# The Origin of Anastomosis in the Upper Columbia River, British Columbia

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## ABSTRACT

To understand the origin of anastomosis on the Columbia River between Spillimacheen and Golden, BC, a geomorphic and sedimentologic survey was undertaken during the summer flood of 2000. On the basis of these observations, the study reach can be divided into two sub-reaches: a highly anastomosed section with 3 to 5 channels, and a weakly anastomosed section with 1 to 2 channels. The highly anastomosed reach occurs immediately downstream from the Spillimacheen tributary and is characterized by a higher channel slope, a higher number of crevasse splays, a larger combined crevasse splay area, a wider valley, and a coarser bedload. Higher rates of floodplain aggradation in the highly anastomosed reach are suggested by modern sediment budgets and radiocarbon dates. These geomorphologic and sedimentary associations are consistent with the hypothesis that anastomosis of the Columbia River is maintained by a dynamic equilibrium between the rates of channel creation and channel abandonment.

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# INTRODUCTION

Anastomosed rivers consist of two or more interconnected, co-existing channels that typically enclose concave-upwards floodbasins. The channels are usually straight or slightly sinuous, but braided and meandering patterns are also known (Makaske, 2001). Thus, anastomosed rivers are different from braided rivers because the latter contain multiple thalwegs enclosing convex bars within a single channel (Makaske, 2001) whereas anastomosis defines a network of anabranched channels. Although the geomorphic characteristics of anastomosed rivers have been recognized and described (Smith and Putnam, 1980; Smith and Smith, 1980; Smith, 1983, 1986; Miller, 1991; Knighton and Nanson, 1993; Smith et al., 1997; Makaske 1998, 2001; Smith et al, 1998), the origin of anastomosis is still an unresolved matter (Nanson and Huang, 1999; Makaske 1998, 2001). Indeed, Makaske (1998) argues that understanding the causes of anastomosis "is one of the major challenges in current fluvial research", and Nanson and Huang (1999) assert that anabranching rivers (including anastomosed rivers) "remain the last major category of alluvial systems to be described and explained".

Three classes of explanation exist for the origin of anastomosis. In the first, anastomosis is a consequence of frequent avulsions and slow abandonment of earlier channels. According to this point of view, the fluvial system exists in a perpetual transition state consisting of multiple co-existing channels. Anastomosis is thus not a "graded" state, but rather a by-product of the competition between channel creation and abandonment. Makaske (2001), for example, defines an anastomosed system as the product of a dynamic balance between frequent avulsions that create multiple channels and slow channel abandonment. According to Makaske, the immediate causes of the frequent avulsions are a rise in base level, subsidence (Smith, 1983), and high rates of aggradation, whether of the channel belt or within the channel. The immediate cause of slow abandonment is conjectured by Makaske (2001) to be low stream power, although few data exist.

In explanations of the second class, anabranching, and in particular anastomosed, rivers are thought to be an equilibrium form where channels are adjusted in geometry and hydraulic friction to just transmit the imposed water and sediment discharges. In cases where gradient cannot easily be increased to carry a larger sediment load, Nanson and Knighton (1996) and Nanson and Huang (1999) propose that a shift from single to multiple channels leads to an increase in sediment transport rate per unit water discharge. Thus, like changes in slope and channel form, anastomosis is conjectured to be another mechanism whereby a fluvial system can maintain grade. Makaske (1998) challenged this idea, however, arguing that the multi-channel state of the upper Columbia River cannot be taken as a response of the system to maximize water and sediment throughput because, in spite of its anastomosed morphology, the bulk of its water and sediment moves through a single channel.

The third explanation was put forward by Galay et al. (1984) from a study of the Columbia River. He postulated that ponding behind alluvial fans led to the formation of large lakes in the upper Columbia Valley. The lakes gradually were filled by river-dominated “bird’s-foot” deltas of which the present anastomosed river system is a final stage. A paleoenvironmental reconstruction from cores by Makaske (1998), however, has shown that this is not a viable hypothesis, and it will not be considered further.

