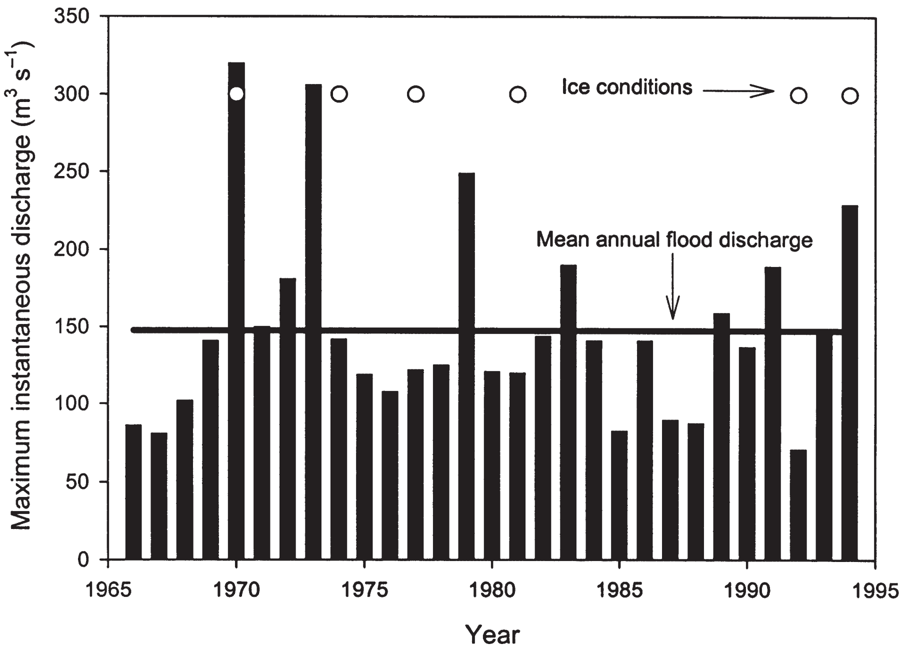

Figure 5. Maximum instantaneous discharge from the Water Survey of Canada gauge (01BO002) on the Renous River at McGraw Brook from 1966 to 1994 (Environment Canada, 1997). The gauge was discontinued in 1994. The horizontal line indicates the mean annual flood discharge and open circles indicate that the maximum instantaneous discharge was associated with river ice conditions.

and Pearce (2002) described the formation of gullies on the floodplain of the Milk River, Montana. The gullies were eroded by flow displaced onto the floodplain by downstream ice-jams that blocked flow within main channels in meander loops. The gully heads migrate upstream during ice-jam events until they encounter the main channel and create an avulsion that cuts off the meander, reorganizing the channels. A similar process of headcut migration of gullies on floodplains due to overbank flooding from ice-jam and open water floods was also described by Gay *et al.* (1998) on the Powder River, Montana.

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

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

A highly seasonal or extremely episodic flow regime has been argued to be a common characteristic of anabranching anastomosed rivers and may cause avulsions (Nanson and Knighton, 1996). Major flooding may be due to tropical summer rain (e.g. Okavango River) (McCarthy *et al.*, 1992), seasonal snowmelt regimes (e.g. Columbia and Alexandria Rivers) (Smith, 1973; Smith and Smith, 1980; Smith, 1983) or a bimodal flood peak (e.g. Magdalena River) that inundates the floodplain for prolonged periods (Smith and Smith, 1980). The combination of frequent or high-magnitude flooding in channels that cannot readily alter their flow capacity is a precondition for avulsion (Nanson and Knighton, 1996). For example, secondary channels within the Fitzroy River are maintained by the overbank flow-dominated regime that has existed for over 3000 years (Taylor, 1999).

Methods

Channel locations for 15 km of the Renous River were mapped from 1:12 000 vertical aerial photographs from 1945, 1965, 1983 and 1999. Aerial photographs were scanned at 300 dpi then resampled and georeferenced using Arcview 3·2 and image analysis (ESRI, 1999). Channel locations were then digitized on screen from the georeferenced aerial photographs for each year. For each map, main-channel length, side-channel length and the number of diffluences were determined. Braid index (total length of all channels/length of the main channel), main-channel sinuosity (main-channel length/valley length) and normalized braid wavelength [(main-channel length/total number of diffluences)/main-channel width] were determined for each year. By determining the differences between years, the frequency of channels formed through avulsion and the emergence of forested islands from mid-channel bars and channel abandonment was determined for each time interval and compared. Changes that may have occurred between the four time periods were not considered in the analysis. However, a cycle of channel avulsion to abandonment would have to occur over less than 20 years to not be detected. This seems unlikely because, as will be shown, one cycle from avulsion to abandonment commonly takes in excess of 50 years. It is possible that small (too narrow to be identified on aerial photographs) failed (lasting less than 20 years) avulsions may not have been identified, but, because this type of channel is small and short lived, it would have a small effect on the river pattern.

Five sections of the Renous River were analysed in greater detail to investigate stable or unstable anabranch geometries. One single-channel reach and four pairs of anabranches (individual channels that flow around islands) at different stages of development were analysed. The lengths of two anabranches around an island or the length of an avulsion path and the corresponding main-channel length were determined for each year. The ratio of the shorter to longer anabranch was calculated.

For each anabranch, bankfull width, bankfull depth, bankfull width–depth ratio, bed slope, bankfull water level slope, bankfull shear stress, mean annual flood, bankfull specific stream power, grain size and bankfull sediment mobility were determined. During the summers of 2000 and 2001, elevations of the thalweg at riffles and pools, and floodplain and bankfull water levels, were surveyed in the field with a laser level and downstream distances measured with a hip-chain. The highest elevation of organic debris deposited by the previous spring flows approximated bankfull water levels. This elevation closely followed the floodplain elevation in single-channel sections. The water level in single-channel sections was compared with floodplain level because discharge is divided among anabranches in multiple channel sections and therefore anabranches may not be equilibrated to the water and sediment supplied from upstream. This is particularly true in avulsion and abandoning channels where the flow supplied to the anabranch systematically is increasing or decreasing. The long profiles of the Renous River were plotted based on the elevation at riffles and pools down the thalweg.

Bankfull channel widths were measured in the field at riffles and were supplemented with measurements from the map of the Renous. Bankfull water surface and bed slopes were determined using regression equations of bed (thalweg at riffles) or water surface elevations and downstream distances. Bankfull depth was determined at the midpoint of each reach by subtracting bankfull water surface elevation from the bed riffle thalweg elevation, calculated using regression equations. Bankfull width–depth ratio was determined using average bankfull width and depth for each reach. Mean annual flood discharge was determined using the maximum instantaneous discharge from 1966 to 1994 for the McGraw Brook gauge (Environment Canada, 1997). Discharge within each anabranch was approximated based on the proportion of the cross-sectional area of each reach to the total area of all channels across the valley.

Hydraulic energy within each channel was estimated using analysis of stream power, and shear stress. Specific stream power,

$$\omega = (\rho g Q_{\mathrm{bf}} S)/w$$

where ρ is the density of water, g is the acceleration due to gravity, Q_{bf} is bankfull discharge within a reach, S is water surface slope and w is the bankfull channel width, is the rate of energy supply at the channel bed for overcoming friction and transporting sediment per unit area of the bed (Knighton, 1998). Shear stress,

$$\tau_{\mathrm{o}} = \rho g R S$$

where R is hydraulic radius (area/wetted perimeter) (Knighton, 1998) was calculated using the bankfull water surface slope as the energy slope and average bankfull depth at riffles as R.

The grain size distribution of the surface of the bed was determined at the heads of riffles within each channel section. The B-axis of 100 randomly chosen clasts was measured on each riffle and then averaged for each reach. The mobility of the bed was estimated using a mobility ratio,

$$\mathrm{Mr} = \tau_o/\tau_c$$

where τ_c is the critical shear stress,

$$\tau_c = 0{\cdot}06(\rho_s - \rho)gD_{50}$$

where ρ_s is the density of sediment and ρ is the density of water. The critical shear stress was approximated by D_{50} in mm (Lapointe *et al*., 2000). Mobility ratio divides the bankfull shear stress by riffle grain size; high values indicate greater bed mobility than low values.

Results and Discussion

Channel pattern dynamics of the Renous River

Although not static, the river pattern characteristics of the Renous River are being maintained and appear to be in a state of dynamic equilibrium because the frequency of channel formation and abandonment were similar over the study period (Figure 6A). Also, braid index and normalized braid wavelength did not display major trends through the study period, also indicating a stable river pattern (Figure 6B). The evidence of paleochannels within the floodplain (Figure 1) also indicates that the Renous River has retained its multiple-channel character over longer time frames (perhaps centuries or millennia). The numerous paleochannels occurring within the floodplain indicate that channels were abandoned before the first aerial photographs were taken. New channels therefore must have been created to allow for channel abandonment, since the river still flows within the valley. New channels were created by avulsions or the emergence of islands from channel bars to allow for channel abandonment, the same process occurring today. This leaves evidence of a floodplain scarred with the abandoned channels because newly formed channels became main channels.

