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Variations in natural levee morphology in anastomosed channel flood plain complexes

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Abstract

Natural levees are common features of alluvial river systems, yet their origin and evolution are poorly understood. In this paper, we present morphologic and sedimentologic data from two anastomosed rivers and offer a hypothesis of natural levee growth in these systems based on mechanisms of sediment transport.

In settings where floodbasins fill at the same rate as the channel, levees form by turbulent diffusion of suspended sediment away from a high-velocity thread into a floodbasin of relatively stagnant water. The theory of diffusive transport suggests that these levees should be narrow, steep, and display abrupt decreases in grain size due to rapid decreases in carrying capacity with distance into the floodbasin. In environments where an appreciable water surface slope is maintained between the main channel and the floodbasin, levees form by advection of sediment out of the channel and into the floodbasin. Advective transport theory indicates that these levees should be broad and gently sloped, with grain sizes gradually decreasing away from the main channel.

Natural levees occurring in the anastomosed reach of the upper Columbia River in SE British Columbia display significantly different morphology from levees in the Cumberland Marshes region of the lower Saskatchewan River in east-central Saskatchewan. At the upper Columbia site, the rise in stage of the floodbasin water nearly keeps up with that of the channel water because of good communication between channel and floodbasins through crevasses. This inhibits the establishment of a water surface slope, and the bulk of the escaping sediment is deposited close to the channel. In contrast, the Cumberland Marshes region is characterized by wide and volumetrically large floodbasins. These conditions keep floodbasin water surface elevations relatively low and maintain an appreciable elevation head between the channel and its floodbasin, fostering levee growth by advective transport.

Keywords: Levees; Anastomosing streams; Sediment transport; Columbia River; Saskatchewan River

1. Introduction

Natural levees commonly occupy the margins of alluvial channels and often play a significant role in

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the agriculture and economics of large alluvial regions (Allen, 1965; Saucier, 1996; Barry, 1997). Levees help to control the distribution of water and sediment, both spatially and temporally (Brierley et al., 1997). From a river engineering standpoint, understanding this distribution is desirable in order to develop mitigation strategies for flooding. The super-elevated channel of the Yellow River in China is one example that illustrates the importance of natural levees to river engineers, where the growth of the alluvial ridge has recently been enhanced by the construction of artificial levees (Ning, 1990; Shu and Finlayson, 1993; van Gelder et al., 1994), resulting in catastrophic flooding when overtopping or breaching does occur.

Natural levees are also significant components of ancient alluvial deposits, where they act as hydrocarbon and potable-water reservoirs (Galloway, 1981; Cant, 1982). Because they often thin and decrease in grain size with distance from a channel (Fisk, 1944; Allen, 1964; Groenwold et al., 1981; Cazanacli and Smith, 1998), taking the form of ‘‘wings’’ on the margins of some channel sandstone bodies (Hirst, 1991; Mjos et al., 1993; Nadon, 1994; Makaske, 1998), levees are likely candidates for stratigraphic traps (Cant, 1982). Because they flank the margins of channel sandstones, levee deposits also play a role in the interconnectivity of hydrocarbon reservoirs in alluvial sediments.

Yet, despite numerous references to natural levees, both in modern systems (Happ et al., 1940; Fisk, 1944, 1947; Lorens and Thronson, 1955; Wolman and Leopold, 1957; Coleman, 1969; Smith, 1983; Farrell, 1987; Tye and Coleman, 1989; Cazanacli and Smith, 1998; Ferguson and Brierley, 1999) and the rock record (Allen, 1964; Jacob, 1973; Ethridge et al., 1981; Flores, 1981; Groenwold et al., 1981; Bown and Kraus, 1987; Kraus, 1987; Dreyer, 1993), relatively little attention has been given to the mechanics of natural levee sedimentation and the resulting morphometries and sediment textures (James, 1985; Pizzuto, 1987; Marriott, 1992; Asselmann and Middlekoop, 1995).

With these considerations in mind, the two principal objectives of this study are to present natural levee data from two geomorphically different fluvial systems and to offer a process-based hypothesis for natural levee formation.

2. Observations of modern levees

2.1. Levee definition

In this study, levee slope is defined as the gradient of a line fitted by eye to the overbank region between the channel edge and the first significant break in topography (Fig. 1). Dimensionless levee width is defined as the ratio of levee width to bankfull channel topwidth. The nondimensional values of slope and dimensionless levee width are chosen in our analysis because they provide intuitive measures of levee shape that should be scale-invariant if levee width and channel width are codependent. Because both sites comprise anastomosed alluvial complexes and are therefore comparable, we use bankfull channel area as a proxy for discharge.

2.2. Field locations and study sites

Data on levee morphology and texture were obtained from the upper Columbia River (Fig. 2A) and compared with data from the lower Saskatchewan River (Fig. 2B), previously collected by Nelson

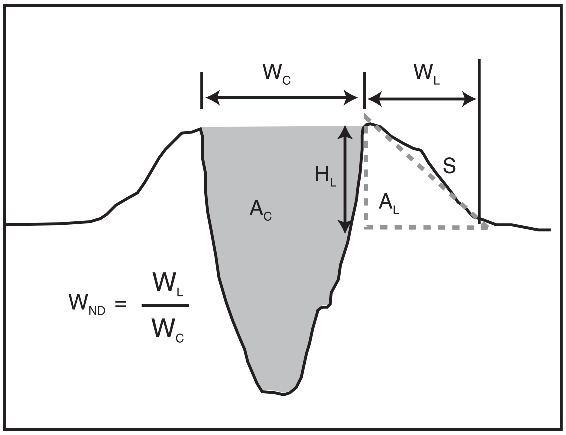

Fig. 1. Definition sketch of morphometric levee variables. Channel area (A_C), shaded in gray, is measured assuming bankfull discharge. Channel width (W_C) is measured as the top width at bankfull discharge. Levee slope (S) is defined as the line best-fit to the flood plain surface in the region adjacent to the channel and channelward of the first significant change in slope. Levee area (A_L) is approximated by a right triangle whose hypotenuse is the levee slope (S). Levee width (W_L) and levee height (H_L) are the lengths of the horizontal and vertical legs of the levee area triangle, respectively.

