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Controls on natural levée development in the Columbia River, British Columbia, Canada

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ABSTRACT

Natural levées of the Columbia River near Golden, British Columbia, were investigated to identify the mechanisms that control levée development and morphology. Topographic profiles of 12 levée pairs were surveyed, and measurements of water-surface elevation, flow velocity, flow direction and turbidity were obtained during an average magnitude flood (1·2 years recurrence interval). Sedimentation rates and grain-size distributions were measured from sediment traps placed along levée-to-floodbasin transects. Results show that water and sediment exchange between the channel and floodbasin was mainly by advection. During flooding, local floodbasins behave more as efficient water pathways than water storage features, resulting in down-valley floodbasin flows capable of limiting basinward growth of levées. Levée shape results primarily from two independent factors: (1) maximum channel water stage, which limits levée height; and (2) floodbasin hydraulics, which control width. In the Columbia River, the competence of floodbasin flows results in relatively narrow and steep levées. Natural levées grow under two general conditions of deposition as governed by flood-stage elevation relative to levée-crest elevation: front loading and back loading. During large floods when crests are inundated, front loading preferentially aggrades the proximal portions of levées with sediment directly from the channel, thus increasing levée slope. During average or below-average floods when many levée crests are not overtopped, back loading preferentially aggrades the distal levée areas and floodbasin floor, reducing levée slope. In the study area, a balance between front and back loading sustains these narrow and steep levée shapes for long periods, reflecting an equilibrium between hydraulic regime, floodplain morphology and deposition.

Keywords Anastomosing river, Columbia River, floodbasin hydraulics, floodplain flows, floodplain sedimentation, natural levée.

INTRODUCTION

Natural levées (hereafter called simply 'levées') are an important sedimentary response to the interactions between waters of river channels and floodplains. Levées provide information on overbank sediment regime (Hudson & Heitmuller, 2003), cause super-elevation of channel belts above floodplains, play important roles in flood routing, and affect the locations of avulsions (Schumm *et al.*, 1996; Brierley *et al.*, 1997); they also play major roles in fixing channel positions and enhancing floodplain accretion, thus significantly influencing floodplain evolution and alluvial architecture. Despite their importance, levées have been generally overlooked in models of floodplain flow and deposition (Rajaratman & Ahmadi, 1981; Knight, 1989; Rameshwaran & Willetts, 1999) or, in the case of mathematical models of floodplain evolution, they are expressed mainly as channel superelevation features through preferential deposition near channels (Mackey & Bridge, 1995; Howard, 1996). Most previous studies of sediment transfer between channels and natural floodplains are based on sediment samples that lack concurrent hydraulic data (Kesel *et al.*, 1974; Hughes & Lewin, 1982; Marriott, 1992; Guccione, 1993; Cazanacli & Smith, 1998; Hudson & Heitmuller, 2003; Adams *et al.*, 2004), and little work has directly addressed the hydraulics of the floodplain (Nicholas & McLelland, 1999, 2004; Nicholas & Mitchell, 2003). There is still a paucity of data related to these issues and their implications for floodplain alluviation.

Both turbulent diffusion and advective transfer have been proposed to explain the origin of levées and channel-to-overbank sediment distribution trends (James, 1985; Pizzuto, 1987; Narinesingh *et al.*, 1999; Adams *et al.*, 2004). The diffusion mechanism (Pizzuto, 1987; Knight, 1989; Marriott, 1992; Knight & Shiono, 1996) is mainly based on laboratory observations of decreasing turbulence away from the channel during flooding. Large eddies generated at the shear boundary between the flooded channel and floodbasin generate progressively smaller eddies away from the channel, resulting in water mixing, reduced competence and consequent decreases in sediment transport, grain size and aggradation rate with increasing distance from the channel. Diffusion has been commonly invoked as the dominating mechanism for controlling levée morphology and overbank deposition (James, 1985; Pizzuto, 1987; Marriott, 1996). By this process, steep levées are thought to result from low diffusivity constants and gentle levées from high diffusivity constants. While theoretically viable, this mechanism to the best of our knowledge has never been measured over mature natural levées. In contrast, advection involves net flow across the channel–floodplain interface (Sellin *et al.*, 1993; Sellin, 1995; Howard, 1996; Narinesingh *et al.*, 1999), either down the levée slope perpendicular to the channel, or in some other direction, as a more general result of down-valley water elevation differences between the channel and floodbasin. Because of its greater competence compared with diffusion, advection may result in even gentler levée slopes.

Variations in grain size are thought by some authorities to play a role in setting levée morphology (Axelsson, 1967; Cazanacli & Smith, 1998; Hudson & Heitmuller, 2003), viz. that coarser levées are steeper than fine-grained levées because coarse sediment tends to be deposited more quickly after leaving the channel. The relative degrees of diffusive vs. advective transfer, combined with sediment grain size, probably play key roles in controlling near-channel floodplain deposition and, therefore, levée size and shape (Pizzuto, 1987; Marriott, 1992).