The wandering pattern of multiple channels surrounding semi-permanent vegetated islands remained while the location of individual channels and islands changed. Equilibrium of the river pattern may be maintained by the diversion of flow into avulsion channels and the equal decrease of flow in the remaining channels, balancing the potential for the formation and abandonment of channels. The frequency of avulsions may not exceed a theoretical limit imposed by the loss of discharge into new avulsions. As new avulsions are formed, discharge decreases in the other channels. This decreases the likelihood of additional new avulsions occurring within this section by decreasing the channel energy within the remaining channels. At the same time, the decrease in flow increases the likelihood of the least efficient anabranch channel becoming abandoned by deposition of less mobile sediment. Diverting flow into new channels and decreasing flow into old channels may thereby regulate the number of channels within wandering rivers.

Changes in the location of channels within the Renous River were seen between 1945 and 1999 (Figure 1). Eight new channels were formed through avulsion and five channels through emergence of islands due to mid-channel deposition, and 11 channels were abandoned over the 54-year study period. The wandering pattern should change if the frequency of anabranch formation or abandonment changes. Avulsion and emergence frequency increased then decreased and abandonment frequency decreased then increased over the study period (Figure 6A). Within the Renous study area, channel formation and abandonment frequencies were similar over the 54 years of analysis (0·04 more channels formed per year than abandoned) (Figure 6A). The difference between channel formation and abandonment frequencies may not be significant because only two additional channel segments were formed than abandoned through the study period.

The highest frequency of channel creation and the lowest rate of abandonment (1965–1983) coincided with the more frequent and larger mean annual flood discharges (Figure 5). During this period, frequent higher mean annual flood discharges maintained channels that may have been abandoned. These frequent large discharges formed avulsion channels more often, and caused the formation of larger bars that emerged to become islands because of increased frequency and magnitude of bed sediment transport. Lower mean annual flood discharges between 1983 and 1999 may have allowed less efficient channels to become abandoned, caused fewer avulsions to occur and decreased the frequency of large channel bar formation.

The changes through the study period in the three channel pattern indices reflect the dynamic nature of wandering river channels and the maintenance of the wandering pattern of the Renous River. The braid index ranged from 1·36 to 1·50 and generally increased through the 54-year study period (Figure 6B); however, this increase was small compared with changes recorded in other rivers. For example, the braid index of a wandering section of the Peace

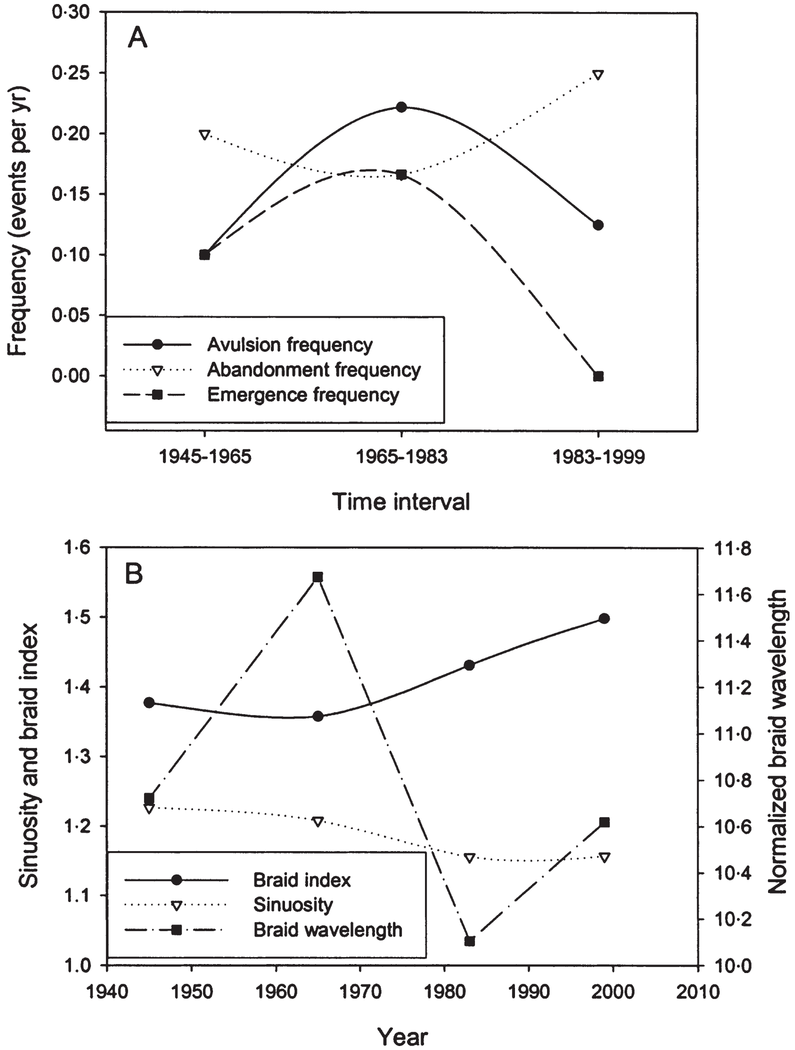

Figure 6. (A) Avulsion, island emergence and abandonment frequencies between years of aerial photographs. (B) Braid index, main-channel sinuosity and braid wavelength normalized by main-channel width between 1945 and 1999 for the wandering section of the Renous River, New Brunswick.

River, downstream of the W. A. C. Bennett Dam, decreased from 2·4 to 1·6 in the first 20 years following the dam's closure (Desloges and Church, 1989). The braid index of the Peace River showed 5·7 times greater change in 20 years in response to flow regulation than seen on the Renous River in 54 years of natural flows. The braid index of the Renous River increased because avulsions cut off two large meanders, decreasing the main-channel length while increasing the length of secondary channels. Sinuosity ranged from 1·16 to 1·23 through the study period (Figure 6B). Sinuosity was consistent between 1945 and 1965, then decreased in 1983 and remained constant until 1999, opposite to the trend in braid index. Changes in sinuosity were also related to the meander cut-offs that shortened the main channel.

Braid wavelength, normalized by the channel width, displayed an average of 10·8 channel widths between diffluences and ranged between 10·1 and 11·6 channel widths over the study period. Normalized braid wavelength showed the greatest variability of the three indices by increasing between 1945 and 1965, decreasing between 1965 and 1983 and increasing between 1983 and 1999 (Figure 6B). Normalized braid wavelength displayed a general decrease through time due to the decrease of the length of the main channel and changes in the number of diffluences through the study period. The increasing and decreasing trend may indicate that normalized braid wavelength is hovering around a mean value. However, it is difficult to establish a mean value over such a short timescale.

Stable single channels

The first system stage in the proposed anabranch cycle is a stable single channel (Figure 4 box 1). This stage is stable in terms of avulsion potential. It is stable because the slope of possible avulsion paths is the same as or less than that of the single channel. Abandoned channels are common on many floodplains and may be used as avulsion paths when encountered by main channels during channel migration. If an avulsion triggering event occurs during this system stage, it is unlikely that anabranches will be formed (Figure 4 path B1). For example, if the single channel is blocked by an ice-jam, flow may not enter an abandoned channel if there is a great distance between the main channel and the abandoned channel. Also, if a high-stage trigger event occurs where the avulsion course is longer than that of the single channel, the avulsion channel will probably be abandoned when the stage decreases and a single channel will be maintained. This creates a failed avulsion (Guccione *et al*., 1999) because the system reverts back to a single channel.

Stable single channels generally occurred within sections of the Renous River with narrow floodplains confined by the valley walls (Figure 1). Panel A of Figure 7 shows a single channel that persisted between 1945 and 1999. The length of the main channel around the meander bend was 760 m while the length of the possible avulsion path down an abandoned channel was 725 m, almost the same. This produced a ratio of possible avulsion path length to main-channel length of 0·95, indicating relatively stable channel geometry. Also, the abandoned channel occurred 250 m from the main channel, making flow into that channel unlikely. An avulsion is unlikely with this channel geometry because the channel must migrate quite a long way to contact the abandoned channel. Overbank flows may enter the abandoned paleochannel, causing the abandoned channel to migrate toward the main-channel by headcut erosion, a process documented by Gay *et al*. (1998) and Smith and Pearce (2002). At some unknown time in the future, the abandoned channel may migrate close enough to the main channel to cause an avulsion. The fact that paleochannels occur within the floodplain at this location indicates that avulsions have occurred here in the past. However, no avulsion was formed in the 54-year study period, even during high-stage events.

The long profile of this section displays a slight downstream concavity and little downstream trend in grain size (Figure 8A). The channel was 62 m wide and 1·78 m deep at bankfull (Figure 9A). The width–depth ratio of the channel was larger than most other channels (Figure 9A), indicating a relatively hydraulically inefficient channel. The bed slope was also relatively high in this section (Figure 9B). The bankfull water surface elevation closely followed the floodplain elevation, indicating that the reach is vertically stable. The section displayed relatively large shear stress and stream power values but bed mobility was compensated by relatively large grainsize on the bed (Figure 9). The bed of this section was less mobile than other sections, also indicating that the bed of this section was relatively stable (Figure 9C).