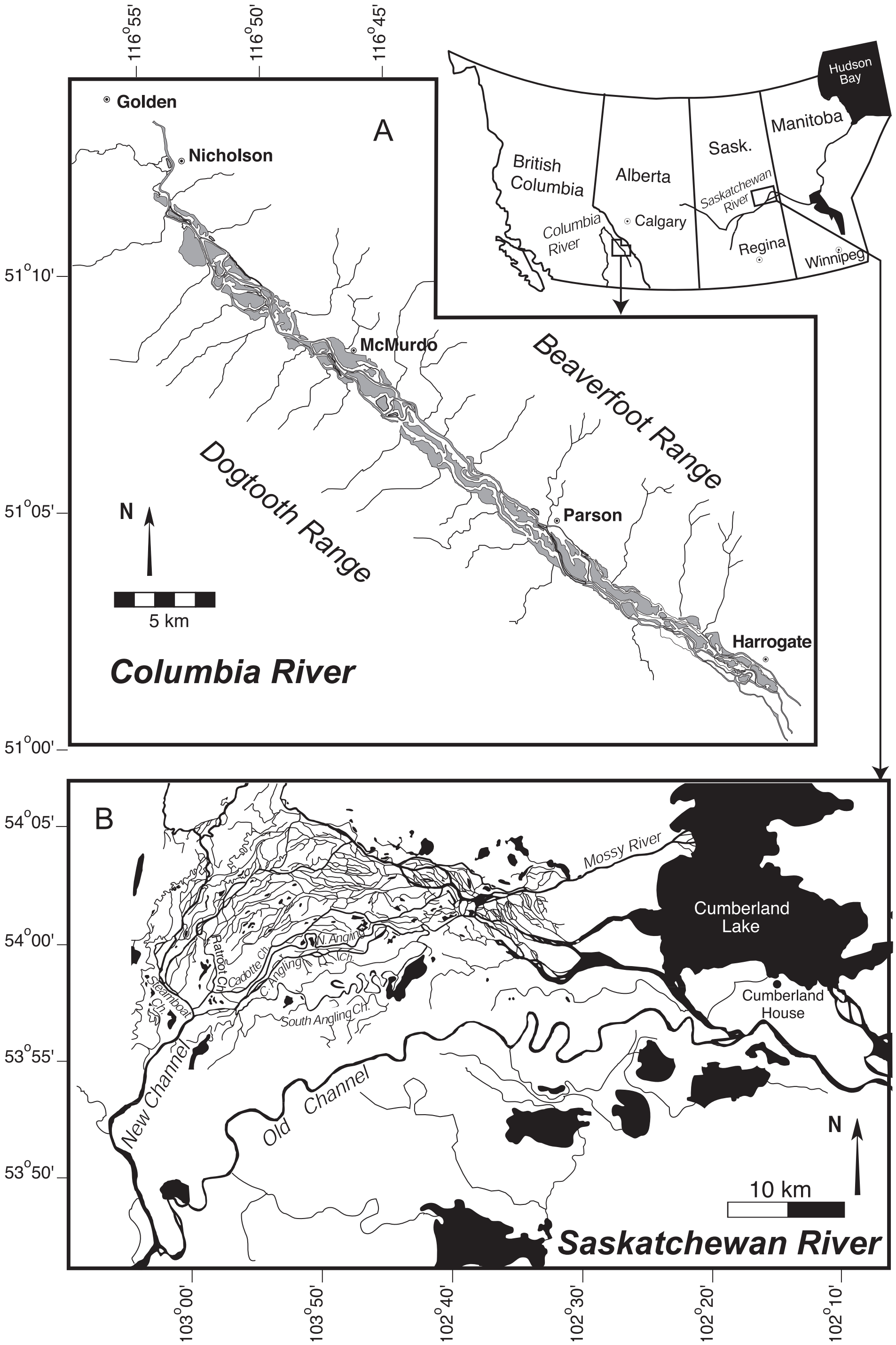

Fig. 2. (A) Location map of field sites on anastomosed reach of upper Columbia River in SE British Columbia. Map traced from NRCan 15 × 30 ft topo series. (B) Location map of the lower Saskatchewan River near Cumberland House. Levees were examined in several channels of the complex avulsion area north of the Old Channel (upper left of main figure). Figure modified from Smith and Perez-Arlucea (1994).

