Dam-induced and natural channel changes in the Saskatchewan River below the E.B. Campbell Dam, Canada

Norman D. Smith^{a*}, Galina S. Morozova^b, Marta Pérez-Arlucea^c, Martin R. Gibling^d

^aDept. of Earth & Atmospheric Sciences, U. Nebraska, Lincoln NE 68588-0340, USA

^bSchool of Environmental Sciences, U. Guelph, Guelph ON N1G 2W1, Canada

^cDpto. de Geociências Marinas, Facultad de Ciencias del Mar, U. Vigo, Vigo, Spain

^dDept. of Earth Sciences, Dalhousie U., Halifax NS B3H 4R2, Canada

*Corresponding author. Tel.: +1 402 472 5362; fax: +1 402 472 4917; nsmith3@unl.edu

ABSTRACT

The E.B. Campbell Dam on the Saskatchewan River, east-central Saskatchewan, was constructed in 1962, forming Tobin Lake (2.2 billion m³ capacity), which today impounds most fluvial sediment and disrupts normal outflow patterns. Thirty-five kilometers below the dam, the river diverts into a 500 km² belt of alluvial sediment initiated by an avulsion ~140 years ago, rejoining the parent channel 108 km from the dam. Effects of the dam on channel geomorphology, including the historical channel (reach I) and the more recent avulsion-affected channels, were investigated by pre- and post-dam cross section surveys combined with grain-size and bedload measurements. Twenty-three sites were surveyed at least twice, and 14 were resurveyed annually in 2003-2014 (except 2007) during which significant floods occurred in 2005, 2011, and 2013. All channel cross sections up to 81 km below the dam have coarsened and enlarged since closure, resulting in excavation of 35.4×10^6 m³ of channel-perimeter sediment since 1962. The most proximal segment is armored and has changed little in recent years. Since 2003, channel enlargement has been greatest in the 35-81 km segment between the avulsion site and the Forks (reaches II, III), manifested as widening and deepening. Enlargement rates were greatest during the three floods, and the paucity of bedload has prevented degraded portions of the channel bed from replenishment following flooding. Budget calculations based on bedload measurements and channel cross-section areas suggest that more than 30 years would be required to replace the sediment removed between 2003 and 2014, assuming all available bedload remains in the affected reach. Dam effects appear to be absent or uncertain beyond 81 km, a multichanneled region of varied stages of activity (reach IV), recombining and eventually rejoining the parent Saskatchewan River channel at km 108 (reach V). Sediment evacuated from reaches I-III is sufficient to sustain modest aggradation in some distal portions of the avulsion belt, including the Mossy delta, but little bedload is returned to the parent channel. Dam-induced sediment starvation is speeding the rate at which a single dominant channel is evolving between the avulsion site and rejoined parent, a process that will likely shift the patterns of flood inundation in the future.

Keywords: dam effects on rivers; Saskatchewan River delta; EB Campbell Dam; avulsion

1. Introduction

The construction of dams and reservoirs on alluvial rivers disrupts the normal patterns of flow and sediment transfer, thereby altering geomorphic processes and forcing modifications of downstream channels. Such modifications have been examined for a large variety of dams and settings (Pemberton, 1976; Petts, 1984; Williams and Wolman, 1984; Brandt, 2000; Petts and Gurnell, 2005; Graf, 2006; Schmidt and Wilcock, 2008; Alexeevsky et al., 2013; Marren et al., 2014). In most cases, the impoundments are effective sediment traps that retain virtually all incoming fluvial bedload and most suspended load, rendering the outflow sediment-deficient and erosive. The downstream geomorphic responses to dams are complex and variably linked to numerous controlling factors. These include variables of dam construction and operation, sub-daily to decadal scales of discharge variations, channel planform and slope, erosional stability of channel floors and banks, tributary effects, and channel history (e.g., Petts, 1979, 1984; Williams and Wolman, 1984; Kondolf, 1997; Grant et al., 2003; Surian and Rinaldi, 2003; Marston et al., 2005; Middelkoop et al., 2015).

For large dams designed to impound and release all inflow, e.g., most hydropower dams, enlargement of the downstream channel is usually, though not always, observed (e.g., Grams and Schmidt, 2005). Enlargement usually begins by scouring near the foot of the dam, shifting downstream with time by widening and/or deepening, and tapering off when tributaries and channel erosion replace the sequestered sediment and eventually bring the sediment load back into equilibrium with the transport capacity of the flow. If the channel perimeter is composed of variously sized sediment, coarsening of the bed is common, especially within short distances from the dam where scouring tends to be the greatest. Such responses are usually evident in channel cross sections where changes in channel dimensions and composition are readily demonstrable (Gregory, 2006). Onsite studies of channel changes commonly involve cross-channel surveys at various distances from the dam, often repeated at multiyear intervals with rates of modification inferred on the presumption of linearity between surveys or sampling intervals (e.g., Petts and Pratts, 1983; Chien, 1985; Hadley and Emmett, 1998; Rinaldi and Simon, 1998; Grams and Schmidt, 2005; Phillips et al., 2005; Grams et al., 2007; Surian and Cisotto, 2007; Wang et al., 2007; Sun et al., 2012).

We investigate here the downstream effects of a large hydropower dam (E.B. Campbell) in the Saskatchewan River upstream from the head of the Saskatchewan River delta (SRD) in south-central Canada. The Canadian Prairie Farm Rehabilitation Administration (PFRA) conducted a series of topographic, hydrometric, and sediment surveys in the mid-1950s that included cross sections of many channels in the SRD as well as the historic channel that feeds it. These cross sections, surveyed several years before dam closure in 1962, provide a basis from which pre- and post-dam channel configurations can be compared. Thus, records are available over a period of some 60 years, with additional survey data extending back to 1911 (Voligny, 1917).

Located in a relatively pristine northern landscape with little historic logging or mining activity, the study location allows an assessment of individual and mutual effects of the hydropower dam and a range of natural processes in a setting with few other anthropogenic impacts on the river. The dam is situated upstream from the site of a major avulsion of the Saskatchewan River ~140 years ago (Smith et al., 1998), which provides us the opportunity to

observe the effects of the dam on relatively recent channels with different morphologies and histories. We conducted annual resurveys of PFRA channel cross sections in 2003-2014 (except 2007), during which three significant floods occurred. In undertaking this 11-year project, we hoped to gain insights into such questions as patterns of degradation (e.g., widening vs. incision, localized vs. general, gradual vs. abrupt), relationships between normal cut-and-fill activity and longer-term trends of aggradation and degradation, and the role of major discharge variations (i.e., unexpected flooding) in producing channel changes in such a sediment-starved system. The study builds on a previous analysis of channel form and sediment dynamics over the distal portion of a 240-km reach of the same river (Smith et al., 2014), here focusing on more proximal reaches downstream from the dam.

2. Setting

The study was conducted in and above the upper reaches of the SRD in east-central Saskatchewan (Fig. 1) where the river flowing off the high plains of south-central Canada enters the low-lying lacustrine plain of former Glacial Lake Agassiz (Schreiner, 1983; Christianson et al., 1995). There, the Saskatchewan River drains an area of 289,000 km², rising in the Rocky Mountains of western Alberta and draining large portions of the Canadian prairies. Downstream of the SRD, the river joins Lake Winnipeg in Manitoba and eventually terminates in Hudson Bay as the Nelson River. Dating from the onset of regional deglaciation of the Laurentide ice sheet ~10,000 years ago, the SRD currently terminates in Cedar Lake, Manitoba, a remnant of Glacial Lake Agassiz. The delta consists of upper (western) and lower (eastern) parts, separated by a large recessional moraine (The Pas Moraine). Together they occupy ~10,000 km², making the SRD the largest inland delta in North America. The E.B. Campbell Dam is situated 35 km upstream from the avulsion site (Fig. 1B), the most recent (1870s) of nine major avulsions in the upper delta in the past 5400 years (Morozova and Smith, 1999). Although the avulsion site is commonly indicated as the present bifurcation of the Old Channel and New Channel, the diversion actually began at a large meander bend now 3.7 km downstream of the present bifurcation, shortly after which a chute cutoff of the bend moved the junction upstream (Smith et al., 1998).

Regional climate is subarctic with strong seasonality including cold winters, mild summers, and no dry season. The mean annual temperature at The Pas, Manitoba, is -0.3°C; mean daily temperature for January is -21°C and for July, 18°C. Total annual precipitation averages about 450 mm (<http://www.the-pas.climateemps.com>). Freeze-up typically lasts 5-6 months beginning late October or November and ending in April.