Unstable single channels

A stable single channel may migrate so that an avulsion course is much shorter than the main channel or it may migrate to contact an abandoned channel, creating an unstable channel geometry prone to avulsion (Figure 4 box 2). An anabranch will be formed if an avulsion-triggering event occurs where unstable single-channel geometries exist. Unstable single-channel sections occurred within the Renous River. Panel B of Figure 7 displays an example of an unstable single channel between 1945 and 1983 and an avulsion channel that formed between 1983 and 1999. The main channel migrated to within 70 m of an abandoned channel by 1983, causing a single channel that was prone to an avulsion. The abandoned channel was also migrating upvalley due to headcut migration during overbank flows, further destabilizing the channel geometry. The length of the main channel was 550 m while the length of the abandoned channel was 490 m, producing a ratio of the possible avulsion path length to the main-channel length of 0·89. This caused a larger slope through the possible avulsion path than the main channel and allowed the use of the abandoned channel by an avulsion.

Anabranch formation

The anabranch cycle may begin with anabranches formed directly from a stable single channel through local sediment deposition and island emergence (Figure 4 Path C1). Five islands emerged from Renous River channels during the study period. Island emergence may occur due to local increases in sediment supply into reaches or decreases in the sediment transport out of the reach. Sediment supply to the reach may increase because of terrace erosion or a recent avulsion upstream (Church, 1983; Carson, 1984; Gottesfeld and Johnson-Gottesfeld, 1990). Causes of decreased sediment transport out of a reach include decreased slope due to base level change, an alluvial fan pinching the channel (Church, 1983; Smith, 1983), interactions with valley walls downstream or local channel widening due to a local decrease in bank strength. Mid-channel bars develop as sediment is deposited within the channel. Islands

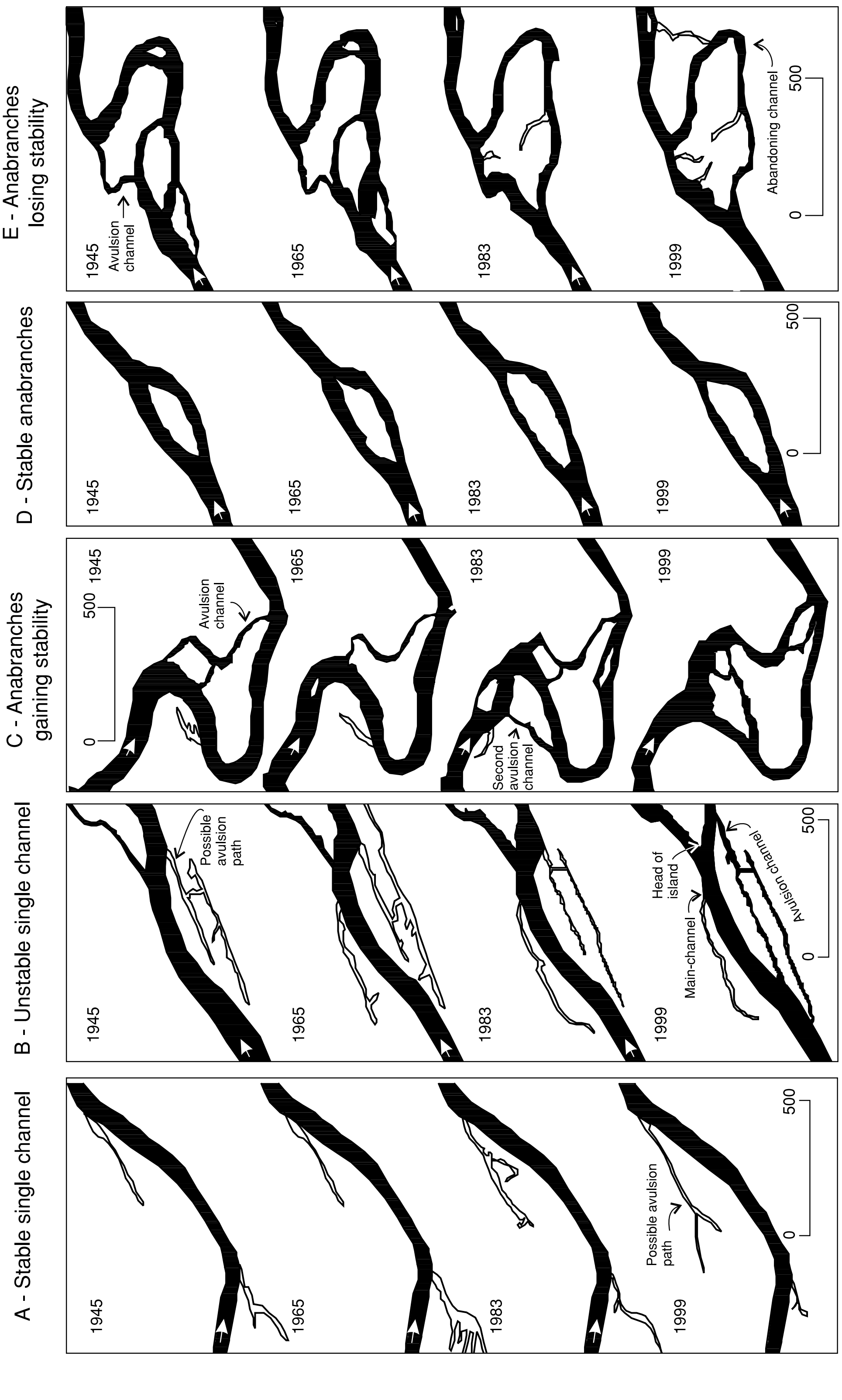

Figure 7. Enlarged maps from Figure 3 displaying (A) a stable single channel, (B) an unstable single channel, (C) anabranches gaining stability, (D) stable anabranches and (E) anabranches losing stability for the study period 1945–1999.

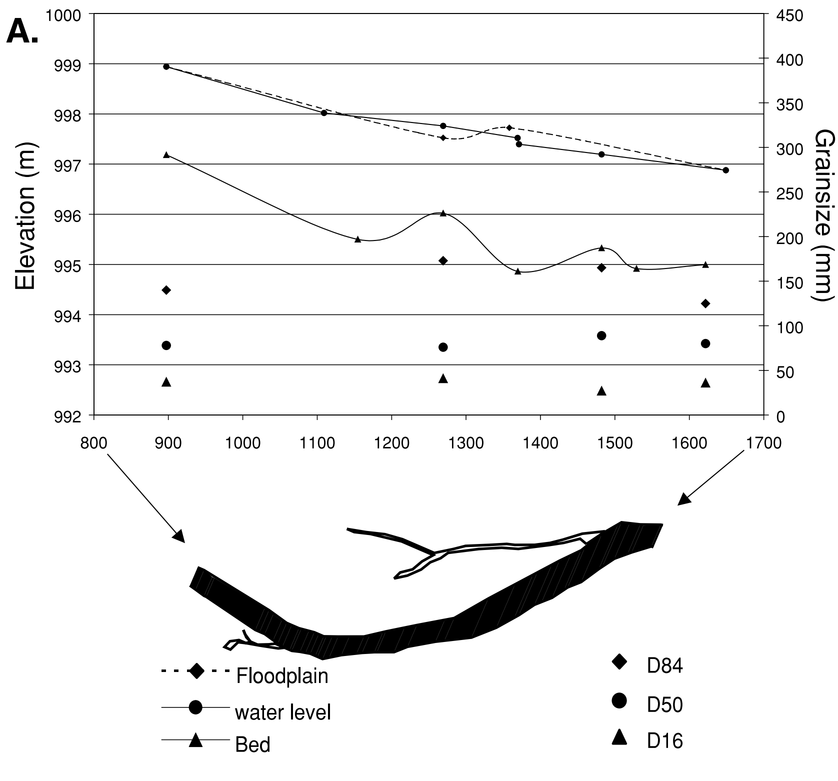

Figure 8. Long profiles, downstream grainsize and maps for five case study sections. (A) Stable single channel located where no avulsion occurred within the study period. (B) Small avulsion channel paired with the primary channel within a section that was unstable prior to the avulsion. (C) Primary and secondary channel pair in a location where the channel characteristics are becoming more similar. (D) Primary and secondary stable anabranches with similar characteristics. (E) Primary and abandoning channel pair where the abandoning channel is infilling with fine sediment.

develop from the mid-channel bars that split the flow and eventually emerge to allow vegetation to establish and stabilize the bars (Ashworth, 1996). Vegetation causes further deposition until a permanent island develops.

The anabranch cycle may also begin with a single unstable channel (Figure 4 box 2) and a floodplain scarred with abandoned channels that are possible avulsion paths. A trigger, such as large floods, log-jams, ice-jams or sediment wave, may force flow over the floodplain into an abandoned channel, initiating an avulsion (Figure 4 path B2 or B3). Avulsions commonly occur at the outside of a bend apex where channels have become unstable following migration to contact abandoned channels (Smith *et al*., 1989; Leddy *et al*., 1993). The outside of bends are also common avulsion sites because of water surface super elevation and higher velocities in the outer bank, overbank flow directed into the floodplain by inertia and, in some cases, levees on the outer bank may have lower elevations than on the inside bend (Smith *et al*., 1989). Newly formed channels enlarge in two steps. First vertical scour occurs because of a lack of armouring on the bed; then channels widen laterally (Fuller *et al*., 2003). Hooke (1995) found that riffles and pools formed in channel cut-offs within 2–4 years, and in one cut-off the channel morphology had stabilized within 8 years.