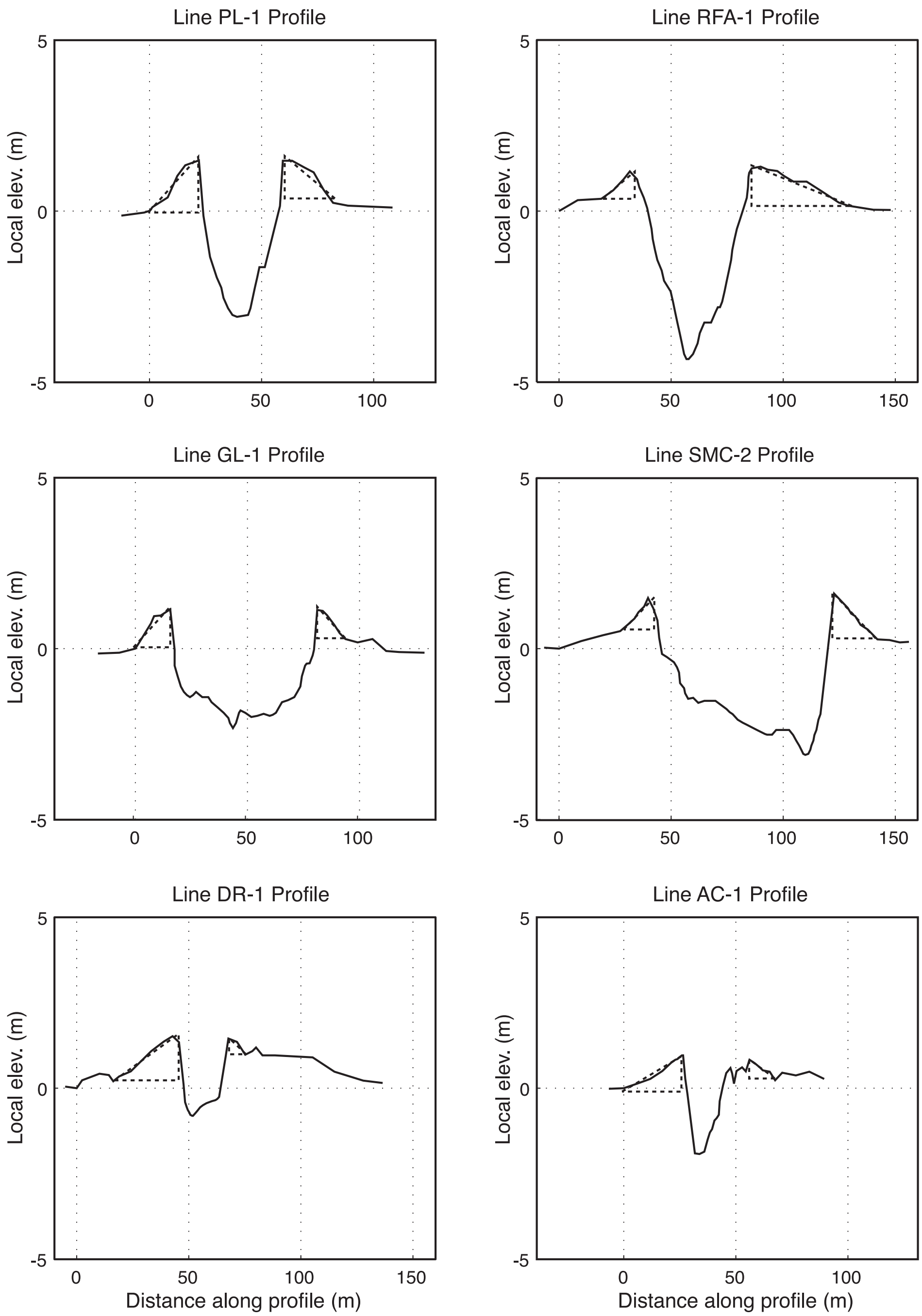

Fig. 3. Columbia River channel and levee profiles. Zero elevation datum is established as the left bank floodbasin elevation, and zero horizontal distance is set at the end of the left bank levee. Levees are relatively steep and narrow, with levee width typically less than channel width. All views are looking downstream.

(1995), Cazanacli (1997), and Cazanacli and Smith (1998). These two sites were chosen because (i) both are actively aggrading systems; (ii) both are relatively unencumbered by anthropogenic influences; (iii) both flood frequently (annually in the case of the Columbia); and (iv) each has a wide range of levee sizes

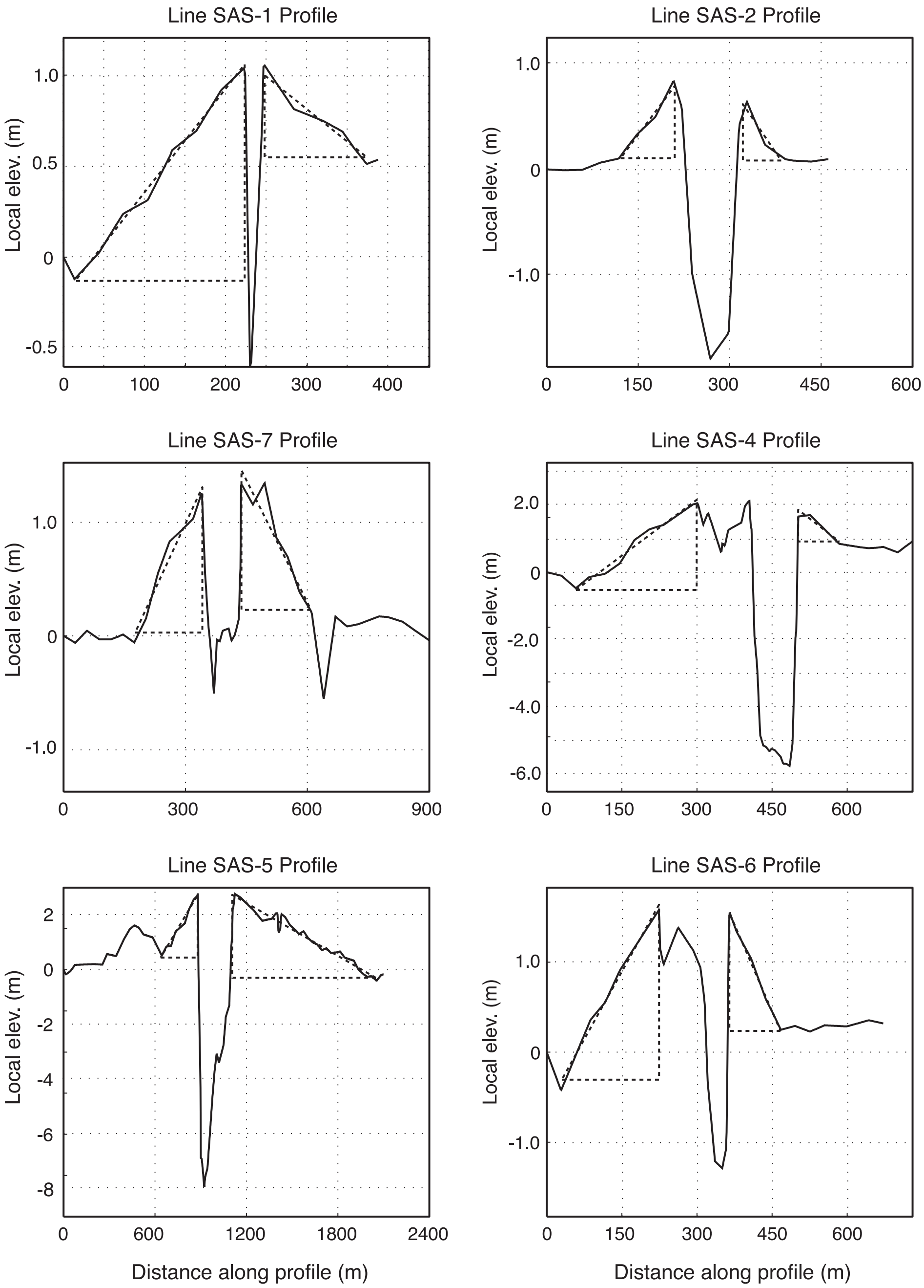

Fig. 4. Cumberland Marshes channel and levee profiles taken from PFRA (1954) surveys. Elevations are reported as meters above mean sea level. Levees have relatively gentle slopes and broad widths typically several times channel width.

Table 1
Morphometric and grain size data for levees of the upper Columbia and lower Saskatchewan Rivers