3. Dam and hydrology

The dam, completed in 1962, is located in an entrenched section of the Saskatchewan River ~20 km upstream from the apex of the delta floodplain. The dam is 33.5 m high, 722 m long, and its reservoir, Tobin Lake, has a capacity of 2.2 billion m³; as such, it is classified as a very large dam (Graf, 2005; Fig. 2A). It is used primarily for hydroelectric power, but also for flood control and recreation. In this paper, all downstream distances are measured in km

from the dam along the mid-channel thread. The reservoir is an efficient trap from which little river-borne sediment escapes (NHCL, 1986; Ashmore and Day, 1988).

Downstream from the dam, entrenched valley walls stand ~25-30 m above the river surface and are composed of weak bedrock and unconsolidated lacustrine and glaciogenic sediment. Nearby gauging stations, operated by the Water Survey of Canada, are located on the Saskatchewan River 8 km below the dam (station 05KD003, since 1962, here termed 'below Tobin') and at The Pas, Manitoba (05KJ001, since 1913) 235 km downstream from the dam. A gauge at Nipawin, Saskatchewan (05KD001), 70 km upstream from the dam with no significant intervening tributaries, operated in 1942-1962 but was discontinued after completion of the dam. It recorded mostly, but not entirely, ice-free flow conditions, but otherwise serves as a reasonable pre-dam surrogate for the current post-dam below-Tobin gauge.

The Saskatchewan River supplies approximately three-fourths of the discharge to the SRD (NHCL, 1986), with the remaining flow provided by tributaries that include the Torch and Mossy Rivers in the upper delta (Fig. 1). Mean daily discharge below the dam (05KD003) for the period 1963-2014 is 455 m³/s. At The Pas, mean daily discharge for the full record (1913-2014) is 647 m³/s and 611 m³/s since 1963. This long-term reduction in mean discharge is partly attributable to upstream consumption dominated by irrigation projects in Alberta and western Saskatchewan (Seneka, 2004). The hydrographs display bimodal peaks, one each in spring and summer, representing runoff maxima of spring snowmelt from the prairies and summer ice and snowmelt from the mountains (Fig. 3). Prior to dam closure, flows during freeze-up periods were consistently low, but dam operations now produce two prominent modifications of annual hydrographs: suppression of spring and summer peaks and elevation of winter lows, both geared to seasonal power production and typical of many large dams elsewhere (Magilligan and Nislow, 2005; Graf, 2006). Shapes of the Nipawin (05KD001) and below-Tobin (05KD003) hydrographs averaged over their periods of record (Fig. 3A) are approximately sustained at The Pas (Fig. 3B), though the peaks are attenuated by passage through the delta wetlands and slightly lagged by distance. The larger spring peak at The Pas is an effect of prairie snowmelt drained by intervening tributaries.

In addition to seasonal variations, dam operations produce daily release pulses that occasionally exceed 2-m water-surface fluctuations within a few kilometers of the dam. These daily variations, largest during summer, tend to decrease by ~50% within 30 km of the dam and attenuate to nearly zero over the next 75-100 km (Euteneier, 2002).

Field data for this study were obtained annually in summer periods from 2003 to 2014, excluding 2007. Significant floods occurred in 2005, 2011, and 2013, each peaking in late June-early July. In each case, field work was conducted after the flood peaks when most flow had returned to its banks. Over the 52 post-dam years of record for gauge 05KD003 (below Tobin), the floods of 2013, 2011, and 2005 ranked, respectively, first, second, and fourth in peak daily discharge with values of 3640, 3270, and 2870 m³/s, respectively. The second highest flood peak (3450 m³/s) occurred in 1974, 29 years before the onset of this study.

4. Study reach

Except for the uppermost 35 km (historical Saskatchewan River), the channel segments of this study are largely the products of floodplain development following the 1870s avulsion, when the flow diverted northward from the parent channel (presently the Old Channel) and subsequently formed a network of interconnected channels, mouth bars, splays, interchannel lakes, and marshy floodbasins that today occupy an alluvial belt of $\sim 500 \text{ km}^2$ (Smith et al., 1989, 1998). Approximately 95% of discharge released by the dam flows through the avulsion belt, with the remaining 5% bypassed through the Old Channel (Fig. 2B). Small additional discharges are provided by the Torch and Mossy tributaries. All flow eventually rejoins the Old Channel, either directly or by way of Cumberland Lake, a shallow (<2 m depth) remnant of Glacial Lake Agassiz. Approximately three-fourths of the study reaches between the dam and the rejoined Old Channel are dominated by a mostly single-thread contiguous channel comprising the Saskatchewan River (dam to Old Channel bifurcation), New Channel, and Centre Angling Channel (Fig. 1B). At 81 km, the Centre Angling Channel undergoes a 3-way split (the Forks; Fig. 2D), which results in approximately half of the discharge flowing northeastward to Cumberland Lake via the Mossy route and the other half flowing southeastward through the Bigstone route, picking up Cumberland Lake outflow before rejoining the Old Channel 108 km from the dam. For the purposes of this study, we identified five contiguous segments, here termed reaches I to V, between the dam and rejoined Old Channel, defined by channel history, geographic waypoints, width/depth ratios (Fig. 4), and other physical attributes. The five reaches are shown in Fig. 1 and summarized in Table 1.

Since its inception, avulsion-belt expansion has been generally progradational and multichanneled, with fewer and larger channels replacing smaller channels with time. This is reflected in the downstream progression of reaches II, III, IV where today a well-defined single-thread channel (II) passes into a mostly single-thread but less well-defined channel (III) to a zone of smaller interconnected channels with varied widths, depths, and stages of activity (IV). This downstream progression from larger and more mature to smaller, more numerous, and less mature channels is also reflected in decreasing gradient and bank heights from upstream to downstream (Fig. 5), features common to other prograding alluvial bodies (Axelsson, 1967; Smith and Pérez-Arlucea, 1994; Ward et al., 2010). Virtually all channels are bound by natural levees deposited by overbank flooding, resulting in bank heights that decrease with distance and decreasing age as the channel network extends by progradation.

5. Methods

5.1. Bed material

The PFRA (1954) presents grain-size data for channel-bed samples collected through most of the present study reaches, allowing comparisons of pre- and post-dam sediment sizes and sorting histories. To minimize sampling errors, we used a sampling device similar to that of the PFRA--- a weighted cylinder dragged several meters over the bed. For sites dominated by sandy beds, the cylinder was a weighted 2-L can. A much larger cylinder (32 kg, 19 cm diameter) was used in coarse-bottom sites nearer to the dam. At most sites, five subsamples

were collected across the active channel: one at mid-channel and four spaced at one-third and two-thirds distances from the center toward each bank, with distance to bank determined by laser rangefinders. The PFRA similarly collected either five or three subsamples in the wide channels of reaches I and II, but only single mid-channel samples in the more distal locations. For each site, all subsamples were combined and riffled to produce a single representative sample that was later sieved to determine median grain diameter (d_{50}). Samples were collected over the contiguous study reach (I-V) in 2009-2011. An earlier set of samples obtained in the same manner was collected in 1991-1992 from reaches II, III, and IVa.

5.2. *Bedload*

Bedload transport was measured at several sites in 2012-2014 to identify general sources and distribution patterns of sediment generated by internal erosion. Measurement sites were selected from 17.5 km below the dam to the bridge near Cumberland House 0.5 km downstream from the Old Channel confluence. Spot measurements were attempted at locations closer to the dam but produced negligible returns. Measurements were made with two Helley-Smith-type bedload samplers during mid-summer periods when mean daily discharges at the below-Tobin gauge ranged from 1.4 to 2.6 (avg. 1.9) x mean annual discharge. Each sampler had a 76-mm (3-inch) orifice, 0.2-mm mesh bag, and was fitted with an aluminum vane to assure proper orientation in the current when lowered to the channel floor. Each sampler was tethered to a small marker float, lowered and retrieved from a boat, and the sample returns weighed in the field. Samplers were spaced at 10-, 15-, 20-, or 25-m intervals across the channel, depending on width; and collection times were held constant at each cross section, usually 10 or 15 minutes. Numbers of measurements per cross section ranged from 8 to 21.