The purpose of this paper is to describe hydraulic and sedimentologic properties of the anastomosed reach of the upper Columbia River in British Columbia, Canada, in order to assess the origin of its anastomosis. The Columbia River near Golden, British Columbia is one of the best-known examples of anastomosis (Locking, 1983; Smith, 1983; Makaske, 1998; Adams, 1999; Machusick (2000); Makaske 2001). Furthermore, hydrologic and photographic records are available starting from the first half of the 1900's. Our conclusion is that anastomosis of the Columbia River is best explained as a by-product of roughly equal rates of channel creation and abandonment, consistent with Makaske's conjecture.

## LOCATION AND GEOMORPHOLOGY OF THE STUDY AREA

The study reach is a section of the upper Columbia River near Golden, British Columbia, Canada (Fig. 1). The Columbia River starts at Columbia Lake in southern British Columbia, approximately 80 km southeast of the study reach, and flows north-northwest in a 1-2 kilometer-wide valley for a distance of 160 km along the Rocky Mountain Trench before turning west and southwest. It comprises a single channel between Columbia Lake and the town of Radium and an anastomosed reach between Radium and Golden. Anastomosis is particularly evident downstream of Spillimacheen, and this report concentrates on the 55-km reach between Spillimacheen and Golden. Access is provided by Route 95 along the northeast side of the valley, by bridges at Nicholson, Parson, and Spillimacheen, and by a railroad right-of-way. The area lies within the Cassiar-Columbia Mountain physiographic region and in the Interior Douglas-Fir biogeoclimatic zone (Farley, 1984). Mean annual precipitation varies between 40-50 cm/yr, and mean daily temperature varies from –12 to 15°C in January and July, respectively.

## Geomorphology of the study reach

In the study reach, the Columbia River consists of multiple, relatively stable channel belts containing low-sinuosity to straight, low-gradient, sand-bed channels. Levees and crevasse splays of the channel belts bound floodbasins containing shallow wetlands and lakes. Thirty-seven tributaries enter along the reach, forming alluvial fans that narrow the valley and act as local sediment sources. The two largest tributaries are the Spillimacheen River (drainage basin of 1430 $km^2$) and the Kicking Horse River (drainage basin of 1850 $km^2$), which respectively define the upstream and downstream limits of the study reach. The Spillimacheen River is a major sediment source for the study reach, contributing silt to fine gravel.

An important observation bearing on the origin of anastomosis is the number and location of channels and their evolution through time. Vibracores show that anastomosed channel deposits in the study reach are characteristically 5-15 m thick, narrow, interconnected stringers of sand (Smith, 1983) that contain sandy crevasse-splay fringes. These facies are stacked vertically, indicating that the channels occupy the same valley location for durations of one to approximately 3000 years (Smith, 1983; Makaske, 1998). Vertical aggradation rather than lateral accretion is the dominant sedimentation pattern, a conclusion also supported by the virtual absence of modern oxbow lake and point bar deposits. In one cross-valley stratigraphic section (Makaske, 1998), at least 11 channels have existed over the past 3000 years. Of these, six came into existence and five became extinct, indicating the long-term existence of the anastomosed pattern and the episodic nature of channel creation. There is also some indication that the longer lasting channels are wider than 30-50 m (Makaske, 1998), possibly because smaller channels can be occluded by logjams or have their gradient strongly diminished by beaver dams.

The Columbia River sediment load consists of 59% to 82% suspended material (Makaske, 1998), or if wash load is also considered, 89% (Locking, 1983). Locking's (1983) sediment budget indicates that at the end of the anastomosed reach near Nicholson (6 km upstream of Golden) the supply of suspended load is much less than the transport capacity of the river. This decline in suspended load is evidence of a significant sediment sink in the anastomosed reach (Locking, 1983). Permanent sequestration of the bedload also occurs. Sixty-six percent of the bedload goes into channel storage (Smith, 1986) and 10-20% is trapped in crevasse splays (Makaske, 1998).

## Hydrology

Hydrographs for the Columbia at Nicholson (1947-present) and the Spillimacheen near its mouth (1950-present) indicate that discharges for both rivers are highly seasonal (Fig. 2). Minimum discharge for the Columbia occurs in February (average=24 $m^3/s$), and maximum discharge occurs in June and July (average=321 $m^3/s$), with overbank discharge of 45 days per year on average occurring almost every year (Locking, 1983). Our field observations were taken during the year 2000 flood which was average in magnitude but short in duration and somewhat delayed due to cold weather in June (Figs. 2b and 2d). The peak flow frequency distribution shows that the maximum peak of 351 $m^3/s$ registered at the Nicholson gauging station during the year 2000 occurs on average every 1.2 years (1-year flood).