Levee name	Slope	Width (m)	Height (m)	Area (m^2)	Chan. width (m)	Chan. area (m^2)	W_{ND}	Φ	Fining exponent
Data Series 1[a]									
PL-1-LB	0.073	22.0	1.5	16.3	37.4	120.0	0.59	–	–
PL-1-RB	0.055	22.5	1.2	13.8	37.4	120.0	0.60	4.52	0.0321
RFA-1-LB	0.063	12.8	0.8	5.1	54.4	160.4	0.23	–	–
RFA-1-RB	0.022	18.7	0.4	4.1	54.4	160.4	0.34	–	–
GL-1-LB	0.077	15.5	1.2	8.9	65.6	168.0	0.24	5.1	0.0593
GL-1-RB	0.073	12.6	0.9	5.4	65.6	168.0	0.19	5.38	0.0104
SMC-2-LB	0.076	12.5	1.0	6.0	83.0	254.0	0.15	4.84	0.0435
SMC-2-RB	0.070	19.3	1.3	12.9	83.0	254.0	0.23	5.21	0.0333
DR-1-LB	0.051	26.5	1.3	17.5	24.8	36.3	1.07	5.17	0.0017
DR-1-RB	0.062	7.6	0.5	1.8	24.8	36.3	0.31	5.08	0.0358
AC-1-LB	0.039	26.4	1.0	12.7	29.7	38.1	0.89	3.7	0.0527
AC-1-RB	0.049	11.5	0.6	3.4	29.7	38.1	0.39	–	–
Data Series 2[b]									
SAS-1-LB	0.006	211.9	1.2	124.1	25.9	21.5	8.18	–	–
SAS-1-RB	0.004	128.0	0.5	35.0	25.9	21.5	4.94	–	–
SAS-2-LB	0.007	91.5	0.7	32.6	122.0	187.6	0.75	–	–
SAS-2-RB	0.008	64.0	0.5	17.0	122.0	187.6	0.53	–	–
SAS-7-LB	0.007	173.8	1.3	114.0	103.7	125.0	1.68	–	–
SAS-7-RB	0.007	179.9	1.1	101.7	103.7	125.0	1.74	–	–
SAS-4-LB	0.010	253.0	2.4	298.1	210.4	667.5	1.20	–	–
SAS-4-RB	0.010	85.4	0.8	34.2	210.4	667.5	0.41	–	–
SAS-5-LB	0.010	240.9	2.3	273.6	247.0	1538.1	0.98	–	–
SAS-5-RB	0.003	945.1	3.2	1516.9	247.0	1538.1	3.83	–	–
SAS-6-LB	0.010	202.7	2.0	202.5	147.9	161.0	1.37	–	–
SAS-6-RB	0.012	106.7	1.3	69.7	147.9	161.0	0.72	–	–
SAS-3-LB	0.012	213.4	2.5	271.5	77.7	84.4	2.75	–	–
SAS-3-RB	0.012	166.2	1.9	159.1	77.7	84.4	2.14	–	–
SAS-8-LB	0.012	105.2	1.0	51.5	36.6	50.7	2.88	–	–
SAS-8-RB	0.004	193.6	0.8	79.2	36.6	50.7	5.29	–	–
SAS-9-LB	0.006	182.9	1.2	107.5	35.1	43.0	5.22	–	–
SAS-9-RB	0.003	910.1	2.4	1112.6	35.1	43.0	25.96	–	–
SAS-10-RB	0.005	699.7	3.7	1279.1	274.4	1012.6	2.55	–	–
UN-1-LB	0.010	44.1	0.4	9.1	22.9	12.1	1.93	–	–
UN-1-RB	0.006	84.8	0.5	22.5	22.9	12.1	3.71	–	–
UN-2-LB	0.008	55.0	0.2	6.5	33.5	8.4	1.64	–	–
UN-2-RB	0.005	27.5	0.2	2.1	33.5	8.4	0.82	–	–
CA-7-LB	0.005	211.5	1.0	104.4	51.8	158.0	4.08	4.5	–
CA-7-RB	0.009	138.4	1.4	97.9	51.8	158.0	2.67	5.8	–
SB-1-LB	0.008	103.2	0.9	45.8	214.9	515.9	0.48	5.9	–
SB-1-RB	0.005	180.5	0.5	47.1	214.9	515.9	0.84	4.6	–
CD-2-LB	0.012	106.5	1.3	69.5	147.9	158.0	0.72	–	–
CD-2-RB	0.010	193.7	2.0	193.4	147.9	158.0	1.31	–	–
NA-1-LB	0.005	353.4	1.5	264.1	73.2	558.6	4.83	5.4	–
NA-1-RB	0.010	60.7	0.4	12.2	73.2	558.6	0.83	6.2	–
Data Series 3[c]									
CA-1-LB	0.014	–	–	–	–	77.1	–	–	0.0136
CA-1-RB	0.016	–	–	–	–	77.1	–	2.9	0.0404
CA-2-LB	0.017	–	–	–	–	5.6	–	–	0.0444
CA-2-RB	0.020	–	–	–	–	5.6	–	2.9	0.0197
CA-3-LB	0.024	–	–	–	–	2.8	–	3.2	0.0284

Table 1 (*continued*)

Data Series 3[c]									
CA-3-RB	0.024	–	–	–	–	2.8	–	–	0.0543
CA-1-RB	0.012	–	–	–	–	11.2	–	3.8	0.0208
CA-5-RB	0.020	–	–	–	–	88.3	–	3.5	0.0305
CA-6-RB	0.011	–	–	–	–	4.6	–	3.2	0.0059

[a] Data series 1: Columbia River levee data collected by Adams, Lazar, and Pinkus (June, 1998).
[b] Data series 2: Saskatchewan River levee data taken from PFRA (1954) profiles.
[c] Data series 3: Saskatchewan River levee data taken from Cazanacli and Smith (1998).

along the channels of their respective anastomosed networks.

2.2.1. Columbia valley

The anastomosed reach of the upper Columbia River, SE British Columbia, lies in the Rocky Mountain trench (Fig. 2A) between the towns of Harrogate (upstream) and Nicholson (downstream). The reach is ~ 120 km long and 1.5–2 km wide. Abbado et al. (in press) noted that the highly anastomosed reach occurs immediately downstream from the Spillimacheen tributary and is characterized by a channel slope of ~ 0.0002, a coarse sand bed load, and rapid flood plain aggradation (2.2 mm/year). These observations 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 (Abbado et al., in press). Flows through crevasse channels form new channels by splay progradation and eventually rejoin other channels down-valley because the valley is well confined. Valley slope in the study reach averages 15 cm/km.

The drainage area of the upper Columbia above the Nicholson gauging station (see Fig. 2A) is 6660 km^2, providing a mean annual discharge through the study reach of 108 m^3/s (Water Survey of Canada, 1991). Annual snowpack melt results in a sharp-peaked spring/summer hydrograph such that a minimum monthly mean discharge of 22.9 m^3/s occurs in February and a maximum monthly mean discharge of 320 m^3/s occurs in July. This summer discharge causes flooding of the valley floor and extensive inundation of individual floodbasins. Consequently, water and sediment are regularly introduced to these floodbasins, and levees are built on the margins of the numerous channels of the anastomosed network. Because of the narrow floodbasins confined by valley walls and extensive connectivity between channels and floodbasins, floodbasin waters rise at roughly the same rate as adjacent channels. As will be shown later, this may provide a critical control on natural levee formation.