Eight avulsions were observed on the Renous River. As channels migrate they may contact abandoned channels, forming a possible avulsion path. This occurred at the site displayed in panel B of Figure 7 between 1983 and 1999, where an avulsion occurred at the outside of a channel bend into an abandoned channel. Figure 10 displays one potential scenario for the avulsion triggered in panel B (Figure 7). Although several high flows occurred that might have triggered the avulsion between 1983 and 1999 (Figure 5), we believe that it is likely that ice-jams were important in triggering this avulsion because of the channel geometry and frequency of ice-jams in this region. Ice-jams commonly occur at island heads (Beltaos *et al*., 1989) and an island head was located between the entrance and exit of the avulsion channel (Figure 10 – 1983). We hypothesize that this avulsion was triggered by an ice-jam that occurred at the downstream island head that caused flooding upstream of the ice-jam and forced flow into the abandoned channel (Figure 10 – 1983–1999). Flow would be reorganized in the years following the ice-jam so that discharge was routed into the avulsion channel during bankfull flows (Figure 10 – 1999) or during subsequent ice-jams. The difference in

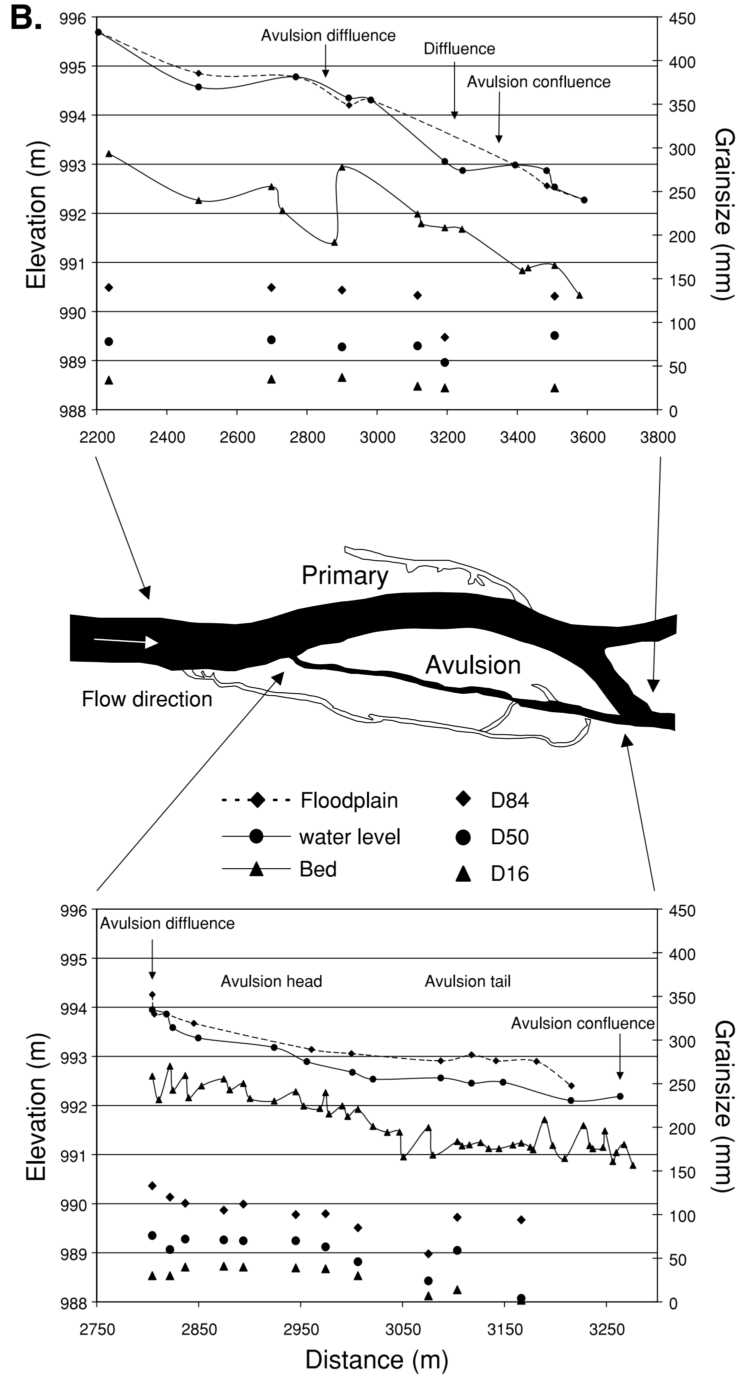

Figure 8. (*Continued*)

length between the path of the avulsion channel and the path of the main channel was not great; the ratio of the avulsion-channel length to the main-channel length was 0·89. This further supports the hypothesis of an ice-jam triggered avulsion, because an open water flood would not have a great hydraulic advantage through the avulsion channel. This also suggests that this avulsion channel may eventually form stable anabranches.

The long profile of the avulsion channel displays a downstream concavity and a downstream trend in grain size (Figure 8B). An abrupt downstream fining occurred downstream of the channel entrance and was concurrent with

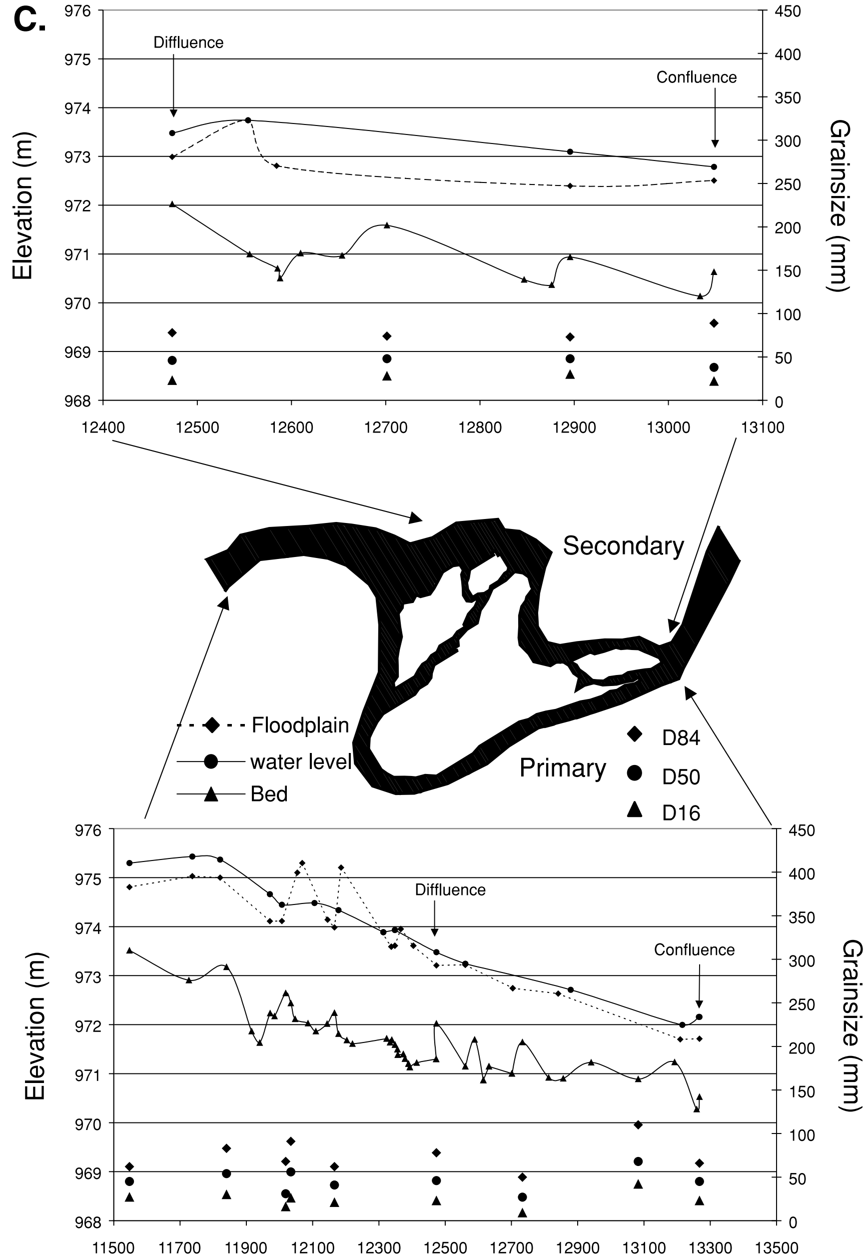

Figure 8. (*Continued*)

greater bed slope here. This may represent down-cutting into floodplain gravels near the channel entrance and transportation of these gravels further down into the channel. The downstream portion of the avulsion channel displayed smaller grain size and lower bed slope than upstream (Figure 9). The maps of this location (Figure 7B) show that the downstream zone of the avulsion channel was an abandoned channel and therefore the lower half of the avulsion channel inherited the abandoned channel characteristics. It appears that a wave of gravel in the upper zone of the avulsion (Figure 8B) is propagating through the avulsion channel from upstream to downstream modifying the channel slope and bed material. As the avulsion continues, sediment eroded during degradation at the avulsion entrance may continue to be transported into the former abandoned channel. It is probable that the gravel wave will continue to move down the avulsion until sediment is transported through the channel and the channel takes on the characteristics of an active secondary channel and loses the characteristics of an abandoned channel.