## LONGITUDINAL VARIATIONS IN ANASTOMOSIS AND RELATED FEATURES

To better understand the necessary conditions that give rise to anastomosis, the degree of anastomosis of the Columbia River was correlated with channel gradient, crevasse splay distribution, valley width, alluvial fan area, and channel-bed grain size. These parameters were measured during the summer of 2000 or were observed on aerial photographs taken in 1996 at high stage when the discharge measured at Nicholson was the third highest of the previous 10 years. Given the hydrologic data available from Environment Canada (formerly Water Survey of Canada) from 1947 to present, the 1996 peak discharge (506 $m^3/s$) occurs on average every 3.3 years (3-year flood).

For our purposes, a channel belt is defined as active, in contrast with non-active, dry, or abandoned, if channels within it contain turbid water on the 1996 aerial photograph, thereby implying at least modest through-flow. Main channels are defined as those wider than 40 m; narrower channels are here termed secondary channels. Figure 3 shows a typical section of the study reach where active/non-active channels and crevasse splays are indicated as well as definition sketches of alluvial fan area, splay area, and valley width.

### Degree of anastomosis

To quantify the degree of anastomosis, the number of active channels at each of 29 valley cross sections was counted. The number of channels, used here as a measure of anastomosis, varies from one to five with an average near two (Fig. 4a). On the basis of these differences, the study reach can be divided into an upper highly anastomosed reach (3-5 channels), a weakly anastomosed reach (1-3 channels), a single channel, and a lower braided reach. The braided reach occurs as the Columbia River crosses the alluvial fan of the Kicking Horse River and will not be discussed further here.

### Longitudinal profile

Absolute water-surface elevations were measured at 34 points along the Columbia River using a Leica 500 differential GPS system with a sub-centimeter vertical accuracy. The points were measured October 13-15, 2000, between the bridge at Spillimacheen and the Kicking Horse River and corrected for a falling water level of 1 cm per day. The water elevations (Fig. 4b) are plotted against along-channel distance rather than valley distance to avoid anomalies introduced by variable sinuosity or when the channel flows across the valley.

The longitudinal profile is divisible into three sections: two relatively steep portions, one each from Spillimacheen to Castledale ($S = 0.000215$) and at Golden ($S = 0.000442$), and a more gentle central portion from Castledale to Golden ($S = 0.000068$). The other minor fans along the valley show little, if any, effect on channel gradient.

### Distribution of active crevasse splays

The study reach was divided into 29 cross-valley swaths, each 2 km wide, in which we determined the numbers of active crevasse splays and their total surface areas. A crevasse splay was considered to be active if turbid water was flowing across its surface in the 1996 aerial photos. The number of active crevasse splays and total crevasse splay areas are both relatively high in the upper 12 km of the study reach (Fig. 4c). Figure 4d shows the percent of the valley floor covered by active crevasse splays. There are 12 active crevasse splays in the upper 18 km and only 6 crevasse splays along the remaining reach. The area covered by active splays decreases monotonically with distance, the exception being an active avulsion site at kilometer 37. At this site, an on-going avulsion blankets the whole floodbasin with sediment, and small levees have formed since 1960 (Adams, 1999). The study reach therefore can be divided into two sections: an upstream reach with a high number of crevasse splays and a downstream reach with a low number of crevasse splays.

### Valley width

Valley width is potentially an important parameter in determining anastomosis because it defines the maximum available space in which channel belts can form. Variation in valley width is controlled by prograding alluvial fans from side tributaries. Measurements from aerial photographs of valley width and alluvial fan area (Fig. 4e) show little correlation with anastomosis.

### Bed material grain size

Bed material was sampled during high stage on June 24 and July 6, 2000 from the mouth of the Spillimacheen River to 5 km upstream of the town of Nicholson. Twenty-five samples were collected along the main thalweg using a bucket sampler (height 15 cm, diameter 10 cm) with three replicates each to capture cross-channel variability. Mean grain size was computed using a Rapid Sediment Analyzer to obtain a mean fall velocity that was then converted to mean particle diameter using the relationship of Dietrich (1982).