5.3. *Channel cross section surveys*

The 1950s survey sites were located from the original set of air photos marked and labeled by the PFRA survey crews. Twenty-one PFRA sites and two non-PFRA sites were selected and numbered consecutively 1-23 between the dam and distal portions of the Mossy and Bigstone routes that terminate, respectively, at Cumberland Lake and the Old Channel confluence. Site selections were based on reasonable spacing, avoidance of islands, and availability (e.g., some long channel segments were not surveyed by PFRA). The PFRA cross sections included the tops and sides of both banks, channel floors, and water-surface level at the date of survey. The PFRA survey points were converted to elevations by tying to local benchmarks and were displayed in paper rolls at 25:1 vertical exaggeration. Copies of rolls and surveyor's air photos were provided by the Agri-Environment Services Branch, Agriculture & Agri-Food Canada, Winnipeg, Manitoba. Identification and map locations of survey sites are given in PFRA (1954).

Starting in 2003, 10 of the 21 PFRA sites and the two non-PFRA sites, 12 and 16, were selected for annual resurveys, concluding in 2014 and omitting 2007 (Table 2). In 2004, two additional PFRA sites (3, 19) were added to the annual resurvey group, bringing the total to 14 sites, one of which (19) comprised three interconnected and closely spaced channels in the same cross section. The remaining nine PFRA sites were resurveyed only once in 2012-2014 for longer term comparison to pre-dam surveys. Three of these were in proximal sites of reach

I (1, 2, 4), two in reach IV (17, 18) and four in distal sites of reaches IVb (20) and V (21-23) (Table 2, Fig. 1).

Because temporary benchmarks used by the PFRA were no longer available, all cross sections were tied to a set of 15 benchmarks installed by the Saskatchewan Water Security Agency in cooperation with this study. These consisted of steel rods inserted 2 m into the ground near the survey sites and tied to a federal benchmark at Cumberland House by GPS. Channel depths were measured by acoustic sounding, joined to banks and exposed parts of the channel by leveling, and converted to elevations. Bankfull cross section area was calculated as the area bounded by the channel perimeter lying beneath a horizontal line extending from the top of the lower bank to the opposing bank. This horizontal reference line at each site served as the datum for comparisons of subsequent resurveys. Mean bankfull depth (D) was calculated from bankfull width (W) and cross section area (A) as $D = A/W$. Mean elevation of the channel floor was then determined by subtracting mean depth from the elevation of the horizontal reference line. All surveys were conducted in either July or August following peak summer discharges.

Following Schmidt and Wilcock (2008), we use the term incision to mean lowering of the stream bed and the term degradation to mean all processes leading to evacuation of sediment from the channel cross section and thus causing channel enlargement. We use the term aggradation to mean accumulation of sediment that raises the mean bed elevation from some previous level. Channel capacity is used here as equivalent to bankfull cross section area.

6. Results

6.1. Bed material size distribution

The upper 12 km of reach I, entrenched and directly downstream of the dam, is armored with boulders and cobbles derived from valley walls, followed by steeply decreasing particle sizes over the next 20 km to the Old Channel bifurcation (Fig. 6). The valley walls become lower and recede away from the channel in the middle portion of the reach, and alluvial banks and islands representing the uppermost portions of the SRD begin to appear and then dominate the remainder of the reach. The most proximal PFRA sample, collected in 1954 12 km below the present dam site, was composed of medium sand, but the site presently consists of cobble- and pebble-sized gravel, indicating major post-dam coarsening. The uppermost 8 km of reach I was mostly rapids before construction, and the dam itself was built over rapids (Squaw Rapids in earlier reports). A detailed 1911 map by river surveyors (Voligny, 1917) shows patchy gravel accumulations as far downstream as 19 km from the present dam site, so the steep decline in particle size along reach I is likely an effect of both post-dam degradation and selective transport away from the coarse upper portions of reach I.

Coarsening of the bed since 1954 is also evident from comparisons of the three successive sets of bed-material samples through reaches II, III, and IV (Fig. 6). In reaches II and III, the 2009-2011 samples are either similar to or slightly coarser than the preceding 1991-1992 samples: mean d_{50} in reach II increased from 0.36 mm ($n = 7$) to 0.40 mm ($n = 8$), and in reach III, mean d_{50} increased from 0.28 mm ($n = 7$) to 0.33 mm ($n = 11$), suggesting that modest coarsening is still ongoing and indicative of dam-starvation effects (Chien, 1985). Farther downstream in reach IVa, the pre-dam samples are much finer grained because at that time (1954) the sand bed channel of the prograding avulsion belt had not yet reached the distal flooded wetlands. With later channel extension, coarsening resumed (km 88-97), though

independent of dam effects. There is little difference between the 1991-1992 and 2009-2011 samples in reach IVa, suggesting minimal dam influence on bed material sorting at that distance (>80 km).

6.2. Bedload

Bedload data are presented as width-normalized transport rate (kg/m/h), where m represents 1 m of channel width, and total transport rate for the entire channel cross section (t/h), which is the product of width-normalized transport rate and channel width. The plots (Fig. 7) indicate low transport rates in the uppermost site 18 km from the dam, increasing rapidly at the three sites in the next 17 km of reach I, which contains sandbars and alluvial islands (Fig. 2B). The next two sites (mid-reach II, upper reach III) show comparatively modest transport rates; however, only one set of measurements (2014) was made at each site and thus may not be representative. Higher rates resume at 73 km, occurring at one of the wide and shallow reaches of the Centre Angling Channel that represents ~15% of reach III. Transport rates then decrease through both main threads of reach IV, levelling off to very low rates in reach V. Four sets of measurements over three years at the bridge near Cumberland House (km 108.5, 0.5 km downstream of the Old Channel confluence) averaged only 0.78 t/h for the full width of the channel (3.95 kg/m/h or 0.0011 kg/m/s). By comparison, eight sets of measurements combined for the three sites between km 24 and 35 (reach I) averaged 38.9 t/h, or nearly 50x larger than that for the recombined flows at the bridge.

The overall pattern (Fig. 7) indicates that significant bedload is produced in the lower half of reach I by erosion of banks and sandbars, corroborated qualitatively by field observations of fresh cutbanks and fallen trees. Nearly all bedload material, however, remains in the avulsion belt, most apparent in reach IV and the medial and lower portions of reach III. The Mossy delta (distal reach IVb) is probably the single largest active repository of bedload in the avulsion belt, but others include crevasse splays (Smith and Pérez-Arlucea, 1994; Farrell, 2001; Toonen et al., 2016), fills of failing and abandoned channels (Pérez-Arlucea and Smith, 1999), levee surfaces during floods (Smith and Pérez-Arlucea, 2008), lateral accretion associated with channel migration at several bends, and in the short term, temporary storage as sandbars and local bed aggradation in active channels. Except for small additions by the Torch and Mossy tributaries, virtually all bedload is generated internally by channel degradation, especially reach I, but little escapes the avulsion belt. Essentially, current bedload transport begins and ends within the study area.

6.3. Channel cross section surveys

6.3.1. Pre-dam to 2014, reaches I-III

Reaches I-III are considered together because they show the most prominent downstream effects of the dam. The cross section areas of sites 1-11, comprising a contiguous and predominantly single-thread channel 0-64 km from the dam, have all increased since the pre-dam PFRA surveys. Enlargement from the 1950s to 2012-14 varies from a minimum of 15% (site 6) to maxima of 145% and 223% (sites 10, 11; Fig. 8). Initial post-dam resurveys (2003-4) show a trend of declining rates of enlargement away from the dam through reaches I and II: ~31-35% for sites 3, 5, 6 in reach I and decreasing to 10, 9, and 4% for sites 7, 8, 9

(respectively) in reach II. This trend, however, is only partly sustained in the 2012-14 resurveys, which show an initially similar downstream decline through reach I, but then increasing through reach II and nearly tripling in sites 7-9.

The most striking enlargement occurs at sites 10 and 11, reach III. Here, much of the pre-2003 enlargement is attributable to diversion of flow from the formerly dominant Steamboat Channel into the initially smaller Centre Angling Channel as an outcome of natural avulsion-belt evolution. A crude 1911 map of Voligny (1917) shows the current Centre Angling Channel as a creek labeled 'Angling Channel' flowing eastward from the Steamboat Channel and used as a canoe route to Cumberland Lake. A trend of increasing diversion from the Steamboat to the Angling Channel began in the 1920s (PFRA, 1953, p. 15) and continued thereafter as the northern portions of the avulsion belt expanded and aggraded, lowering the Steamboat gradient and forcing more discharge into the Angling route. Air photos from 1945 and 1953 show the Steamboat to still be the dominant channel, but by the 1970s and 1980s, Centre Angling discharge had equaled and surpassed that of the Steamboat, a trend that continued to the end of the century by which time nearly all Steamboat flow had diverted into the Centre Angling (Fig. 2C). For the past 15 years, little flow (est. <5%) has remained in the Steamboat Channel during normal discharge periods. This is significant because enlargement of sites 10 and 11 continued between 2003 and 2014 (79% to 145% of pre-dam capacity for site 10; 165% to 223% for site 11; Fig. 8), indicating that factors other than increasing mean discharge dominated recent channel degradation at these two sites.