2.2.2. Cumberland marshes

The Cumberland Marshes region of the lower Saskatchewan River in east-central Saskatchewan (Fig. 2B) contains a region of anastomosed channels formed after an avulsion of the Saskatchewan River in the 1870s. Smith et al. (1998) provided a discussion of the avulsion, and others have described the avulsion deposits (Smith, 1983; Smith et al., 1989; Smith and Perez-Arlucea, 1994; Cazanacli and Smith, 1998; Slingerland and Smith, 1998; Perez-Arlucea and Smith, 1999). In ~ 125 years since the initial avulsion, numerous channels have formed by both levee growth and channel erosion into preexisting floodbasin deposits, providing a wide range of channel sizes and levee morphologies. Bed slopes along the numerous channels in the study are variable but average 10 cm/km.

Anastomosis in the Saskatchewan River avulsion belt in large part formed by mouth-bar progradation as the avulsion belt itself prograded down-flood-plain. For an example of this process, see Smith and Perez-Arlucea (1994). Some anastomosis at the Cumberland Marshes also originates by crevassing processes, which dominate at the upper Columbia River site described above.

Mean annual discharge of the Saskatchewan River immediately upstream of the study area is ~ 450–500 m^3/s with high water typically occurring in July when the snowmelt from the Rocky Mountains reaches the site. Peak flows last for about a month and have discharges of 1000 to 1400 m^3/s. In the study area proper, the numerous individual channels pass varying fractions of the total flow; consequently, channels from which levee data have been collected span 2 orders of magnitude in cross-sectional area (from 10^2 to 10^4 m^2).

In contrast to the valley-confined Columbia River site, the Cumberland Marshes region contains wide floodbasins that allow rising channel floodwaters to overtop the banks and flow less hindered away from the main channel.

Notably, levees at both the Columbia and Saskatchewan sites are densely vegetated with trees

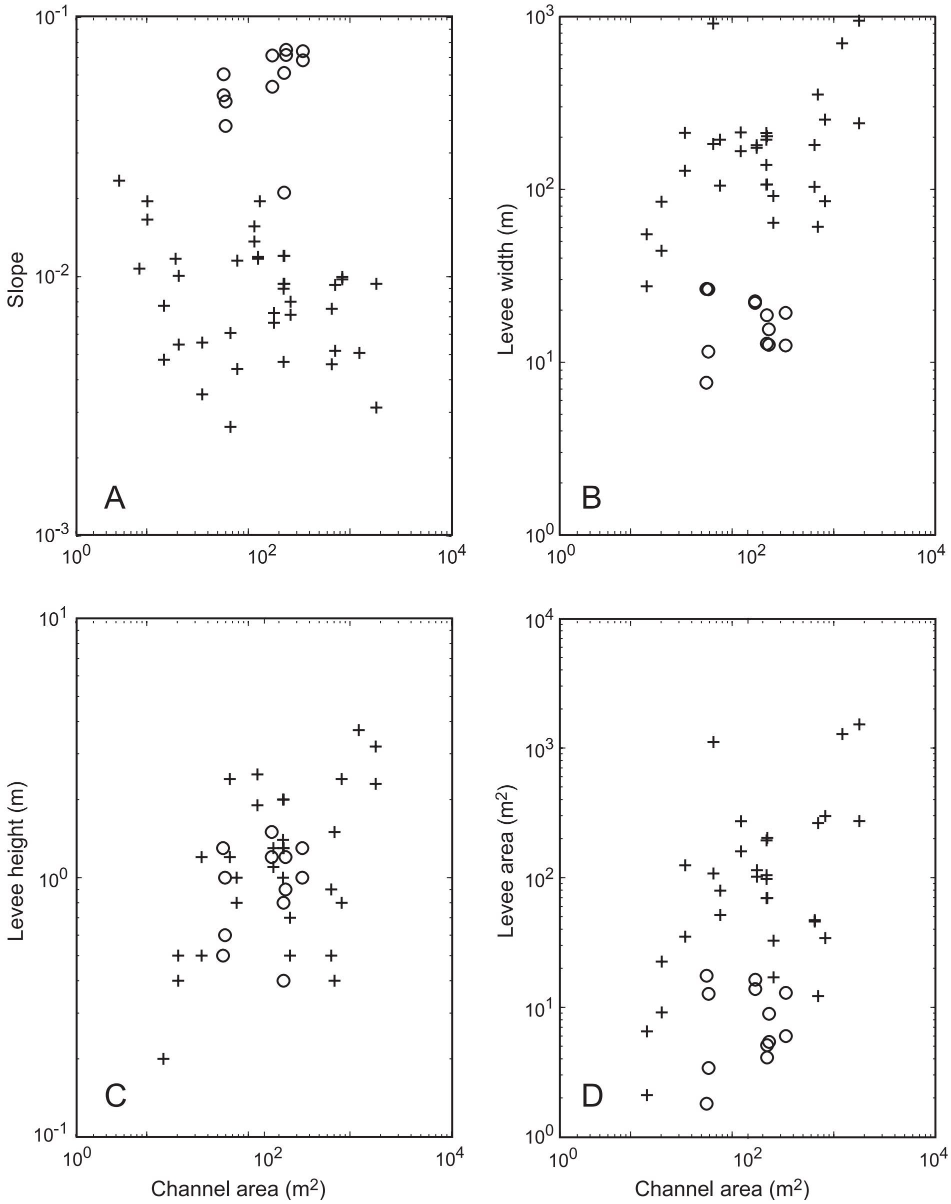

Fig. 5. Morphometric comparison plots for natural levees of the Columbia River (shown in circles) and the Saskatchewan River (shown in crosses) using bankfull channel area (A_C) as the independent variable. Slope, levee width, levee height, and levee area are defined in Fig. 1. A levee that is steep and narrow will plot high on the slope diagram and low on the width diagram. As a group, the Columbia River levees are significantly steeper and narrower than the Saskatchewan River levees. Data are given in Table 1.

and brushy understory near the channels (nearly 100% cover), grading into dense fen and marshland vegetation toward the adjacent floodbasins. Though vegetation type and density are likely important variables in levee growth, we report that the two sites are not glaringly different in this respect.