Mean grain size shows considerable scatter (Fig. 4f), probably due to variations in texture at the crest and troughs of dunes and the occasional introduction of coarse material from tributaries. Nevertheless, the bed material fines appreciably downstream in the study reach from 1.4-2.2 mm upstream to 0.5-1.1 mm downstream.

## Discussion

The above data indicate that the study reach of the Columbia River (excluding the braided section) can be divided into two sub-reaches, a 10-km long, highly anastomosed reach with 3-5 channels starting immediately below the confluence with the Spillimacheen River, and a 50-km long, weakly anastomosed reach containing 1-3 channels. The highly anastomosed reach is characterized by a relatively steep channel slope, a higher number of crevasse splays, a higher total crevasse splay area, a higher splay-area/valley-area ratio, and coarser bed material (Table 1). These are particularly interesting observations because previous studies have concluded that low gradients and fine grain sizes are necessary conditions for anastomosis (cf., Makaske, 2001).

We interpret the intensity of crevasse splay activity to indicate that alluviation rates are higher in the upstream, highly anastomosed reach. Testing this interpretation with actual measured aggradation rates is difficult, however. The spatially averaged sedimentation rate during the 1982 flood cycle for the entire reach from Spillimacheen to Nicholson was 3.7 mm/yr (Locking, 1983). This probably is an over-estimation of the long-term average because it is based on the 1982 flood, which was well above average. A detailed sediment budget and geomorphic study of a floodbasin in the highly anastomosed reach (Fig. 1, Soles Basin) during the year 2000 flood (Abbado, 2001), shows that it is being actively filled at a rate of 2.2 mm/yr by a combination of short-lived crevasse splays, intra-floodbasin channels, and settling of grains in temporary lakes. This must be considered a minimum because the flood of 2000 was shorter in duration than the average flood (Fig. 2b) and only suspended load was measured. In contrast, 16 km further down the study reach, an average aggradation rate of 1.7 mm/yr was obtained using a radiocarbon date of 4,500 yrs from *Scirpus Lacustris* nuts buried 7.9 m in a floodbasin (Makaske, 1998). Although the data are inconclusive, they are at least consistent with our conjecture that aggradation rates are higher upstream in the more anastomosed reach. Also consistent is the steep slope observable in the longitudinal water profile, which can be interpreted as a wedge of sediments prograding downstream as alluviation occurs. Finally, as Paola (2000) and Robinson and Slingerland (1998) have argued, the downstream-fining itself is suggestive of preferential aggradation in the upstream reach. Although upstream bed-armoring could produce a similar downstream fining trend, we do not think this is a sufficient explanation for our data because at the time of sampling the pavement appeared to be broken and the bed was in general motion.

## SEDIMENT TRANSPORT MODELING

The observations presented so far do not discriminate between the two remaining hypotheses for the origin of anastomosis in the Columbia because both predict that the degree of anastomosis will be correlated with excess sediment supply. Here we explore whether the Columbia channels are adjusted to maximize sediment transport rate, as suggested by Nanson and Huang (1996). In traditional equilibrium channel theory, a river adjusts its slope, geometry, and roughness to convey the supplied water and sediment discharge. Nanson and Knighton (1996) and Nanson and Huang (1999) suggested that a river might also change its number of channels to yield the same effect. Based on field observations, they asserted that a reduction in total top-width causes a multi-channel network to convey more sediment per unit discharge than a single channel. Thus if an original channel is 100 m wide and say 3 m deep, three channels, each 25m wide and carrying the same discharge at the same slope, will carry more bedload because a reduced width-depth ratio (W/D) is more conducive to water flow and sediment discharge.

The hypothesis to be tested here is that the highly anastomosed reach of the Columbia River is adjusted in channel number and channel width/depth ratios to carry more sediment than a single channel, all other factors being equal. To test the hypothesis consider an idealized Columbia channel network (Fig. 5) in which cumulative top-width, depth, and bed slope are kept constant at 120 m, 3 m, and $10^{-4}$ respectively, consistent with values observed in the upstream portion of the study reach. A single channel with $W/D \cong 40$ progressively bifurcates into second order channels with $W/D \cong 20$ and third order channels with $W/D \cong 10$. These values have been determined from published and unpublished cross sections along the upper study reach (Fig. 6) where W/D is defined as top-width divided by the hydraulic depth (ratio of channel cross sectional area divided by its top-width). Inspection of Table 2 shows that the distribution of channel widths is bimodal with the division occurring between 40-50 m. Interestingly, the width-depth ratios of main channels decrease with an increasing number of channels along any valley cross-section (Fig. 7), which could be interpreted as consistent with the Nanson-Huang conjecture. In contrast, the ratio for secondary channels increases. An additional important characteristic of secondary channels is that their thalwegs sit at higher elevations compared to the main channels and thus they are active only during high stage.