Changes in cross section areas arise from changes in width and/or mean depth. Plots of channel-bed elevations show that between the 1950s and 2012-14, incision was greatest in reach I, ranging from 1.6 to 1.9 m and averaging 1.8 m in sites 1-4, 12 to 24 km downstream from the dam (Fig. 9). Comparison of sites closer to the dam was not possible because the PFRA surveys did not extend upstream of site 1; however, significantly deeper incision is unlikely because most of the uppermost portion of reach I contained rapids before dam construction and was well armored. By 2003, sites 5 and 6 had incised 1.2 and 1.0 m (respectively) below the pre-dam bed, but aggradation of 0.4 and 1.0 m occurred between 2003 and 2014, restoring site 6 to its pre-dam elevation. Incision is also evident in the 2014 surveys of sites 7-11 (reaches II and III), averaging 1.0-m lowering of the channel bed since the 1950s and ranging from 0.3 to 1.7 m. Unlike sites 1-6, however, most of this incision (avg. 0.9 m) occurred after 2003 (see section 6.3.4.). This zone of recent incision apparently extends to the Forks (sites 12, 13), although there is no pre-dam survey at site 12 for comparison (Table 2). This recently incised reach (II, III) is narrower and relatively deeper than reach I, with width/depth ratios approximately one-fourth to one-half those of sites 1-6 (Fig. 4). This pattern of decreasing W/D ratios is partly a vestigial effect of channel annexation and reoccupation during early development of the avulsion belt (Smith et al., 1998).

Except for sites 1 and 3, both located in entrenched upper portions of reach I, all cross sections in reaches I-III have widened since dam closure, but especially reach III where sites 10 and 11 have more than doubled in width since the 1950s (Fig. 10), in part caused by flow diversion from the Steamboat Channel. For contiguous reaches I-III, the averaged post-dam rate of widening is 0.71 m/y and ranges from 0 (sites 1, 3) to 1.63 m/y (site 10). Separate calculations of widening for the intervals 1963-2003 and 2003-2014 using only sites 5-11 and 13 (i.e., pre-dam sites resurveyed annually after 2003, see below), and assuming all widening began after dam closure, yield average widening rates of 0.88 m/y for 1963-2003 and 0.94

m/y for 2003-2014. This small difference suggests that widening rates for reach II-III have changed little between the two post-dam intervals. If width ratios (Fig. 10) are converted to post-dam widening percentages and sites 1 and 3 (entrenched, stable banks) and 10-11 (Steamboat Channel diversion) are omitted, the remaining seven sites widened in the range of 5-24% (avg. 13%) since the 1950s surveys. This is an unusually large amount of widening for channels downstream of hydropower dams (Williams and Wolman, 1984, p. 46), possibly attributable to low alluvial-bank stability associated with relatively recent deposition of the 1870s avulsion (reach II) and apical SRD (lower reach I).

Relative roles of widening vs incision in reaches I-III were estimated by a simple method of overlapping rectangles. This involved first converting the initial cross section area A_1 to a rectangle of the same area defined by width W_1 and mean depth D_1 in which the top of the rectangle (W_1) is fixed at bankfull elevation as determined by the initial PFRA survey. Subsequent enlargement of the cross section from A_1 to area A_2 is then depicted by an overlapping rectangle composed of horizontal and vertical sides W_2 and D_2 , with the top of the A_2 rectangle (W_2) fixed to the same PFRA bankfull elevation datum as W_1 . Change in the cross-section area (ΔA) then equals the difference in the areas of the two rectangles. This change in area can be apportioned as

$$\begin{aligned} (W_2 - W_1)D_1 &= \text{portion of } \Delta A \text{ attributed to } \Delta W \text{ only,} \\ (D_2 - D_1)W_1 &= \text{portion of } \Delta A \text{ attributed to } \Delta D \text{ only, and} \\ (D_2 - D_1)(W_2 - W_1) &= \text{portion of } \Delta A \text{ attributed to both } \Delta W \text{ and } \Delta D; \text{ half value added to} \\ &\text{each.} \end{aligned}$$

Values of channel-area enlargement apportioned to changes in width and depth can then be expressed as percentages of change in cross section area ΔA . Net changes between 1950s (pre-dam) and 2012-14 resurveys are shown in Table 3. Although reaches I, II, III appear to have persistently widened since dam closure (Fig. 10), changes in mean channel depths are more variable through time (Fig. 9), thus the apportionment values are also likely to vary with time. For example, site 6 (Table 3) indicates that 100% of cross section area change observed in 2014 is attributed to widening alone; however, Fig. 9 indicates that over 1 m of aggradation occurred at site 6 between 2003 and 2014, regaining pre-dam bed elevation and indicating that the apportionments in Table 3 may represent only short periods in time. Nevertheless, it is clear that widening and deepening have each been important in increasing channel capacity 12-64 km below the dam since dam closure. Averages of values in Table 3 are approximately 46% widening and 54% deepening for the 11 sites, but deepening dominates the most proximal sites (1-4), whereas widening becomes increasingly important farther downstream.

6.3.2. Pre-dam to 2014, reach IV

Compared to the predominantly single-thread reaches I-III, reaches IVa and IVb comprise a more complex and ill-defined portion of the avulsion belt characterized by interconnected and variously sized and shaped channels associated with two dominant threads separated by non-alluvial Pine Island (Figs. 1, 2D,E). Some of the channels within the two flow routes, active during the PFRA surveys, are now infilled or active only during floods. An indication of the relative immaturity of reach IV channels is their abrupt increases in channel-floor elevation at the Forks where the discharge from the Centre Angling Channel (reach III) abruptly subdivides into smaller and shallower channels (Fig. 9). Except for site 20, all reach IV sites are clustered within 7 km of the Forks, including three interconnected channels at site 19 (Fig.

1C). Because of these complexities, summary results for reaches IV and V are shown as unconnected points in the right-hand sides of Figs. 4, 8, 9, and 10.

Channel characteristics of reach IV survey sites display no discernible relationship to distance. Most sites have undergone some post-1950s modification as enlargement (14, 15), shrinkage (13, 17, 18), or both (19, three channels, Fig. 8). Sites 17 and 18, formerly active channels in the 1950s, have narrowed or shallowed to near abandonment (Figs. 9, 10). The three channels of site 19 have each undergone significant changes in width, depth, and capacity; but their combined cross section areas shrunk by only 12% since the 1950s and virtually none in the past decade (Fig. 11, see section 6.3.4).

In contrast to the Forks sites, site 20, located in the single-channel distal portion of reach IVb, shows virtually no changes in channel dimensions since the pre-dam surveys (Figs. 4, 8-10). It represents the single-thread Mossy River, historically a tributary but annexed by avulsion-belt expansion and now carrying mostly Saskatchewan River flow to Cumberland Lake. It feeds the Mossy delta, initiated in the 1930s, and over its 10-km single-thread reach to the delta apex has remained remarkably stable since at least 1947, the earliest aerial photography. The banks are densely vegetated and composed of predominantly cohesive silt (Lazar, 2002). The Mossy channel and most of its sediment load ends in the delta and Cumberland Lake. Most discharge and some wave-reworked suspended sediment rejoins reach IVa at the southwest outlet to begin reach V (Fig. 2F). The delta traps all bedload fed by reach IVb and comprises approximately equal portions of sand and mud, ~1.5 m mean thickness, and is underlain by peat and lacustrine mud (Oosterlaan and Meyers, 1995).

6.3.3. Pre-dam to 2014, reach V

Reach V, the most distal reach and represented by sites 21-23, carries nearly the full discharge of the Saskatchewan River, conjoining most Cumberland Lake outflow with reach IVa. Site 21 is located in floodplain formerly occupied by the lake, and its banks lie only slightly above lake level (Fig. 5, km 102; Fig. 2F). Sites 22 and 23 pre-date the 1870s avulsion and are incised into Spruce Island, which separates the lake from the Saskatchewan River. Channel capacities of all three sites have increased since the pre-dam surveys (16 to 31%; Fig. 8). Site 21 enlarged by deepening and widening (Figs. 9, 10), yielding little change in W/D (Fig. 4); site 22 by deepening and narrowing, resulting in reduced W/D ; and site 23 by widening and slight shallowing, yielding a greater W/D . These different patterns of enlargement are likely related to different properties of the channel perimeters. The floor and both banks of site 21 are predominantly cohesive mud. Site 22 narrowed by deposition in the west portion of the channel and incision in the eastern portion, and site 23 has erodible alluvial banks and a coarse armored floor from locally derived glacial and bedrock material. The three sites carry little bedload (Fig. 7).