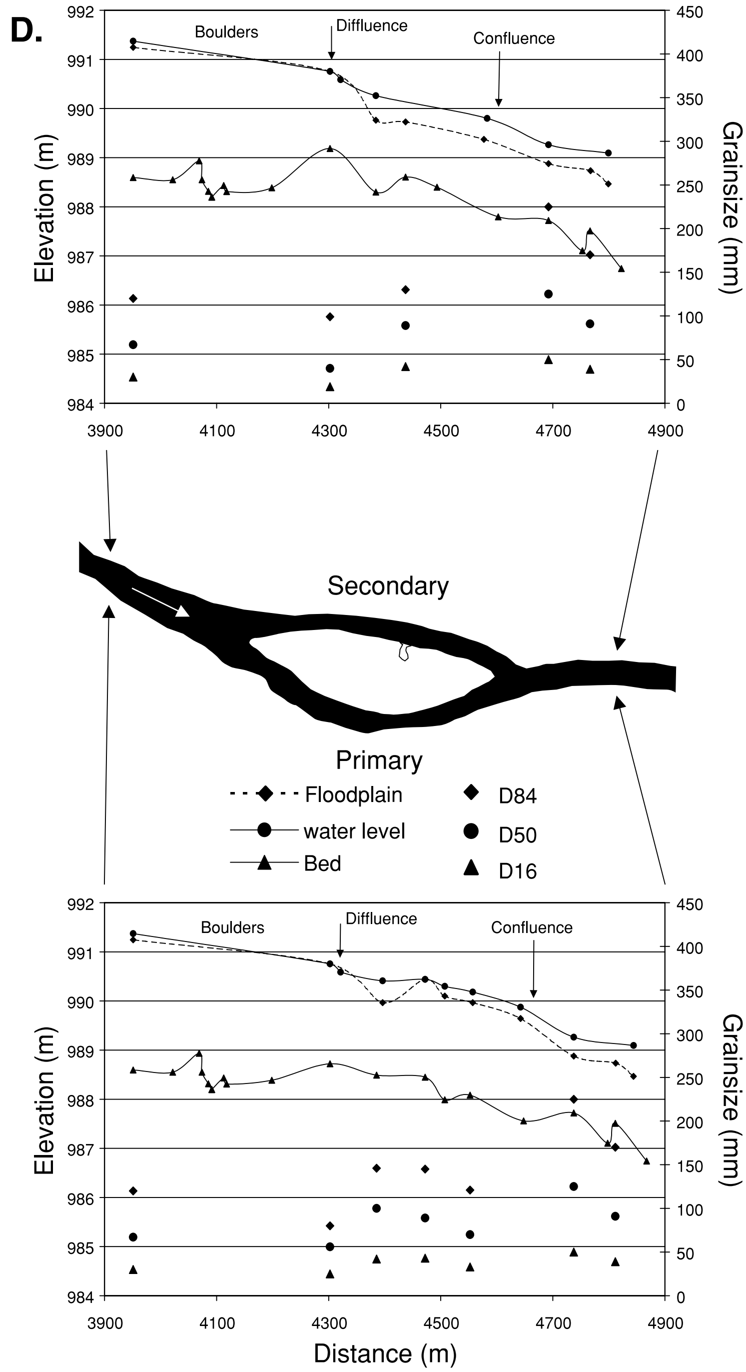

Figure 8. (*Continued*)

The avulsion channel was only 15 m wide and 0·93 m deep at bankfull (Figure 9A) and therefore had a low width–depth ratio, indicating an efficient hydraulic geometry. The left primary channel was 70 m wide and 2·10 m deep, and displayed a larger width–depth ratio, indicating a less hydraulically efficient channel, similar to the other larger channels. This suggests that the avulsion channel is probably still down-cutting and its bed is not well armoured. This is the first of two stages described by Fuller *et al.* (2003); during the second stage, the new channel will widen. The bankfull water surface elevation within the avulsion channel was concurrent with the floodplain elevation at its

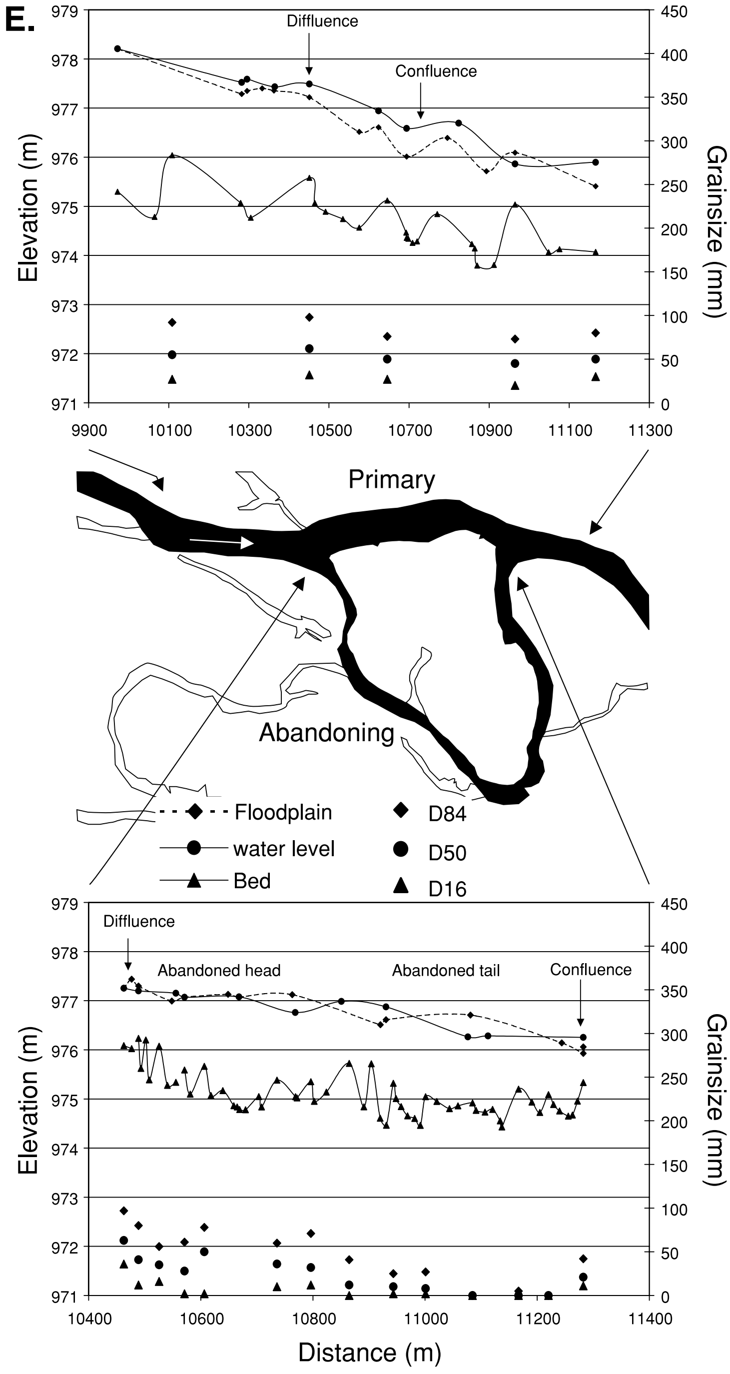

Figure 8. (*Continued*)

entrance but then diverged below the floodplain elevation downstream of the entrance (Figure 8B), indicating that the cross-sectional channel geometry is not in equilibrium with the discharge supplied to the avulsion channel. The section displayed relatively large stream power values but lower shear stress due to shallow depth. Bed mobility (Figure 9C) was moderate due to the lower values of shear stress even though grain size was relatively small (Figure 9B). In comparison, the paired primary channel displayed greater shear stress but lower stream power and had a larger bed grain size. A bed slope increase downstream of the avulsion entrance within the primary channel is probably related to