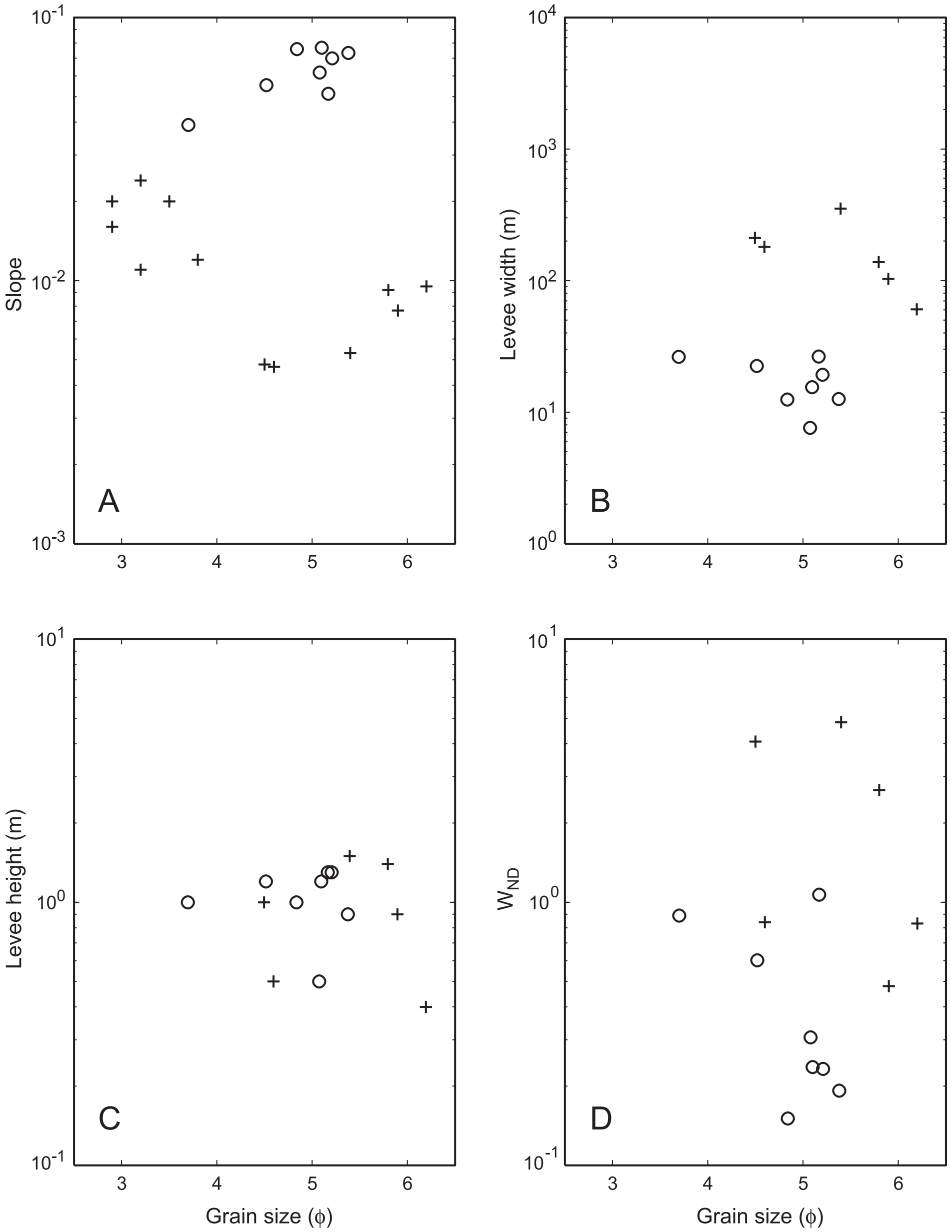

Fig. 6. Morphometric comparison plots for natural levees of the Columbia River (shown in circles) and the Saskatchewan River (shown in crosses) using levee crest mean grain size (d_{50}) as the independent variable. Note lack of grain size control on levee morphometry at both sites. Data are given in Table 1.

2.3. Methods

Total station topographic profiles were surveyed and surface sediments collected at 13 cross-channel transects during May and June of 1998 at the Columbia River site (Fig. 3). In-channel bathymetries were obtained by acoustic depth profiler.

Surface sediment samples were collected at varying distances from the channel on each transect of the levees using an 8-cm diameter Dutch auger. After removal of organic material (leaf litter and woody debris) from the sample, the top 10 cm of sediment was removed and bagged for analysis. Grain-size analyses were conducted by sieve and hydrometer techniques following the method of Royce (1970).

Surveyed profiles and surface sediment data for the Cumberland Marshes site were taken from Prairie Farm Rehabilitation Administration (PFRA) (1954) surveys, Nelson (1995), and Cazanacli and Smith (1998) (Fig. 4).

2.4. Results

Tabulated data on morphometric and textural features are presented in Table 1. Levee slope, width, height, and area are plotted as functions of cross-sectional bankfull channel area, used here as a proxy for discharge (Fig. 5).

Results show that the morphometric data define two separate populations corresponding to the two field areas. For channels of the same cross-sectional area (e.g., 10^2 m^2 in Fig. 5), Columbia River levees are steeper, narrower, and smaller in area than their Saskatchewan River counterparts. Furthermore, levee slopes within each population (Columbia vs. Saskatchewan) appear to be independent of channel size and no correlation is apparent between levee height and bankfull channel area (Fig. 5).

To explore whether these differences between sites may be due to different grain sizes, slope, width, height, and dimensionless width are plotted against levee grain size in Fig. 6. Mean grain size of the levee

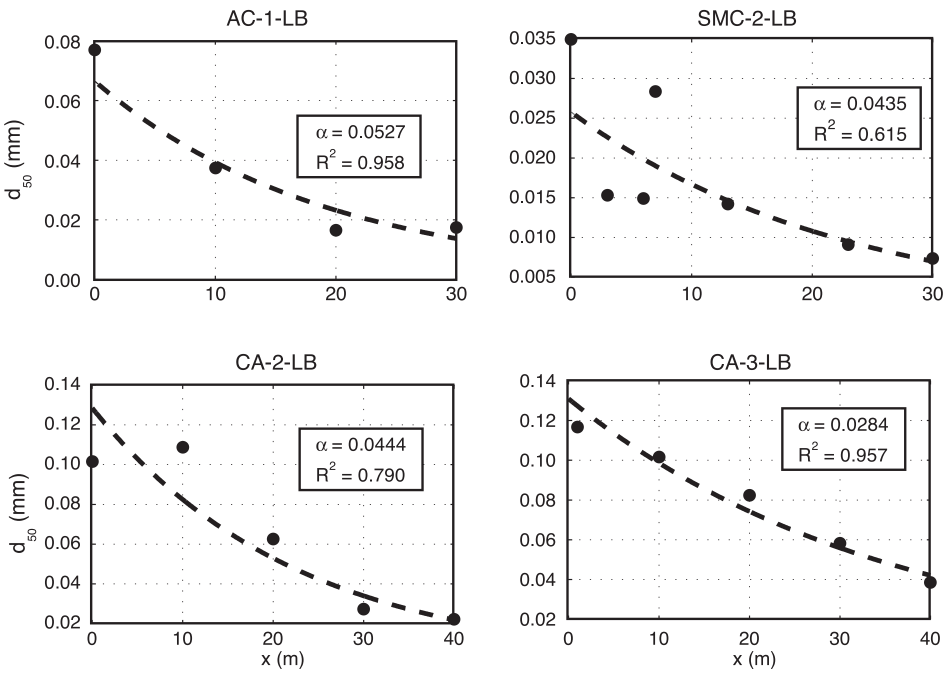

Fig. 7. Surface grain size (d_{50}) fining curves for two natural levees of the Columbia River (top) and two natural levees of the lower Saskatchewan River (bottom). The left edge of the plot is the channel margin and the dashed lines are exponential fits to the data of the form of Eq. (1). R-squared values (R^2) and fining exponents (α) are shown in the text block of each plot. Saskatchewan River data are from Cazanacli (1997).