6.3.4. Annual resurveys, 2003-2014

The annual resurveys permit closer inspection of the processes and events that distinguish the post-dam data fields in Figs. 8-10. Sites selected for annual resurveys included three each in reaches I (3, 5, 6), II (7-9), III (10-12), and five sites in the Forks area of reach IV (13-16, 19; Table 2). Results showing annual changes in cross section area for each site, together

with mean and peak discharges for each year, are shown in Fig. 11. Three prominent features emerge from the results.

First, the dominant overall pattern is one of channel degradation--- increased channel capacity caused by widening and/or deepening over the 11 years of record. This is most apparent in reaches II and III (sites 7-12) and sites 13, 15, and 19n in reach IV. Except for a slug (Nicolas et al., 1995) that moved into site 6 in 2014, possibly a trailing effect of the 2013 flood, the sites of reach I experienced either little change (3) or slight aggradation (5, 6) over the 11-year period. In reach IV, sites 14 and 16 experienced, respectively, slight aggradation and slight degradation; but in both cases the channel bed returned to its initial (2003) capacity by 2014. Of the three interconnected channels in site 19, two aggraded during the survey period (19s, 19m) and one degraded (19n). When the site-19 cross sections are combined, however, total capacity for the three channels changed little between 2004 and 2014 (Fig. 11, 19-combined).

Second, in general, the largest changes in cross section areas occurred during the floods of 2005, 2011, and 2013; but the effects of flooding were not consistent over the whole study area. Some sites aggraded even during periods of greatest overall degradation. Sites 7, 9, 10 were significantly enlarged by the 2005 flood, two of them (9, 10) increasing channel capacity by 23% and 21% (respectively) from the preceding year, the highest observed 1-year changes in the 11-year resurvey period. One-year channel enlargements of over 10% at sites 8-10 and 13 resulted from the 2011 flood, as did sites 7 and 19n for the 2013 flood. In all, >10% channel enlargement from the previous year occurred in 11 sites during the three flood years compared to six sites during seven nonflood years (2007 excluded). With the exception of site 5 in 2010, all >10% enlargement events occurred in reaches II, III, and IV.

Third, despite the overall trend toward increasing degradation shown by the majority of sites, especially reaches II and III, annual fluctuations in bed elevation were observed throughout the entire study reach, regardless of discharge magnitude. In each year, mean bed elevations decreased at some sites and increased at others. When these elevation changes are summed and averaged for each annual survey, additions and removals of channel material mostly, but not completely, cancel each other, resulting in relatively small changes in net aggradation (+) or incision (-) each year (Fig. 12). Similar observations have been made by other workers at a variety of temporal and spatial scales (Goff and Ashmore, 1994; Lane et al., 1996; Paige and Hickin, 2000). Over the period of study, the proportion of individual aggradational events (49.3%) and incisional events (50.7%) were virtually equal. Five of the annual surveys showed net aggradation from the previous year (2004, 2008, 2009, 2012, 2014) and five displayed net incision (2005, 2006, 2010, 2011, 2013). The overall pattern, however, is dominated by the large net incisional events generated by the three floods (Fig. 12). This can reasonably be expected in a sediment-deficit situation whereby insufficient bedload is available to replenish the evacuated bed material after the flood passes and incision ceases (Lindsay and Ashmore, 2002). This appears to be a key factor in generating and sustaining long-term channel degradation.

Cumulative annual changes in bed elevation, width, and channel capacity were calculated by averaging sites separately for reaches I, combined II-III, and IV. All show that reaches II and III experienced the greatest net degradation over the 11-year period (Fig. 13). Plots of bed elevation and channel capacity dip steeply to higher degradation values for the three flood years (Figs. 13A, C). The intervening normal-discharge years (2006-2010, 2012) indicate modest regrading in reaches II-III, but little change in the average of the combined study

reaches. Nevertheless, between 2003 and 2014, reaches II-III incised nearly 1 m and increased average channel capacity by 25% compared to nearly zero net incision and 5% greater capacity for the reach-IV sites. Reach I varied between slight aggradation and brief degradation during the 11-year period, mainly reflecting changes in sites 5 and 6. Site 3, 17.5 km from the dam, was the coarsest and most proximal site of the annual surveys and changed little (Fig. 11).

Annual width changes were mostly small but positive and incremental (Fig. 13B). Only one site (15, reach IV) narrowed during the resurvey period, associated with thalweg migration and formation of a large bank-attached bar in the three years following the 2005 flood. This is seen as a slight dip in the reach IV plot that otherwise shows mean widening of over 3 m for the seven sites, including three at site 19. By comparison, mean width in reach II-III sites increased steadily to over 12 m between 2003 and 2014. The plots of cumulative bed elevation and cross-channel area change (Fig. 13A,C) show similar patterns that reflect the minor effects of width changes on channel capacity over short time intervals, but exercise increasingly larger control when measured over longer time periods. Overall, the general pattern of channel change in reaches II-III during 2003-2014 appears to be one of steady and gradual widening, rapid flood-generated incision, and slow but incomplete re-aggradation controlled by availability of bedload.

6.4. Early post-dam degradation

Although significant changes in downstream channel capacity, bed elevation, and width occurred between the mid-1950s and 2003 (Figs. 8-10), little information exists as to when these changes took place in relation to the time of dam closure. We know of only one set of data that bears on this question--- a series of cross-channel profiles measured by Ducks Unlimited Canada (DUC) and incorporated into a consulting report (NHCL, 1976). Precise bank locations and heights were not shown in the cross sections, so only bed elevations could be compared. The DUC surveys were made between 1962 and 1975 at a site 31.6 km downstream from the dam and ~100 m downstream from site 5 in reach I. Except for 1973 and 1974, the bottom profiles were surveyed annually, mainly in July and September. The survey period included two significant floods that peaked at 3450 and 2790 m³/s in 1974 and 1965, respectively, the second and fifth highest since dam closure. For purposes of comparison, site 5 and the DUC survey site are considered as the same due to their proximity and qualitative similarities in the field.

When profiles are reduced to mean values of bed elevation, the DUC data show a clear trend of post-dam incision reaching nearly 2 m between 1962 and 1971 (Fig. 14). By the onset of dam closure, the bed had aggraded approximately a half meter from its 1954 level, possibly initiated by availability of fresh bed material associated with dam construction (Nilsson, 1976). Rapid rates of incision directly following closure are commonly observed in dams elsewhere (Williams and Wolman, 1984), although incision in this case is unusual in being so abrupt so far downstream from the dam. This implies that pre-2003 rates of channel change in reach I may have been similarly rapid during the few years following dam closure. Although data are lacking from 1975 to 2003, the mean bed elevation appears to have risen slightly over the intervening 28 years, suggesting that despite short-term (annual) fluctuations in bed elevation, time-averaged net incision has levelled off at this site since the mid-1970s.

7. DISCUSSION

7.1. Downstream limits of dam effects on channels

All PFRA cross section sites in reaches I-III have enlarged since the pre-dam surveys of the mid-1950s. This is conventionally attributable to sediment deficit and clear-water erosion following dam closure, the ‘hungry water’ of Kondolf (1997). Not surprisingly, dam-induced degradation is most apparent in the proximal sites of reach I, which is well armored and displays the deepest post-dam incision (nearly 2 m) of the sites examined over the 108-km study reach. Other effects include coarsening of bed material through reaches I-III, downstream gravel-to-sand fining as far as ~km 20, decreasing rates of channel enlargement with distance, and decreased W/D ratios in the upper 25 km caused by the predominance of incision over widening (Pemberton, 1976; Williams and Wolman, 1984; Chien, 1985; Collier et al., 1996; Brandt, 2000; Graf, 2006).