Sediment transport through this idealized system is calculated under uniform and steady flow conditions assuming channels of rectangular cross sectional shape in which:

$$Q = VA \qquad (1)$$

where Q ($m^3/s$) is water discharge, V(m/s) is average velocity, and A ($m^2$) is channel cross sectional area. V is expressed by the Chezy formula:

$$V = C\sqrt{RS} \qquad (2)$$

where R (m) is hydraulic radius, S is channel slope, and C ($m^{1/2}/s$) is the Chezy constant. R and C are given by:

$$R = \frac{A}{2D + W} \qquad (3)$$

$$C = \frac{1}{n} R^{1/6} \qquad (4)$$

in which D (m) is the water depth, W (m) is the channel width, and *n* is the Manning constant. The system of Equations 1-4 yields the following 10th order exponential equation:

$$W^4 D^{10} - 16xD^4 - 32xWD^3 - 24xW^2D^2 - 8xW^3D - xW^4 = 0 \qquad (5)$$

where $x = \frac{Q^6 n^6}{W^6 S^3}$. For fixed Q, n, S, and width-depth ratio, Equation 5 can be solved for D.

Bedload and suspended load sediment transport rates are calculated by two methods: 1) the Bagnold (1977) bedload formula coupled with the Rouse (1937) suspended sediment formulation, and 2) the Van Rijn functions for bedload and suspended load (Van Rijn, 1984a, 1884b; Makaske, 1998). These methods were selected because they are appropriate for the grain sizes and slopes observed in the Columbia River and because they compute both bedload and suspended load.

Solutions of the above system of equations for total sediment transport rate indicate that total sediment load is reduced as the flow is divided into additional channels (Table 3). Total transport rate decreases by approximately 11% and 21% for the Bagnold-Rouse and Van Rijn formulas, respectively. In particular, bedload transport rate, which is more important because it controls in-channel alluviation, decreases by 16% and 22%, respectively. Water velocities decrease by 2% moving from one to two channels, and 5% moving from two to four channels. Note that although the magnitudes of the transport rates are sensitive to the choice of Manning's *n*, the general conclusions are not.

## DISCUSSION

The multiple channels of the Columbia do not increase water velocity and sediment transport rates over that of a single channel, all other factors being equal. We interpret these results to mean that the Nanson and Huang (1999) hypothesis does not apply to the particular case of the Columbia River. This is not to say that the Nanson-Huang conjecture is everywhere invalidated. In cases where the cumulative top width of multiple channels is reduced relative to a single channel, we agree that sediment transport rates will be increased. In the Columbia however, the observed width-depth ratios and cumulative top-widths do not effect increases in sediment transport rates as the number of channels is increased.

Rather, we conclude that anastomosis of the Columbia River is an incidental consequence of frequent avulsions (i.e., crevassing) and slow abandonment of earlier channels. High sediment flux from the Spillimacheen River has overloaded the Columbia, causing high in-channel alluviation rates. These high alluviation rates increase the probability of levee overtopping as well as levee crevassing and crevasse splay formation. These in turn create numerous new channels through floodbasins. The new channels, flowing generally cross-valley, are usually superelevated compared to the main channel. For this reason they are mainly active during high stage and are slowly abandoned because of low flow velocities. Thus, long-lasting channels and complete avulsions of the main channel are tied to gradient advantages. Because of the narrow valley, cross-valley gradient advantage rarely occurs and the main down-valley channels remain active for hundreds to thousands of years. In contrast, secondary channels are short-lived. Therefore, the number of channels active at any time is proportional to the rate of creation of new channels and to their average lifespan, and inversely proportional to their rate of abandonment. If the rate magnitudes are comparable and relatively constant through time, then the number of active channels at any instant is also relatively constant, the exact number being fixed by the channel lifespan. It is only in this sense that anastomosis of the Columbia River is a dynamic equilibrium pattern.