crest is assumed to correlate with the mean sediment size of the entire levee. The range of grain sizes at the two sites is similar and therefore is not an obvious cause of the differences in levee morphologies.

If the differences between levee shapes from the two sites are due to differences in genesis or sediment source, they might show different textural trends. To explore this idea, textural trends across levees from the two field sites were compared by computing fining rates of the levee surface sediment samples. Cazanacli and Smith (1998) noted that a useful way of comparing lateral variation in levee texture is to fit exponential curves to the data of the form

$$d = d_0 e^{-\alpha x} \quad (1)$$

where d is the mean grain size at a distance from the main channel x, d_0 is the mean grain size of the levee surface at the channel margin, and α is an empirical coefficient here termed the "fining exponent." High values of α indicate a more rapid fining rate. Examples of fitted curves for two Columbia and two Saskatchewan River levees are shown in Fig. 7. Fining exponents are summarized in Table 1 and Fig. 8. Fining rates are highly variable at both sites and show considerable overlap. As a quantitative check on the fining rates, we performed a t-test, which shows that the means are not statistically significantly different at the 95% confidence level.

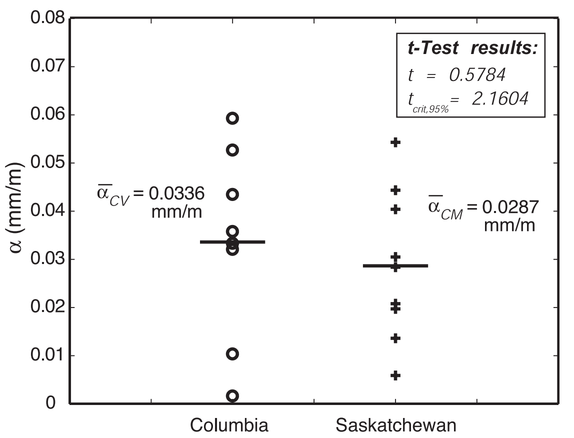

Fig. 8. Comparison of spatial fining rates of levees of the Columbia and Saskatchewan Rivers. Each data point represents the fining exponent of a single levee and solid lines indicate value of mean fining exponent for levees of each site. Results of the t-test, given in the text block, show that the mean fining rates of the two sites (α_{CV} and α_{CM}) are statistically insignificant at the 95% confidence level.

3. Mechanisms of sediment transport

What processes give rise to the differences in levee morphology at these two anastomosed systems? A common qualitative explanation of flood plain sedimentation marginal to an alluvial channel suggests that natural levees grow by differential deposition of sediment falling out of suspension as flood waters lose competency and capacity with distance from the source channel (Wolman and Leopold, 1957; Allen, 1965). Although this explanation may be essentially correct, it sheds no light on the question of why all levees are not of the same morphology and textural character. While the origin of natural levees (and flood plains in general) almost certainly arises from multiple processes, as a starting point, it is convenient to assume two end-member sediment-transport models of levee formation: pure turbulent diffusion and pure advection (Knight and Shiono, 1996). As will be shown, levee morphology and internal characteristics depend strongly on the hydraulic conditions implicit in each model. Our objective is to present a qualitative hypothesis of natural levee growth in anastomosed channel–flood plain complexes that explains the observed differences in morphology and texture between levees of the upper Columbia River and those of the Saskatchewan River.

3.1. Levee growth by turbulent diffusion

Consider a reach of a straight river channel flowing directly down-valley, on each side of which is a flat flood plain without levees (Fig. 9). During flooding, suppose that flood plain waters rise simultaneously with rising stage in the main channel, thereby maintaining nearly equal elevations of water surface across the entire valley. An example of this kind of flood plain inundation is given by Mertes (1997).

Along the free shear boundary between channel and floodbasin (Fig. 9), turbulent eddies will arise because of the interaction of the swiftly moving, unidirectional main channel flow and the relatively stagnant flood plain waters. This formation of free shear eddies has been reproduced and verified in laboratory studies (Sellin, 1964), and the effects of the interaction zone have been well documented (Rajaratnam and Ahmadi, 1979). Eddies from the main channel transfer their suspended sediment to the free shear eddies.

As the free shear eddies move across the flood plain, their turbulent intensity decreases and, consequently, so does suspended sediment concentration. In this manner, sediment "diffuses" away from the main channel where its concentration is highest. This analogy to Fickian diffusion has been discussed in detail by several workers (Myers and Elsawy, 1975; Hsu et al., 1980; Middleton and Southard, 1984; James, 1985; Pizzuto, 1987; Marriott, 1992; Nezu and Nakagawa, 1993). Because of the decreasing ability of the flow to maintain the grains in suspension, sediment is deposited preferentially adjacent to the channel, thereby forming levees. Because of the rapid decrease in turbulent intensity (cf., Nezu and Nakagawa, 1993), these diffusive levees are narrow and steep and rapidly become finer-grained away from the channel.

3.2. Levee growth by advection

Alternatively, one can consider the same geometry as for the diffusive case, but assume that water surface elevations on the flood plain lag behind the rising main channel waters during a flood event (Fig. 10). The amount of lag should be proportional to the storage capacity of the flood plain, or in one dimension, proportional to valley width. This causes a water surface gradient orthogonal to the direction of the main channel flow. Main channel waters are diverted to flow down this water surface slope, thereby transporting sediment onto the flood plain. In the simplest case, the water discharge of these flows decreases linearly across the flood plain and, insofar as suspended sediment load is proportional to a power (1–2) of water discharge, sediment is deposited preferentially adjacent to the channel but not as rapidly as in the diffusive case. Consequently, advective levees should be wider, more gently sloped, and fine less rapidly than diffusive levees. Following this line of reasoning, a continuum of levee slopes, from steep to gentle, should exist and correspond to a range of increasing valley widths, from narrow to broad.