In reach IV, dam-induced channel changes are less apparent. There is no indication of bed coarsening between 1991-2 and 2009-11, and sites within the Forks area (13-19) carry histories of enlargement and shrinkage as the multichannel system evolves toward fewer and larger channels through annexation and abandonment, processes that have characterized development of the avulsion belt (Smith et al., 1989, 1998; Pérez-Arlucea and Smith, 1999). In 1947 and 1953 air photos, sites 17 and 18 show large active feeders to large splays, but today are much shrunken and transmit flow only during medium and high discharge periods. Site 15 enlarged ~20% after 2006 (Fig. 11), but in so doing, drew flow from the adjacent branch channel at site 14, possibly initiating its eventual abandonment. On the other hand, site 16 has displayed little effect from the three floods. Similarly, the combined capacities of the three site 19 channels changed little since 2004, suggesting an equilibrium of mutual interdependence whereby each channel adjusts to the changes of the others without significantly changing their summed cross section areas.

Downstream from the Forks near Cumberland Lake, site 20 experienced very little post-dam change. It continues to route sediment eroded from upstream reaches to the Mossy delta, the areal growth rate of which has been essentially linear since 1947 (Wolinsky et al., 2010), suggesting negligible effects of the dam on sediment supply to Cumberland Lake. From these observations, we infer that the channel changes related to the dam currently extend to approximately the Forks area, after which its effects are either uncertain or absent. Not surprisingly, other workers have commented on this difficulty in distinguishing effects of sediment impoundment from other causes of downstream channel changes below dams (Williams and Wolman, 1984; Lyons et al., 1992; Gilvear and Winterbottom, 1992; Phillips, 2003; Petts and Gurnell, 2005).

Reach V lies beyond the present area of significant bedload transport (Fig. 7). All three sites have enlarged since the pre-dam surveys, and probably earlier, to which we attribute two probable causes: (i) starvation of bedload by avulsion-belt deposition, and more recently, (ii) transfer of some outflow away from the southeast outlet of Cumberland Lake to its current southwest outlet, which now feeds reach V (Morozova, 2013). We cannot assess the relative importance of these two factors, but the direct effects of sediment impoundment by the dam are probably negligible. Reach V has enlarged naturally through time, but little bedload has

been available to refill the evacuated space because of sequestration by avulsion-belt deposition.

7.2. Reaches I-III, where dam effects are the greatest

Site 3, the most proximal site of annual resurveys, experienced little change in bed elevation or channel capacity since 2004 despite the passage of three floods, reflecting the present stability of proximal reach I. Farther downstream at sites 5 and 6, variations in channel capacity since 2003 (Fig. 11) and bedload produced by local channel erosion (Fig. 7) suggest that the distal portion of reach I is currently adjusting to the discharge and sediment regimen following several years dominated by flood disruptions. Both sites experienced net aggradation between 2003 and 2014 despite sustained degradation in contiguous reach II. This may be a temporary overloading effect of sandy bedload produced by flood-induced erosion of islands and sandbars upstream of site 5, possibly exacerbated by daily discharge pulses from dam operations (Euteneier, 2002), aiding in redistribution of freshly eroded bed and bank material. Annual resurvey data are lacking for this portion of reach I, however, so this interpretation remains uncorroborated.

Reaches II and III, extending from 35 to 81 km below the dam, experienced overall degradation through the 2003-2014 survey period (Fig. 11), mainly in response to the floods of 2005, 2011, and 2013. Reach II begins at the 1870s avulsion site and narrows downstream following the configurations of two preexisting channel segments annexed during early stages of avulsion. Differences in bank composition and inherited channel size caused downstream reduction in W/D ratios (Smith et al., 1998) which, unlike reach I, have changed little since the 1950s (Fig. 4) because degradation has involved increases in width and in depth (Figs. 9, 10) and thus maintained low variability in their ratios. This is probably an outcome of less resistant and fully alluvial banks associated with the avulsion belt compared to substantially nonalluvial banks of reach I, particularly in its upper portions. From 1950s to 2003, reach II sites show only modest increases in channel capacity which, when combined with reach I, formed a trend of linear downstream decrease approaching zero at site 9 (Fig. 8), a distance of 53 km. Between 2003 and 2014, however, channel capacity at sites 7-9 increased nearly 25% on average. In reach III, the approximately doubled W/D ratios since the 1950s (Fig. 4) indicate widening as the dominant component of increased channel capacity (Table 3) associated with discharge diverted from the Steamboat Channel. Sites 10 and 11 enlarged by 79% and 165% (respectively) between 1955 and 2003 and an additional 65% (site 10) and 58% (site 11) since 2003 (Fig. 8). Expressed as annual rates and averaged, sites 10 and 11 enlarged by 2.5% per year between 1955 and 2003 from captured discharge and 5.6% per year from 2003 to 2014 mainly due to flood erosion. Expressed in units of evacuated cross section area, averaged sites 10 and 11 enlarged $9.2 \text{ m}^2/\text{y}$ from 1955 to 2003 and $23.4 \text{ m}^2/\text{y}$ from 2003 to 2014 mainly due to flood erosion. The non-PFRA site 12 enlarged by 23% between 2004 and 2014 (Fig. 11), equivalent to $20.6 \text{ m}^2/\text{y}$ of cross section area and similar to sites 10 and 11.

The general pattern of channel change in reaches II and III during 2003-14 was maximum degradation during floods followed by either modest aggradation or continued but reduced degradation (Figs. 13A,C). Post-flood regrading is evident in the four normal flow years following the 2005 flood, a reasonable expectation provided bedload is available to replenish the evacuated bed material, but more tenuous in bedload-deprived settings downstream of

dams. An estimate of time required to replace all material removed from reaches II-III between 2003 and 2014 was made by comparing the volume of evacuated channel space with estimated bedload flux and assuming all incoming bedload is deposited in the reach. Evacuated volume was calculated from net changes in 11-year cross-section areas for sites 7-12, weighted for the distances between sites and omitting 15% of reach III. Bedload was taken as the average of the eight sets of measurements in reach I between km 23 and 35 (Fig. 7), assuming reach I to be the primary source of new bed material for reaches II-III and assuming Torch River bedload contributions are negligible, a reasonable assumption based on spot measurements and field observations following floods. Sediment bulk density was taken as 1.8 t/m^3 . Bedload produced by widening of reaches II and III was not considered, though this was likely to be minor because the banks of both reaches are composed of predominantly fine-grained material removable as suspended load (Smith et al., 1998).

Results show that $5.8 \times 10^6 \text{ m}^3$ of channel material ($10.4 \times 10^6 \text{ t}$) were evacuated from reaches II and III since 2003 and that 30.7 years would be required to re-aggrade the vacated space under the assumed conditions. This estimate is crude and probably conservative given that (i) it requires in-channel deposition of all incoming bedload, and (ii) the assumed bedload rate is based on eight mid-summer measurements in 2012-2014 during above-average discharges, virtually certain to be higher than annual averages that include ~5 months of low-flow ice-covered conditions. This recent flood-induced degradation is likely to be permanent for as long as the dam exists and will probably increase with future floods as local bedload sources, mainly the island and bar portions of reach I, diminish with time. In the meantime, cut-and-fill patterns (Fig. 12) will likely continue for as long as mobile bed material is available from upstream in-channel sources; however, the ratio of 'cuts' to 'fills' will inevitably increase with declining sediment load until the bed becomes either stabilized by armor or other resistant substrate or attains a new equilibrium at a lower gradient on a mobile bed. The operating variable that ultimately results in permanent channel degradation appears to be the deficiency of available bedload to replenish and re-aggrade the bed following scour events rather than the greater erosive power attributed to sediment-deficient ('hungry') flows themselves.

7.3. *Dam vs avulsion belt*

The expansion of the 1870s avulsion belt has been largely characterized by encroachment of multichanneled and coalesced sediment wedges into low-lying wetlands flooded by the discharge diverted from the Saskatchewan River. As the sediment wedge grew northward and eastward toward Cumberland Lake, small channels feeding the margins of the prograding body were replaced by fewer and larger channels as expansion continued, eventually resulting in a single proximal channel routing all flow and sediment from the parent channel to the rest of the alluvial belt. This process is likely to continue until avulsive deposition ceases and, in time, a single channel remains (Smith et al., 1989, 1998).

By starving the avulsion belt of new sediment, the E.B. Campbell Dam is speeding the process toward a single dominant channel. The New Channel (mainly reach II) has been the main feeder to the avulsion belt since the earliest reports following the 1870s event (McInnis, 1913; Voligny, 1917), partly because it appropriated segments of two existing channels and developed a single thread quickly. For the ensuing decades up to the 1950s, the New Channel

plus Steamboat Channel distributary system dominated deposition and formed most of the present area of the avulsion belt.