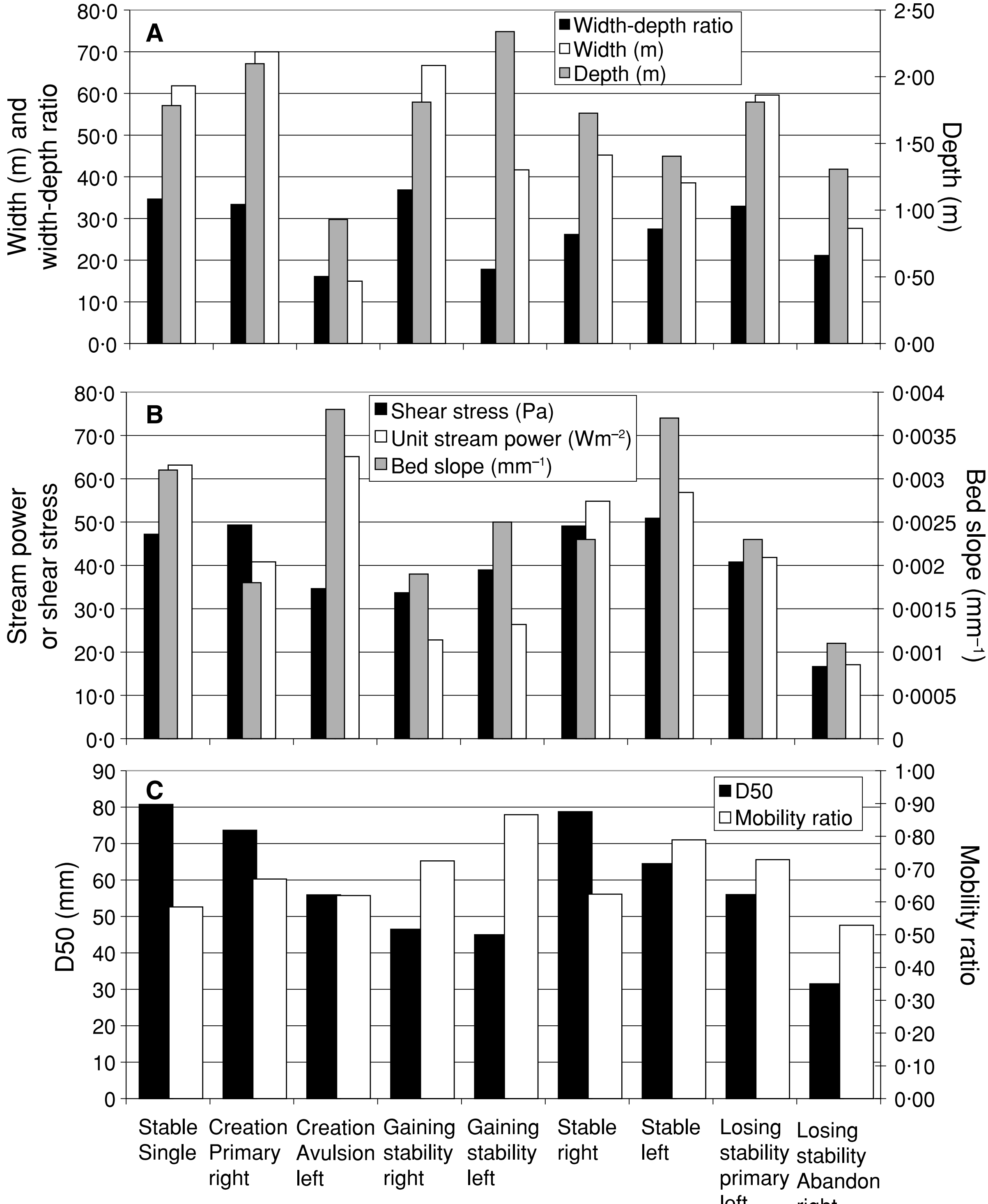

Figure 9. Characteristics of channels used in case studies. (A) Hydraulic geometry variables (width, depth and width–depth ratio) for each channel. (B) Channel energy variables (shear stress, specific stream power and bed slope) for each channel. (C) Grain size and sediment mobility variables (D_{50} and mobility ratio) for each channel.

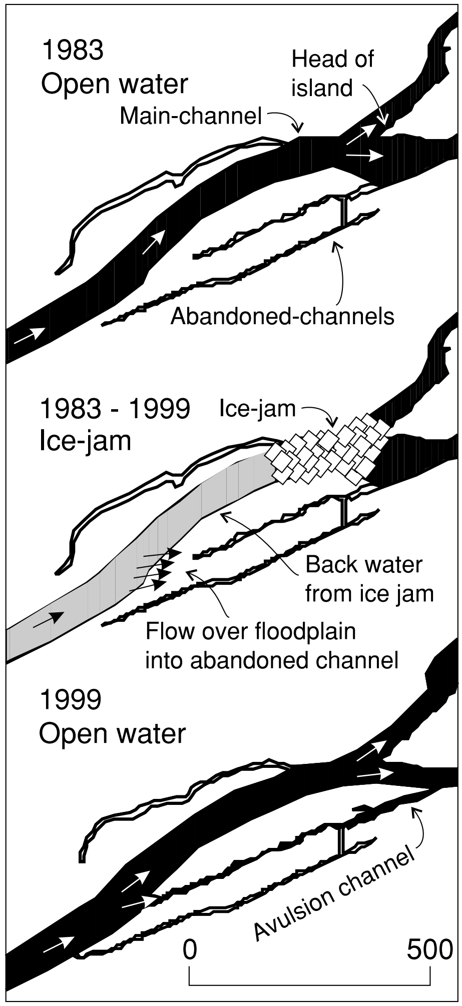

Figure 10. Proposed model showing the triggering of an avulsion by an ice-jam. The channel geometry in 1983 displayed an island head between the possible entrance and exit of an abandoned channel. Between 1983 and 1999, we propose that an ice-jam occurred at the island head that forced water over the floodplain, into the abandoned channel, thereby triggering the avulsion. The ice-jam was not observed but its location at the downstream island head is probable because ice-jams are frequent on these rivers and island heads are common locations of ice-jam formation. By 1999 the open water configuration of the river section was reorganized, with open water bankfull flow entering the avulsion channel.

slight bed aggradation within the channel due to decreased transport capacity associated with decreased discharge within this channel due to flow into the avulsion.

Anabranches gaining stability

A period during which anabranches gain stability (Figure 4 box 3) may occur following an avulsion. Stability increases as discharge and sediment input decreases to the main channel and increases to the side channel until stable anabranches develop (Figure 4 path B2).

Panel C of Figure 7 displayed two anabranches that were formed following an avulsion that began prior to 1945 on the outside of a meander bend. The lengths of the two anabranches have become more similar through time after reorganization of the channel entrance. The length of the initial avulsion in 1945 was 511 m while the length of the main channel was 860 m, producing an avulsion-channel to main-channel ratio of 0·59. The length of the main channel increased slightly by 1983, slightly decreasing the ratio of the channel lengths, but the width of the avulsion channel grew throughout the study period. A similar geometry remained until 1999, when the lengths of the avulsion

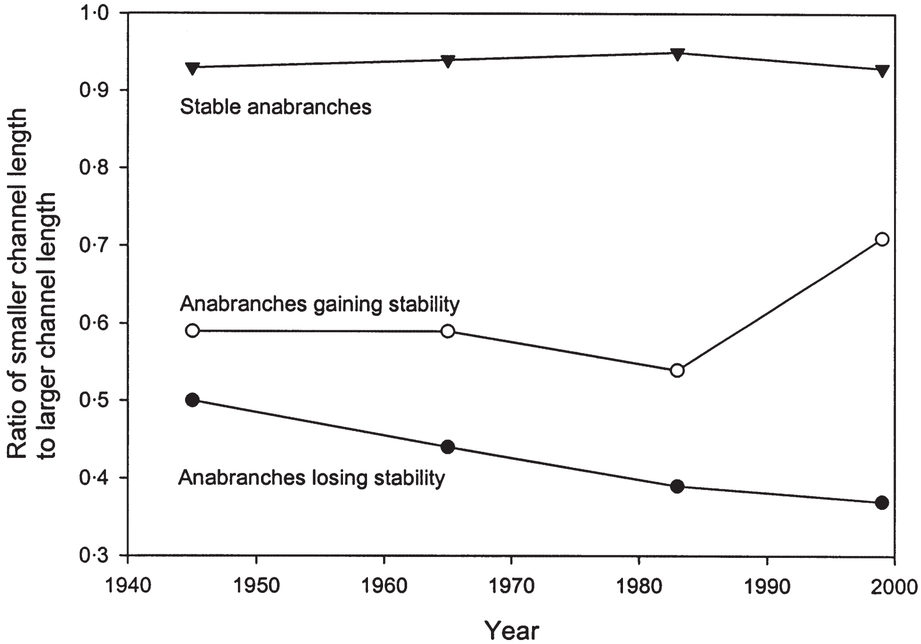

Figure 11. Plot of the ratio of the length of the smaller anabranch channel to the length of the larger anabranch channel through time for panels C, D and E in Figure 8. The lengths of stable anabranches are similar and remain constant through time. The lengths of anabranches that gain stability become more similar through time, while the lengths of anabranches that lose stability become more dissimilar through time.

and main channels increased due to reorganization of the channels at their entrance. A small avulsion channel that was seen in 1983 grew to carry a large proportion of the flow and became the main channel by 1999. The length of the original avulsion channel grew to 633 m and the main channel length grew to 891 m, producing a ratio of 0·71 (Figure 11). If this trend continues, this anabranch pair may become stable.

The long profile of this section displays little downstream concavity or downstream trend in grain size (Figure 8C). The right primary channel and left secondary channel within this section were 67 m and 42 m wide, and 1·81 m and 2·34 m deep at bankfull, respectively (Figure 9A). The width–depth ratio of the older right channel was much greater than the younger left channel, indicating that the hydraulic geometry of the left channel is more efficient (Figure 9A). In the larger right channel, bankfull water surface elevation was slightly below the floodplain elevation, perhaps indicating the loss of flow to the secondary channel following the avulsion. In the smaller left channel, the bankfull water surface elevation was also below the floodplain elevation, perhaps indicating bed degradation. The channels within this section displayed relatively small shear stress and stream power values but bed mobility was compensated by relatively small, and similar, grainsize on the bed (Figure 9B). The left channel displayed greater sediment mobility than the right channel (Figure 9C). The left channel may still be degrading following the avulsion of this channel that began prior to 1945, while the right channel may be aggrading. We speculate that the left channel will continue to degrade and widen and the right channel will aggrade and narrow until they are in balance with the flow of sediment and water supplied to them.