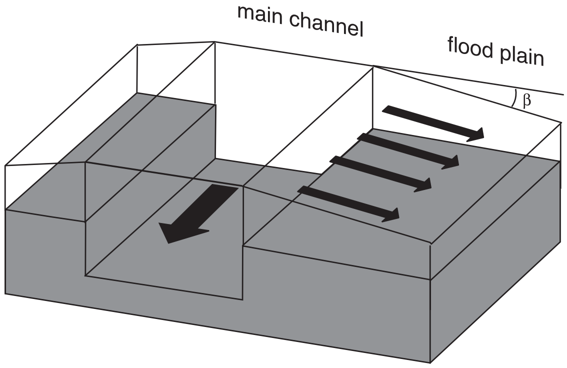

Fig. 10. Schematic diagram of conceptual model of levee formation by advection of suspended sediment. Figure shows the angle of water surface slope (β) that drives water and sediment away from the main channel. The slope arises from the difference in elevation between the main channel water surface and that of the flood plain.

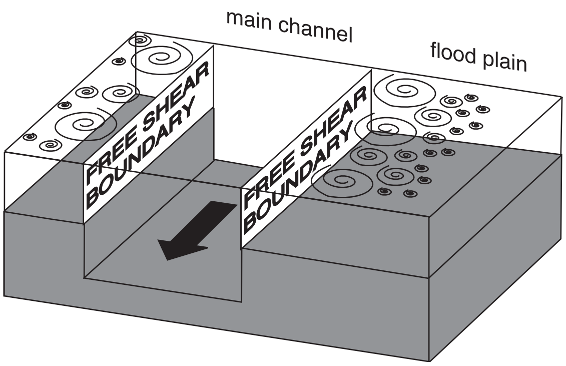

Fig. 9. Schematic diagram of conceptual model of levee formation by turbulent diffusion of suspended sediment. Turbulent eddies form by the interaction of the swiftly moving water of the main channel with the relatively stagnant water of the flood plain. Eddies carry sediment away from the main channel and deposit successively finer sediment with distance into the flood plain.

4. Discussion

Earlier studies (Lane, 1955; Schumm, 1969) indicate that levee shape and lateral textural trends may vary with (i) channel area (or discharge); (ii) mean particle size and range; and (iii) the dominant mechanism (diffusion or advection) transporting sediments to the floodbasin.

Fig. 5 weakly indicates that levee morphology and channel cross-sectional area correlated over both sites; but when comparing data from either site individually, levee morphology appears to be independent of channel size. The noticeable difference in levee morphology between the two sites suggests that something is fundamentally different in their origin.

A correlation is not clear between levee morphology with mean grain size of the levee crest (Fig. 6). This suggests that levee shape is not simply a function of mean grain size or sorting of the sediment in transport.

Are shape differences in levees at the two study sites due to differences in process? The Columbia River levees plot significantly higher in Figs. 5A and 6A and lower in Figs. 5B and 6B than the Saskatchewan River levees. In accordance with the aforementioned hypothesis, we propose that this difference in morphometries reflects the fact that the Columbia River and Saskatchewan River levees are dominated by diffusive and advective processes, respectively, because diffusive levees should exhibit higher slopes and narrower relative widths than their advective counterparts.

The channel–floodbasin complex at the Columbia River site has a high degree of connectivity. The extensive network of channels, crevasses, and floodbasins in the confined valley of the Columbia River should allow floodbasin waters to rise nearly simultaneously with rising main channel waters during annual flooding, inhibiting the establishment of a water surface gradient between the channel and flanking floodbasin. As the water levels are virtually the same in both the channel and floodbasin, we suggest that sediment can only be transported to the floodbasin by diffusion, causing narrow steep levees to grow.

In contrast, the channels of the avulsion belt of the lower Saskatchewan River occupy wider and more unconfined floodbasins, allowing rising water in the channels to inundate the floodbasin either by overbank sheet flooding or through crevasse channels. Because the floodbasin is not well confined, it does not fill up quickly; and an appreciable water surface gradient is likely established between the main channel and the floodbasin. This water surface gradient promotes advection and broad, gently sloped levees.

Although the morphologic data seem to suggest that Columbia Valley and Cumberland Marshes levees grow by diffusive and advective transport, respectively, their fining rates are nearly indistinguishable, contrary to our qualitative predictions. We offer three explanations for this inconsistency. First, the study sites presented here may not be representative of our "end-member" conceptual models. For example, an advective component to the Columbia levees, which dampens the diffusive signal, may exist. Second, Eq. (1) may not accurately reflect grain size fining conditions for diffusive transport. The exponential fits used to compute fining exponents for Columbia Valley levees possess low correlation coefficients (Fig. 7), possibly because diffusive levee fining does not follow an exponential function. Third, advective growth of natural levees may be growth by the superposition of crevasse splays. Crevasse splays are sand-dominated, sheet-like deposits that form from the transport and deposition of main-channel sediment in narrow channelized flows through a topographic low point in a channel's levee and, in some systems, dominate the bulk volume of near-channel floodbasin deposits (Mertes, 1994; Brierley, 1996; Dunne et al., 1998). Coleman (1969) first suggested that it is the coalescence of laterally adjacent, sheet-like crevasse splays that is responsible for the bulk of the volume in natural levee deposits. Although this may be true, a levee must exist before a crevasse can form and subsequently convey sediment to the floodbasin by advection. One could test this hypothesis by coring levees and examining the floodbasin strata.

The aforementioned conjecture that levee morphology is controlled by dominant sediment transport mechanism applies to the two study sites presented herein. In meandering systems, levee position on the meander may strongly control levee growth. The outside bank of a meander bend experiences a very different flow field of overtopping channel waters than does the inside bank. Age of channel, flood frequency, and vegetation type and density must also be considered as potential controls on levee morphology. These caveats aside, further field studies of natural levee morphology would certainly help test the hypothesis presented in this paper and might also shed light on the importance of other variables.

5. Conclusions

Comparison of morphometric measurements of levee slope and levee width indicates that mature levees of the upper Columbia River are steeper and narrower than those of the Cumberland Marshes region. This observation, when viewed in the context of the local physiographies of the two regions, leads to a hypothesis that levees of the upper Columbia are diffusion-dominated, whereas those of the Cumberland Marshes region are advection-dominated.

Other factors such as levee age, flood frequency, position on meander, and vegetation may certainly contribute to levee development. However, at the two channel–flood plain complexes we present in this paper, levee morphology appears to be controlled by the dominant sediment transport mechanism operating. Sediment fining rates across levees on the Columbia and Saskatchewan Rivers do not vary as predicted, for reasons that remain unknown.

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