Since dam closure, however, the contiguous Centre Angling Channel (reach III), formerly a system of smaller interconnected channels, has become increasingly larger at the expense of its smaller cohorts. How much of this is ultimately the result of sediment-starved flow vs captured Steamboat discharge is uncertain. However, observations of ancillary channels following the three recent floods included clear examples of channel plugging and new sandbars blocking smaller bifurcated channel mouths, both tending to reduce outflow from the main channel and either initiate or increase abandonment of the ancillary channel. Lowered bed elevation associated with increased channel capacity can undercut smaller bifurcates, leading to reduced flow and eventual abandonment of the latter, a process that may have begun in the areas of sites 14 and 15 following the 2005 flood. This, together with reduced sediment supply, might also explain the recent low activity of several crevasse splays along the Centre Angling Channel (Toonen et al., 2016). Although the causes may be varied, the Centre Angling (reach III) is approaching a status of single-channel dominance in its otherwise multichanneled setting that, together with the New Channel, will eventually route all flow in the upper two-thirds of the avulsion belt. With continued deprivation of bedload, the contiguous reaches II-III are destined to become larger, more incised, more dominant, and more stable with time. One outcome of this development will likely be a shifting of maximum flood inundation areas to increasingly distal regions of the avulsion belt as the ever-enlarging channel is able to contain increasingly larger flood discharges within its banks. This pattern appears to be currently in progress (Sagin et al., 2015).

The proximate outcome for reach IV is less clear, though in time the assemblage of active and barely active channels in the Forks area (Fig. 2E) is likely to resolve into two better-defined channels following the routes of reaches IVa and IVb. Eventually, one of them will likely emerge as the ‘winner’ to the exclusion of the other as both channels adjust to ever decreasing sediment supplies from upstream excavation. At present, sufficient sediment is being generated and transported to Cumberland Lake via reach IVb to sustain growth of the Mossy delta. From air photos and recent satellite imagery, we estimate Mossy delta growth of 15 km² since dam closure which, assuming a mean thickness of 1.5 m, yields a sediment volume of $22.5 \times 10^6 \text{ m}^3$ ($40.5 \times 10^6 \text{ t}$). In reaches I-III, where most post-dam channel enlargement is observed, enlargement of cross section areas (see section 7.1.2. above) yields an estimated $35.4 \times 10^6 \text{ m}^3$ ($63.7 \times 10^6 \text{ t}$) of sediment excavated from channel perimeters since the 1950s, or approximately one-third more than Mossy delta deposition over the same period. If all net degradation is assumed to have initiated after dam closure (1962), this represents a mean excavation rate of $0.6 \times 10^6 \text{ m}^3/\text{y}$ ($1.1 \times 10^6 \text{ t/y}$) averaged over 52 years. This is a minimum estimate as it excludes the uppermost 12.5 km of reach I for which no pre-dam survey data were available.

Although these two estimates of ‘source’ and ‘sink’ values are quite similar, it does not imply that all excavated material ends up in Cumberland Lake or that other unobserved and unmeasured sources of sediment might not also be operating, e.g., the Mossy and Torch tributaries or degradation products of small channels interconnected with reaches I-IV. Moreover, some of the cannibalized sediment is clearly redeposited in other sites within the avulsion belt. Nevertheless, it appears that channel degradation supplies sufficient sediment to maintain at least a minimal level of continued development of the avulsion belt, including the Mossy delta. It retains nearly all bedload and as such, serves a function similar to the E.B.

Campbell Dam in creating a sediment deficit for reach V as well as the rejoined Saskatchewan River. Avulsion-belt impoundment has led to similar outcomes for the Saskatchewan River between the Old Channel confluence and The Pas 125 km downstream (Smith et al., 2014).

8. Conclusions

Investigation of channel cross-sections in the Saskatchewan River and associated avulsion belt downstream from the E.B. Campbell Dam before and after dam closure, together with bedload and bed-material grain-size data, permit the following conclusions:

- The historical channel, 0-35 km below the dam (reach I), displays downstream features typical of many other large dams in which all inflow is released following impoundment: coarsening and armoring in the proximal segment, fining to sandy bed material downstream, incision and channel enlargement (up to 49%) near the dam, decreasing with distance. Effects of flooding during the 2003-2014 resurvey period were manifested mostly in reworking of sandbars and alluvial islands in the distal portion of the reach to create new bedload and some modest aggradation.
- Reach II (35-54 km, starting at avulsion site) slightly enlarged from pre-dam surveys to 2003 (4-10%), but nearly tripled in percent capacity increase during the flood-prone decade that followed. Reach III (54-81 km) enlarged by gradual capture of Steamboat Channel flow that began before dam construction, but enlargement rates more than doubled after 2003. Calculations based on excavated channel volume suggest that more than 30 years would be required to replace the missing channel material in reaches II and III at current bedload rates and assumption of zero bedload loss, together suggesting that the flood-induced degradation is probably permanent for as long as the dam exists. The overall pattern of channel change in reaches II-III during 2003-2014 was one of gradual widening, rapid flood-induced incision, and only partial reaggradation controlled by availability of bedload.
- Reach IV, beginning 81 km at the Forks and representing the distal portions of the avulsion belt, bears little evidence of dam perturbation and likely represents the trailing edge of dam-related effects on channel morphology. Reach V, connecting reach IV to the rejoined Saskatchewan River (108 km), receives little bedload, and increases in channel capacity are attributable to sediment removal by avulsion-belt deposition and possibly shifts of Cumberland Lake outflow. Dam effects are minimal.
- Most channel enlargement involved increases in both width and bankfull depth. Width changes have tended to be small but cumulative. Bed elevations have fluctuated from year to year and site to site; however, mean elevation changes were most negative during the three flood years. Short-term changes in channel capacity tended to be dominated by depth variations whereas width increases assumed increasingly larger proportions of capacity changes over longer periods.
- The total volume of sediment excavated from reaches I-III (0-81 km) since dam closure is estimated at $35.4 \times 10^6 \text{ m}^3$ ($0.6 \times 10^6 \text{ m}^3/\text{y}$, or $1.1 \times 10^6 \text{ t/y}$), which has permitted continued deposition in some portions of the avulsion belt, including the Mossy delta where progradation is still active.
- Sediment impoundment is increasing the rate at which a single dominant channel is evolving in the downstream avulsion belt, a process that is likely to shift the patterns of flood inundation to more distal locations in the future.

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FIGURE CAPTIONS

Fig. 1. Maps showing locations of (A) region of study; (B) location coordinates, principal physiographic features, study reaches, and survey sites; (C) enlargement of Forks area showing locations of survey sites 13-19.

Fig. 2. Representative photos of study area. (A) E.B. Campbell Dam, Tobin Lake, and uppermost portion of reach I showing spillage during 2005 flood period. (B) Old Channel/New Channel bifurcation, distal reach I; arrows in upper left show portions of two wooded alluvial islands. View to the southwest. (C) Conjoining of reaches II (New Channel, left) and III (Centre Angling Channel, right) at bifurcation with Steamboat Channel (away from viewer), formerly dominant but now nearly abandoned. View to the northwest. (D) The Forks, view to the northeast, showing juncture of reaches III and IVa, IVb. The third channel joined at the forks (unlabeled, center to upper left) carries only small discharges that eventually join reach IVb. (E) Portions of reaches IVa and IVb (Bigstone and Mossy routes; Fig. 1) during 2005 flood showing variously sized interconnected channels, mostly inactive or abandoned at normal discharges. View to the southeast; Cumberland Lake in upper-left background. (F) Confluence of reach IVa and Cumberland Lake outflow to form reach V. View to the northwest. Approximate channel widths: (A) lower right, 360 m; (B) tip of right flow arrow, 390 m; (C) II label, 220 m; III label, 130 m; (D) III label, 100 m; (E) IVa label, 90 m; IVb label, 160 m; (F) V label, 310 m.

Fig. 3. Hydrographs of Saskatchewan River at gauging stations (A) below Tobin Lake (1964-2014) and Nipawin (1946-1962), and (B) The Pas, showing post-dam suppression of spring and summer flow peaks and elevation of winter base flows. Plots represent averaged daily discharge means for periods of record. Data from Water Survey of Canada.

Fig. 4. Plot showing downstream changes in width/depth ratios from 1950s (pre-dam) to 2014. Spans of reaches I-V are shown at top.

Fig. 5. Downstream changes in bank-top and water-surface elevation at discharge of 450 m³/s (approximate annual mean) for main channel thread of avulsion belt showing reduction of bank heights between avulsion site and Old Channel confluence.