It still remains for us to explain the reduction of width-depth ratio of main channels as the number of channels in a valley cross-section increases (Fig. 7). We think this reflects the fact that it is the main channels of the Columbia that transport most of the bedload. Because the bed elevations of the secondary channels are generally higher than the bed of the main channel, more water than bedload is siphoned off by secondary channels. The main channel must adjust to carry its bedload with less discharge, and does so by decreasing its width-depth ratio by an amount greater than would arise from the reduction in water discharge alone. In this restricted sense the Columbia main channels are behaving as postulated by Nanson and Huang (1999).

This model of anastomosis is consistent with the correspondence between degree of anastomosis and high slope. As shown by the sediment routing model, anastomosis induces a decrease in sediment transport rates, which is manifested by differential deposition.

## CONCLUSIONS

The anastomosed reach of the Columbia River can be divided into highly anastomosed and weakly anastomosed sub-reaches. The highly anastomosed reach occurs immediately downstream of the confluence with the high-sediment-load Spillimacheen River. The highly anastomosed reach is characterized by a higher channel gradient, a greater number of crevasse splays, a greater crevasse splay area, greater splay-area to valley-area ratio, and coarser channel-bed grain size. Circumstantial evidence indicates aggradation rates are higher in the highly anastomosed reach as well.

Calculations using Bagnold, Rouse, and Van Rijn sediment transport formulae show a decrease in sediment flux with increasing number of channels, given typical Columbia channel geometries, bed slope, and grain size. This is contrary to the predictions of Nanson and Huang (1999), leading us to conclude that anastomosis of the Columbia River is maintained by a dynamic equilibrium between the rates of channel creation and channel abandonment.

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**Table 1. Comparison between the upper and lower anastomosed reaches of the Columbia River in the study area.**

| Reach | Anastomosis | Number of channels | Slope (cm/km) | Number of crevasse splay/10km* | Area of crevasse splay $m^2$/km | Splay area/valley area (%) | Valley width (km | Grain size (mm) |
|---|---|---|---|---|---|---|---|---|
| Upper | High | 3-5 | 21.5 | ~10 | ~60000 | 3.3 | 1.4-2.2 | 0.5-1.1 |
| Lower | Low | 1-3 | 6.8 | ~1 | ~500** | 0.035 | 0.7-1.8 | 0.3-0.6 |

* Average number of crevasse splays per 10 km wide transverse swath. ** Excluding avulsion site.

**Table 2. Width-depth ratios of cross-sections in the upper study reach (main channels in bold).**

| Line # | Time of measurement | Top-width (W) | Average depth (D) | W/D | # of channels[1] | Cumulative width | Source |
|---|---|---|---|---|---|---|---|
| **1** | **May 2000** | **125.7** | **2.86** | **44** | **1** | **126** | **This Work** |
| 2 | May 2000 | 19 | 1.96 | 10 | 2 | | Filgueira, 2000 |
| 3* | May 2000 | 18.7 | 2.23 | 8 | 2 | | This Work |
| **4** | **July 2000** | **125** | **2.9** | **43** | **2** | **120** | **This Work** |
| **5** | **May 2000** | **88.9** | **2.87** | **31** | **3** | **120** | **Filgueira, 2000** |
| **6** | **May 2000** | **88** | **2.88** | **31** | **3** | **120** | **Filgueira, 2000** |
| 7 | May 2000 | 23.2 | 2.07 | 11 | **3** | | Filgueira, 2000 |
| **8** | **July 2000** | **90** | **2.95** | **31** | 3 | **180** | **This Work** |
| 9 | May 2000 | 13.7 | 2.25 | 6 | **3** | | Filgueira, 2000 |
| **10** | **May 2000** | **38** | **2.95** | **13** | 4 | **172** | **Filgueira, 2000** |
| **11** | **May 2000** | **55** | **2.82** | **20** | **4** | **188** | **Filgueira, 2000** |
| **12** | **June 1988** | **67.6** | **2.6** | **26** | **3** | **150** | **Adams, 1999** |
| 13 | June 1988 | 30.4 | 1.58 | 19 | 5 | 160 | Adams, 1999 |
| 14 | May 2000 | 38.9 | 2.9 | 13 | 5 | | Adams, 1999 |
| 15 | May 2000 | 31 | 3.64 | 9 | 5 | | Filgueira, 2000 |
| 16 | May 2000 | 35 | 3.49 | 10 | 4 | | Filgueira, 2000 |