Stable anabranches

Stable anabranches (Figure 4 box 4) are formed through island emergence (Figure 4 path C1) or develop after unstable anabranches formed through avulsion gain stability (Figure 4 path C2). When anabranches are stable, the lengths of the two anabranches are similar (the ratio of the shorter to longer anabranch is near one). In the Renous River, the formation of stable anabranches appears to be less common than the formation of unstable anabranches; however, their influence on the pattern is long lasting and important due to their persistence.

Stable anabranches occurred within the Renous River. Panel D of Figure 7 displays an anabranch pair that was stable throughout the 54-year study period. Its geometry did not change substantially during this time. The lengths of the two anabranches were similar. The ratio of the shorter channel to the longer channel ranged between 0·93 and 0·95

(Figure 11). The length of the shorter north channel increased from 345 m in 1945 to 355 m between 1945 and 1999, while the longer south channel increased in length from 370 m to 430 m. The dominant channel switched from the north to the south channel through the study period. This anabranch pair is stable and will probably remain stable for a number of decades, unless either an ice-jam, log-jam or sediment wave causes instability.

The long profiles of the stable anabranches within this section display little downstream concavity. The larger right channel displays a downstream decrease in grain size while the smaller channel does not (Figure 8D). The right primary channel and left secondary channel within this section were 45 m and 39 m wide, and 1·73 m and 1·40 m deep at bankfull, respectively (Figure 9A). The width–depth ratios were similar (Figure 9A). Both channels showed the spring floodwater surface elevations above the floodplain elevation. This may indicate aggradation of the bed or narrowing of the channels. Although the two channels displayed different slopes and depths, the shear stress values were almost identical, as were the specific stream power values (Figure 9B). Higher bed slope within the secondary channel was due to a slightly shorter secondary channel. The grain size of the larger channel was greater than in the smaller channel, causing the mobility ratio to be greater in the smaller channel (Figure 9C). These channels appear to be in balance because they displayed similar hydraulic geometry and channel energy values.

Anabranches losing stability

Anabranches losing stability (Figure 4 box 5) may be formed following many years of stability (Figure 4 box 4), or following an aggressive avulsion, where the path of the avulsion is much shorter than the path of the main channel (Figure 4 path B3). Stable anabranches may become unstable where sediment transport patterns are altered. Sediment input into one anabranch channel may increase or decrease due to avulsion or terrace erosion upstream, the migration of an upstream meander or altering diffluence entrance geometry (Figure 4 path D). Where sediment input to one anabranch increases beyond its transport capacity the deposition of a bar at the entrance of an anabranch may occur and block flow (Burge, 2003). Where sediment input to one anabranch decreases, degradation of the entrance to the anabranch might occur, causing the anabranch to capture more flow. Stability may be regained with a change in upstream channel geometry that allows sediment to divide evenly between the two anabranch channels. Although not documented, stability may also be regained when a sediment wave, formed by increased terrace erosion or an avulsion upstream, exits the reach (Figure 4 path E).

Where an avulsion course is much shorter than the main channel, avulsions are aggressive and the main channel may quickly switch into the avulsion channel, causing the eventual abandonment of the former main channel. These aggressive avulsions may create a short period of unstable anabranches while the main channel switches and the former primary channel becomes abandoned (Figure 4 box 5). As diffluence stability breaks down, a bar may form to block an abandoning channel. Hooke (1995) described a rapid rate of infilling at the entrance to abandoned channels, with sedimentation to nearly floodplain level within about six years.

While anabranches lose stability, channel characteristics are out of balance and the abandoning channel loses flow while the other channel gains flow (Figure 4 path F and G). Anabranches are abandoned when flow of sediment and water into a channel decreases due to channel inefficiency, changes in entrance geometry (Bridge, 1993), or where an anabranch is choked by sediment or log-jams. The abandonment of an anabranch may be rapid or slow depending on the abandonment process. Channels may abandon where the diffluence angle becomes large and inefficient (Bridge, 1993). Where this occurs, the channel at a high angle to the main flow will become abandoned, and a zone of flow separation may occur at the channel entrance enhancing deposition, further promoting abandonment. Once an anabranch becomes less efficient it becomes susceptible to blockages from log-jams at its entrance that further encourage its decline. In some western Canadian wandering systems, the former entrances to abandoned channels commonly show evidence of log jams that block one channel (Gottesfeld and Johnson-Gottesfeld, 1990). Channel abandonment leaves low semi-filled channels scarring floodplains.

Anabranches losing stability occurred within the Renous River. Panel E of Figure 7 displays an anabranch pair that was unstable and continued to lose stability throughout the 54-year study period. Its geometry changed substantially during this time. The ratio of the shorter channel to the longer channel decreased from 0·50 to 0·37 (Figure 11). The dominant channel switched from the southern meander loop to the northern avulsion channel. An avulsion occurred prior to 1945 that initiated a meander loop cut-off. Four separate small channels were observed near the head of the island in 1945. The avulsion channel continued to expand and became larger than the former main channel by 1983 when all but the two largest channels were abandoned. The length of the avulsion channel decreased from 390 m in 1945 to 330 m in 1999, while the length of the main channel increased from 785 m to 885 m over the same period. The anabranch pair has been losing stability through the study period and the former main channel is being abandoned.

The long profiles of the left anabranch within this section display little downstream concavity; however, the right abandoning anabranch displays significant downstream concavity (Figure 8E). Both anabranches display downstream fining but the fining is more pronounced in the right abandoning channel. The long profile of the abandoning channel displayed two zones. The upstream zone extended 150 m into the channel and had higher D_{50} and bed slope values than the downstream zone. It appears that the upper zone is the result of a bar composed of fine gravel that has blocked the entrance to the abandoning channel, increasing the bed slope. The lower zone displays much lower slope and is being infilled by sand and silt.

The left primary channel and right abandoning anabranch were 60 m and 28 m wide, and 1·81 m and 1·31 m deep at bankfull, respectively (Figure 9A). The width–depth ratio of the abandoning channel was much lower than seen in the primary channel (Figure 9A). The water surface elevation within the left anabranch was above the floodplain elevation. In this location, because the primary channel was an avulsion channel, the bed of the channel is probably still degrading following the initial avulsion and as it captures more of the flow through time. The two channels displayed very different slopes, causing the shear stress and specific stream power values to be relatively high in the primary channel and very low in the abandoning channel, as expected (Figure 9B). It appears that the abandoning channel is more hydraulically efficient than the primary channel; however, it has much less energy to transport water and sediment. Lower bed slope within the abandoning channel was due to its long length relative to the other channel. The grain size of the abandoning channel was smaller than the primary channel; however, the mobility ratio was greater within the primary channel because of its greater level of shear stress (Figure 9C). The bed of the abandoning channel within this section was less mobile than any other channel, indicating deposition on the bed of this channel (Figure 9C). This channel will likely continue to abandon until it is completely cut off from the active channel and infills.

Anabranch infill

Where channels are not reoccupied for long periods, the rate at which abandoned channels infill is determined largely by the size and amount of sediment carried into the channel and the growth of vegetation within the channel (Figure 4 path G). The size and amount of sediment entering an abandoned channel is largely controlled by how connected the abandoned channel is to an active channel. The more connected a channel is, the coarser the material entering the channel and the faster it infills (Piet, 1992). If a channel is not connected to an active channel, the suspended load of the river during flood largely controls the infill rate; the greater the suspended load, the faster the infill rate. The filling process is preserved in channel-fill sediments. When they are abandoned slowly, oxbow lake deposits are coarser in the upstream arms of meander loops, while channels that are rapidly abandoned fill with mud (Piet, 1992). Channel-fills fine upward from horizontal and cross-bedded fine gravel and sand to poorly bedded or massive sand, silt and clay-silt (Passmore and Macklin, 2000). Beaver head ponds on abandoned channels enhance deposition of suspended sediment due to decreased water velocities during floods and the growth of aquatic plants (Butler and Malanson, 1995). Beaver dams may eventually become beaver meadows. Yet, even without the aid of beavers, abandoned channel-fills may be largely organic due to the growth of water plants (Smith, 1983), the amount and type of which are controlled largely by climate. Where abandoned channels completely infill, a stable single channel (Figure 4 box 1) is more likely to be maintained.

Although channels become abandoned, they remain important because they provide sites for future avulsions. The Renous River floodplain has many abandoned channels. The total length of all abandoned channels was on average 2·5 times longer than the main channel and therefore provides many possible avulsion sites. If abandoned channels become avulsion sites they restart the anabranch cycle, allowing multiple-channel systems to be maintained indefinitely.

Conclusions

A mosaic of channel types occurs within the wandering Renous River. The characteristics of these channels changed as anabranches were formed, maintained and abandoned. The location of channels within the Renous River changed through time while the wandering pattern remained. The anabranch cycle model was used to investigate different channel types within the Renous River. The model worked well to organize the possible pathways from one channel geometry to another and was consistent with the channel characteristics in different channel types. The cycle may begin with the formation of an anabranch by avulsion into an abandoned channel, triggered by an ice-jam, log-jam or large flood or the emergence of a mid-channel bar that evolves into an island. Anabranches may be short lived or stable over long periods depending on local conditions. Future prediction of the stability of anabranches is difficult but it appears that stable anabranches have similar hydraulic geometries and channel energies. Anabranches that gain stability have hydraulic geometry and energy characteristics that are out of balance but not as great as abandoning anabranches. The anabranch cycle explains how river pattern characteristics may appear stable through time while individual anabranch channels within channel sections change.