Fig. 6. Downstream distribution of bed material grain size (D_{50}) for three sampling periods. Coarsening is prominent in reaches I-IVa between 1954 and 1991-2, more subtle from 1991-2 to 2009-11 and mainly in reaches II-III.

- 1041 Fig. 7. Bedload distributions at selected sites over three years shown as (A) total bedload for
 1042 full width of channel and (B) normalized to width. Measurements were made during periods
 1043 when daily discharge at WSC gauge (05KD003, below Tobin) exceeded mean annual
 1044 discharge by ratios ranging from 1.4 to 2.6. Mean ratios for each year were 2012- 2.40; 2013-
 1045 1.60; 2014- 1.66.
- 1046 Fig.8. Downstream changes in channel cross section area from 1950s to 2003-4 and 1950s to
 1047 2012-14. Note that not all 1950s (PFRA) sites were resurveyed in 2003-4 (closed circles)
 1048 whereas all were resurveyed in 1912-14 (open circles).
- 1049 Fig. 9. Downstream changes in mean bed elevation in 1950s (PFRA), 2003-4, and 2012-14.
- 1050 Fig. 10. Downstream changes in width ratio for two intervals beginning in 1950s. W_o is
 1051 1950s width and W_n is subsequently measured width.
- 1052 Fig. 11. Annual changes in channel cross section area in the 14 sites resurveyed from 2003 to
 1053 2014 (except 2007), arranged in order of increasing distance from dam, upper left to lower
 1054 right. Site 19 consists of three interconnected channels (Fig. 1C) with results shown
 1055 individually and combined.
- 1056 Fig. 12. Plots of annual changes in mean bed elevations for 2003-2014 resurvey sites,
 1057 arranged in order of increasing annual peak daily discharge. Although both aggradation and
 1058 incision were observed at the various sites each year, the greatest values of net incision
 1059 (highest mean negative values) occurred in the flood years of 2005, 2011, and 2013.
- 1060 Fig. 13. Cumulative changes in (A) bed elevation, (B) channel width, and (C) proportion of
 1061 channel area removed by net degradation, plotted separately for reaches I, II-III, and IV from
 1062 2003 to 2014. A plot of all sites combined is included for comparison. The zero horizontal
 1063 line in each plot represents the 2003 reference datum. Note steeply dipping segments of
 1064 reaches II-III plots (A, C) associated with flood years 2005, 2011, 2013.
- 1065 Fig. 14. Bed elevations at site 5 (distal reach I) showing rapid incision immediately following
 1066 dam closure and slight aggradation three decades later. No data available 1975-2003.

Table 1.

The five reaches of this study (Fig. 1); distances in km below E.B. Campbell Dam (w/d = width/depth ratio)

Reach	Distance (km)	General Setting	Banks & Riparian Vegetation	Comments
I	0-35.0	Historic Saskatchewan River between E.B Campbell dam and 1870s avulsion site. ~350-500 m wide; bankfull w/d ~45-75 (Fig. 4).	Mature forests line most banks. Sand-rich cutbanks common in distal portion, especially along alluvial islands.	Upper 20 km entrenched with rapids and armored boulder/cobble bed (0-12 km); grades to sand downstream. Sand bars and wooded alluvial islands appear ~15 km and continue to near Old Channel bifurcation (Fig. 2B). Distal 3.7 km occupies east arm of pre-avulsion meander bend of Saskatchewan River, now uppermost portion of New Ch.
II	35.0-54.4	New Channel between avulsion site and Steamboat Channel bifurcation; main feeder to avulsion belt. Narrows downstream from ~325 to 200 m, w/d decreasing from ~60 to 30 (Fig. 4)	Well-defined silt-rich banks and riparian forest. Several inactive crevasse splays from early stages of avulsion, now mostly sealed. Bank heights decrease downstream from avulsion site (Fig. 5).	Channel formed by annexation and modification of two older channels. Downstream width and w/d changes reflect reoccupation history after avulsion. Flow lost to Old Channel and gained from Torch River tributary are ~equal. Steamboat Channel system, now nearly abandoned, formerly conveyed most flow and sediment to the large northern region of the avulsion belt (Fig. 1, 2C).
III	54.4-80.7	Steamboat Channel bifurcation to Forks (Fig. 2C,D); dominated by Centre Angling Channel with several diversions and rejoins of smaller channels. Width of Centre Angling ~90-150 m, but ~15% of reach has wider and shallower segments with sand bars. w/d for typical main channel ~ 20-30.	Banks lower than in II and decline in height downstream (Fig. 5). Banks mainly silt and very fine sand. Riparian vegetation variable but mostly thick willow and alder brush and immature forest.	Progressive capture of flow away from the Steamboat Channel beginning in the 1920s and continuing through dam-construction period, now largely ceased since the mid-1990s. Steamboat Channel now diverts <5% of the discharge away from contiguous New and Centre Angling channels. Reach has ~10 moderate-sized crevasse splays, now mostly inactive except during high flows.
IV	IVa: 80.7-101 IVb: 80.7-106	IVa (Bigstone route) extends southeast from Forks to main outlet of Cumberland L. IVb (Mossy route) begins at Forks, later joined by Mossy River tributary, terminates northeastward at Cumberland L.	Riparian vegetation mostly willow and alder brush; marsh vegetation increases down-reach towards lake. Bank heights decline toward lake to <1 m above mean discharge stage (Fig. 5).	Complex and multichanneled. IVa and IVb are separated by Pine Island (Fig. 1), composed of glacial sediment and limestone bedrock. Channels vary in size, shape, and level of activity, with numerous moribund and abandoned segments (Fig. 2E).
V	101-108	Main outlet of Cumberland Lake to Old Channel confluence (Fig. 2F). Widths range ~320-200 m, narrowing downstream.	Distal 3.6 km dissects glacial sediment and limestone bedrock of Spruce I; descends short rapids to rejoin Old Channel as the Saskatchewan R. (Fig. 5).	Except for small outlet in southeast corner of lake (out of view in Fig. 1), all discharge through avulsion belt is recombined in reach V. Channel narrows and deepens as it exits avulsion belt to Old Channel confluence (Fig. 4).

Table 2.

Years of initial site surveys
(PFRA) and resurveys; site
locations shown in Fig. 1

Site	PFRA	Annual, first	Last
1	1955	----	2012
2	1955	----	2012
3	1957	2004 -	2014
4	1955	----	2012
5	1954	2003 -	2014
6	1955	2003 -	2014
7	1955	2003 -	2014
8	1955	2003 -	2014
9	1955	2003 -	2014
10	1955	2003 -	2014
11	1955	2003 -	2014
12	----	2004 -	2014
13	1957	2003 -	2014
14	1955	2003 -	2014
15	1955	2003 -	2014
16	----	2003 -	2014
17	1955	----	2012
18	1955	----	2012
19	1955	2004 -	2014
20	1957	----	2012
21	1955	----	2014
22	1955	----	2012
23	1955	----	2013

Table 3

Enlargement of bankfull cross-section areas (ΔA) for sites 1-11, PFRA (1950s) to 2012-14, apportioned to widening ($\% \Delta W$) and incision ($\% \Delta D$); A_1 is cross section area at time of initial PFRA survey; A_2 is area of most recent resurvey (2012-14)

Site	km	$A_1 \text{ m}^2$	$A_2 \text{ m}^2$	$\Delta A \text{ m}^2$	$\Delta A \%$	$\% \Delta W$	$\% \Delta D$	Reach
1	12.5	1870	2522	652	34.9	0	100	I
2	14.2	2070	3090	1020	49.3	25	75	“
3	17.5	1875	2599	724	38.6	0	100	“
4	23.7	2071	2967	896	43.3	17	83	“
5	31.5	1921	2475	554	28.8	44	56	“
6	35.0	1558	1788	230	14.8	100	0	“
7	42.2	1306	1689	383	29.3	82	18	II
8	47.2	1333	1654	321	24.1	20	80	“
9	53.5	1080	1540	460	42.6	54	46	“
10	55.8	506	1238	732	144.7	85	15	III
11	63.8	294	950	656	223.1	78	22	“

Figure 1 (Greyscale)

Figure 2 (Greyscale)

Figure 3 (Greyscale)

Figure 3

Figure 4

Figure 5 (Greyscale)

Figure 5

Figure 6 (Greyscale)

Figure 7 (Greyscale)

Figure 8 (Greyscale)

Figure 9 (Greyscale)

Figure 9

Figure 10

Figure 11 (Greyscale)

Figure 12

Figure 13 (Greyscale)

Figure 13

Figure 14 (Greyscale)

Figure 13