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|---|---|---|---|---|---|---|---|
| **17** | **June 1988** | **84.5** | **2.94** | **29** | 4 | **160** | **Adams, 1999** |
| 18 | June 1988 | 20.3 | 1.25 | 16 | **4** | | Adams, 1999 |
| 19 | July 1994 | 22.5 | 1.84 | 12 | 4 | | Makaske, 1998 |
| **20** | **July 1994** | **57.5** | **4.44** | **13** | 4 | **100** | **Makaske, 1998** |
| 21 | July 1994 | 22.5 | 2.1 | 11 | **4** | | Makaske, 1998 |
| **22** | **May 2000** | **141** | **3.12** | **45** | 1 | **141** | **Filgueira, 2000** |
| **23** | **May 2000** | **101.6** | **3.34** | **30** | **2** | **130** | **Filgueira, 2000** |
| 24 | May 2000 | 21 | 2.27 | 9 | **3** | | Filgueira, 2000 |

[1] Number of channels equals the sum of main plus secondary channels along a cross-valley transect running through the channel cross-section.

**Table 3. Theoretical sediment transport magnitudes as a function sediment transport formula and number of channels. Q approximately 270 $m^3/s$.Tot $Q_{bl}$ = total bedload flux; Tot $Q_{sl}$ = total suspended load flux; Tot $Q_s$ = total sediment load.**

| Formula | # channels | Width (m) | Depth (m) | W/D | Water Velocity (m/s) | Tot $Q_{bl}$ ($m^3/s$) | Tot $Q_{sl}$ ($m^3/s$) | Tot $Q_s$ ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|
| Bagnold and Rouse | 1 | 120 | 2.94 | 40.8 | 0.7795 | 0.0061 | 0.0161 | 0.0222 |
| | 2 | 60 | 3.00 | 20 | 0.7649 | 0.0058 | 0.0156 | 0.0214 |
| | 4 | 30 | 3.11 | 9.6 | 0.7369 | 0.0051 | 0.0147 | 0.0198 |
| Van Rijn | 1 | 120 | 2.94 | 40.8 | 0.7795 | 0.0036 | 0.0336 | 0.0372 |
| | 2 | 60 | 3.00 | 20 | 0.7649 | 0.0033 | 0.0310 | 0.0343 |
| | 4 | 30 | 3.11 | 9.6 | 0.7369 | 0.0028 | 0.0264 | 0.0292 |

# FIGURE CAPTIONS

Figure 1. Location of the Study area. The Columbia River flows NNW between the Kootenay Range of the Rocky Mountains and the Purcell Mountains. Soles Basin, selected as a typical floodplain of the anastomosing reach, lies immediately downstream of the Spillimacheen River, an important tributary.

Figure 2. a) Discharge of the Columbia River at Nicholson 1947-2000; b) average monthly discharge of the Columbia over the interval 1947-1999 compared with year 2000 average monthly discharge; c) discharge of the Spillimacheen River at Spillimacheen 1950-2000; d) average monthly discharge of the Spillimacheen over the interval 1950-1999 compared with year 2000 average monthly discharge. Year 2000 flood was average in magitude but of short duration and delayed due to cold weather in June (Data from Environment Canada, 2001).

Figure 3.a) 1998 aerial photograph of the Columbia River showing active and inactive channels and crevasse splays, and b) definition sketch showing how crevasse splay area, alluvial fan area, and valley width were computed .

Figure 4. Comparison of selected morphological parameters of the Columbia River: a) number of channels; b) elevation; c) number and area of splays; d) splay-valley area ratio; e) valley width and alluvial fan area; f) mean grain size. See text for explanations.

Figure 5. Generic model of anastomosing river with width/depth (W/D) ratios typical of the Columbia. W/D progressively decreases with increasing number of channels.

Figure 6. Air photo collage of the highly anastomose reach of the Columbia River. Measured cross sections are indicated with a white mark; W/D ratio in parentheses.

Figure 7. Width-depth ratios of channels as a function of number of channels passing flow through any valley cross-section. Main channels are defined as those possessing widths greater than 40 m.