Acknowledgements

We would like to thank NSERC and FCAR for funding this research through grants to Lapointe and the Atlantic Salmon Federation for a grant to Burge. The Department of Geography, McGill University, provided laboratory and office support. Barbara Ramovs, Andre Zimmerman and Sandra Maigler are thanked for field assistance. Department of Fisheries and Oceans Catamaran Brook project is thanked for lodging during preliminary fieldwork. Miramichi River Environmental Assessment Committee is thanked for extra hands during grain size measurement. André Roy provided important advice and feedback. The manuscript was greatly improved by reviews from Derald Smith and an anonymous reviewer.

References

Allen WTR, Cudbird BSV. 1971. *Freeze-up and break-up dates of water bodies in Canada*, CLI-1-71. Canadian Meteorological Service: Toronto.

Ashmore P. 1993. Anabranch confluence kinetics and sedimentation processes in gravel-braided streams. In *Braided Rivers*, Best JL, Bristow CS (eds). Geological Society: London; 129–146.

Ashworth PJ. 1996. Mid-channel bar growth and its relationship to local flow strength and direction. *Earth Surface Processes and Landforms* **21**: 103–123.

Ashmore P. 2001. Braided phenomena: statics and kinetics. In *Gravel-Bed Rivers V*, Mosley P (ed.). New Zealand Hydrological Society: Wellington; 95–114.

Beltaos S. 1995. *River ice-jams*. Water Resources Publications: Highlands Ranch, CO.

Beltaos S, Burrell BC, Davar KS, Dublin J, Ismail S, Lane RJ, Prowse TD. 1989. *New Brunswick ice manual*. The New Brunswick Subcommittee on River Ice, Environment Canada, New Brunswick Inland Waters Directorate, Department of the Environment: Fredericton.

Bridge JS. 1993. The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In *Braided rivers*, Best JL, Bristow CS (eds). Geological Society: London; 13–71.

Brierley GJ. 1989. River planform facies models: the sedimentology of braided, wandering and meandering reaches of the Squamish River, British Columbia. *Sedimentary Geology* **61**(1/2): 17–35.

Burge LM. 2003. *Dynamics of a transitional river pattern: A multi-scale investigation of controls on the wandering pattern of Miramichi Rivers, New Brunswick, Canada*, Ph.D. Thesis, McGill, Montreal; 193.

Burge LM. 2004. Testing links between river patterns and in-channel characteristics using MRPP and ANOVA. *Geomorphology* **63**(3–4): 115–130.

Burge LM. In press. Wandering Miramichi rivers, New Brunswick, Canada. *Geomorphology*.

Butler DR, Malanson GP. 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. *Geomorphology* **13**: 255–269.

Caissie D, El-Jabi N. 1995. Hydrology of the Miramichi River drainage basin. In *Water, Science and the Public: the Miramichi ecosystem*, Chadwick EMP (ed.). Canadian Special Publication Fish and Aquatic Science; 83–93.

Carson MA. 1984. Observations on the meandering–braided river transition, the Canterbury plains, New Zealand: part two. *New Zealand Geographer* **40**(2): 89–99.

Church M. 1983. Pattern of instability in a wandering gravel bed channel. In *Modern and Ancient Fluvial Systems*, Collinson JD, Lewin J (eds), International Association of Sedimentologists–Blackwell: Oxford; 169–180.

Church M, Jones D. 1982. Channel bars in gravel-bed rivers. In *Gravel-Bed Rivers*, Hey R, Bathurst J, Thorne C (eds). Wiley: New York; 291–338.

Desloges JR, Church M. 1989. Wandering gravel-bed rivers. *The Canadian Geographer* **33**: 360–364.

Environment Canada. 1997. *Canadian Hydrological Data*, Hydat computer file, Version 2, CD-ROM.

ESRI. 1999. *ARCVIEW*, Version 3.2.

Fuller IC, Large ARG, Milan, DJ. 2003. Quantifying channel development and sediment transfer following chute cutoff in a wandering gravel-bed river. *Geomorphology* **54**(3/4): 307–323.

Gay GR, Gay HH, Gay WH, Martinson HA, Meade RH, Moody JA. 1998. Evolution of cutoffs across meander necks in powder river, Montana, USA. *Earth Surface Processes and Landforms* **23**: 651–662.

Gottesfeld A, Johnson-Gottesfeld LM. 1990. Floodplain dynamics of a wandering river, dendrochronology of the Morice River, British Columbia, Canada. *Geomorphology* **3**: 159–179.

Guccione MJ, Burford MF, Kendall JD. 1999. Pemiscot Bayou, a large distributary of the Mississippi River and a possible failed avulsion. In *Fluvial sedimentology VI*, Smith ND, Rogers J (eds). Blackwell: Oxford; 211–220.

Harwood K, Brown AG. 1993. Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. *Earth Surface Processes and Landforms* **18**: 741–748.

Hicks FE. 1993. Ice as the geomorphologic agent in an anastomosing river system. In *Proceedings of the Workshop on Environmental Aspects of River Ice*, Prowse TD (ed.), NHRI Symposium Series No. 12. National Hydrology Research Institute: Saskatoon, Saskatchewan; 3–20.

Hooke JM. 1995. River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England. *Geomorphology* **14**(3): 235–253.

Jones LS, Schumm SA. 1999. Causes of avulsion: an overview. In *Fluvial sedimentology VI*, Smith ND, Rogers J (eds). Blackwell: Oxford; 171–178.

Knighton, AD, 1998. *Fluvial forms and processes – a new perspective*. Arnold, New York.

Kondolf GM, Piegay H, Landon N. 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. *Geomorphology* **45**(1/2): 35–51.

Lapointe M, Eaton B, Driscoll S, Latulippe C. 2000. Modelling the probability of salmonid egg pocket scour due to floods. *Canadian Journal of Fisheries and Aquatic Sciences* **57**(6): 1120–1130.

Leddy JO, Ashworth PJ, Best JL. 1993. Mechanisms of anabranch avulsion within gravel-bed braided rivers: observations from a scaled physical model. In *Braided rivers*, Best JL, Bristow CS (eds). Geological Society: London; 119–127.

Mackay JR, Mackay DK. 1977. The stability of ice-push features, Mackenzie River, Canada. *Canadian Journal of Earth Science* **14**: 2213–2225.

McCarthy TS, Ellery WN, Stanistreet IG. 1992. Avulsion mechanisms on the Okavango fan, Botswana: control of a fluvial system by vegetation. *Sedimentology* **39**: 795–799.

Nanson GC, Knighton AD. 1996. Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms* **21**: 217–239.

Neill CR. 1973. *Hydraulic and morphologic characteristics of the Athabaska River near Fort Assiniboine*, REH/73/3. Alberta Research Council, Highway River Engineering Division: Edmonton; 23.

Passmore DG, Macklin MG. 2000. Late Holocene channel and floodplain development in a wandering gravel-bed river: the River South Tyne at Lambley, northern England. *Earth Surface Processes and Landforms* **25**: 1237–1256.

Payne BA, Lapointe MF. 1997. Channel morphology and lateral stability: effects on distribution of spawning and rearing habitat for Atlantic salmon in a wandering cobble-bed river. *Canadian Journal of Fisheries and Aquatic Sciences* **54**: 2627–2636.

Piet LJM. 1992. *Paleogeography and sedimentology of fluvial point bars, chute-fills and oxbow-fills in the lower Liard River, N.W.T.*, M.S. Thesis. University of Calgary: Calgary; 107.

Smith DG. 1973. Aggregation of the Alexandra–North Saskatchewan River, Banff National Park, Alberta. In *Fluvial Geomorphology*, Morisawa M (ed.). Allen and Unwin: London; 201–219.

Smith DG. 1980. River ice processes: thresholds and geomorphologic effects in northern and mountain rivers. In *Thresholds in Geomorphology*, Coates DR, Vitek JD (eds), Geomorphology Symposium (9th), Binghamton, NY; 323–343.

Smith DG. 1983. Anastamosed fluvial deposits: modern examples from western Canada. In *Modern and Ancient Fluvial Systems*, Collinson JD, Lewin J (eds), Special Publication of the International Association of Sedimentologists. International Association of Sedimentologists: Oxford; 55–168.

Smith DG, Pearce CM. 2002. Ice-jam-caused fluvial gullies and scour holes on northern river flood plains. *Geomorphology* **42**(1/2): 85–95.

Smith DG, Smith ND. 1980. Sedimentations in anastomosed river systems: examples from Alberta, Canada. *Canadian Journal of Earth Sciences* **17**: 1396–1406.

Smith ND, Cross TA, Dufficy JP, Clough SR. 1989. Anatomy of an avulsion. *Sedimentology* **36**: 1–23.

Taylor CFH. 1999. The role of overbank flow in governing the form of an anabranching river: the Fitzroy River, north western Australia. In *Fluvial sedimentology VI*, Smith ND, Rogers J (eds). Blackwell: Oxford; 77–91.

Wathen SJ, Hoey TB. 1998. Morphological controls on the downstream passage of a sediment wave in a gravel-bed stream. *Earth Surface Processes and Landforms* **23**: 715–730.