To develop more realistic models of floodplain sedimentation and evolution, there is a need to better understand the physical processes that control sediment transport to overbank areas as well as the fate of suspended sediment once it reaches the floodbasin. This study focuses on the mechanisms of sediment transfer between the channel and adjoining floodbasins during flood stages in an anastomosed reach of the upper Columbia River. In an earlier study of levée morphology in the same system, Adams *et al.* (2004) hypothesized that channels adjacent to small or well-confined floodbasins should possess narrow and steep levées that are built predominantly by turbulent diffusion of sediment away from the channel during overbank flooding. Diffusion was thought to dominate fluvial systems of this type because water-surface elevations of the channel and adjacent floodbasins were presumed to be equal during most of the flood cycle. Conversely, channels adjacent to wide or unconfined floodbasins were supposed to build wider and more gently sloped levées through advection of sediment out of the channel because these basins would take longer to fill, allowing channel stage to remain higher than floodbasin stage for longer periods. While these conjectures about basic differences in levée morphology would appear reasonable, given the presumptions about relative water-surface elevations during flooding, Adams *et al.* (2004) did not present actual measurements of flood flows or sediment transport to support their interpretations. This paper reports on the results of such measurements made during a flood 2 years later and assesses the implications of these observations for levée morphology and floodplain alluviation.

STUDY AREA

The study was conducted in the upper Columbia River in south-eastern British Columbia, Canada, located in a floodplain valley that lies between the Kootenay Range and the Purcell Mountains (Fig. 1). The work focused on a 26 km reach (valley distance) situated between the villages of Spillimacheen and Parson. A gauging station with a continuous record of discharge since 1903 is located at Nicholson, 27 km downstream

Fig. 1. Map showing location of upper Columbia River and study reach (rectangle). Flow is to the north-west.

from Parson. The alluvial valley is 1·5–2 km wide and presents a variety of floodplain environments and depositional features at different scales and stages of evolution (Smith, 1983; Makaske *et al.*, 2002). The study reach floods nearly every year. The annual hydrograph, controlled mainly by seasonal rainfall and snowmelt run-off, attains its normal maximum around mid-June and its minimum around February. Most of the field data for this study were obtained in 2000 when the flood peak was approximately average in magnitude but of slightly shorter duration than typical floods recorded at the Nicholson gauge. Based on daily peak flows, the recurrence interval for the 2000 flood is 1·2 years, with a peak discharge of 351 m^3 sec^{-1} occurring on 3 July.

The reach displays an anastomosed pattern where one to five, slightly sinuous to straight, interconnected channels occupy the valley floor. Typical bankful widths and depths of primary channels are *ca.* 50–125 and 2·5–4·5 m, respectively, whereas secondary channels are typically 20–50 m wide and 1·5–3·5 m deep (see also Tabata & Hickin, 2003; Abbado *et al.*, 2005). The floodplain system is confined by high valley walls and is characterized by longitudinal channel gradients ranging from 0·000215 to 0·000068 (Abbado *et al.*, 2005). Channels are relatively stable and bounded by well-developed levées that separate small to moderately sized floodbasins (order 0·1–1·0 km^2) typically occupied by shallow lakes or marshy wetlands. Most levées are covered with dense stands of trees and brushy vegetation that grade into open wetland vegetation away from the channels. One of the larger floodbasins, here termed the Soles Basin, was the subject of a more detailed study in collaboration with D. Abbado during the 2000 field season (Abbado, 2001). Soles Basin is located in the upstream part of the study reach (Fig. 1) adjacent to a main channel and immediately downstream from the confluence with the Spillimacheen River.

The floodplain is actively aggrading (Locking, 1983; Makaske, 1998; Makaske *et al.*, 2002; Abbado *et al.*, 2005), and previous work suggests a long-term average aggradation rate of 1·75–1·95 mm $year^{-1}$ (Makaske *et al.*, 2002). Channel bed material comprises mainly medium sand to fine gravel. Over the main thalweg of the study reach, mean grain sizes of bottom samples show a statistically significant downstream fining trend of 1·4–2·2 mm upstream to 0·5–1·1 mm downstream (Abbado *et al.*, 2005). Levée and proximal floodbasin sediments typically range in size from very fine sand to medium silt ($d_{50} = 0{\cdot}15$–0·014 mm; Lazar, 2002). Newly formed channels, associated with crevasse splays, and older abandoned channels, are common throughout the study reach. Vertical aggradation is the dominant sedimentation pattern. Lateral accretion is relatively minor, as inferred from the absence of oxbow lakes and paucity of point bar deposits (Smith, 1983). The upper Columbia River is a suspended-sediment-dominated system (Makaske, 1998), but the supply of bedload apparently exceeds the transport capacity of the channels, forcing aggradation (Abbado *et al.*, 2005).

METHODS

Topographic profiles were surveyed over sightlines cleared across the channel, adjacent levées and into the flanking floodbasins along 11 transects oriented perpendicular to the channel axes. Locations were selected to represent a variety of configurations. The transects included a total of 24 individual levées (Figs 2 and 3). For each transect, staff gauges were positioned at one channel bank and at both ends of each transect line in the adjacent floodbasins. Gauge elevations were then surveyed so that water elevations could be read directly at all three locations for each transect. The deepest part of the channel was taken to be the arbitrary zero-elevation datum for constructing topographic profiles. Transect III comprises a comparatively long transect across

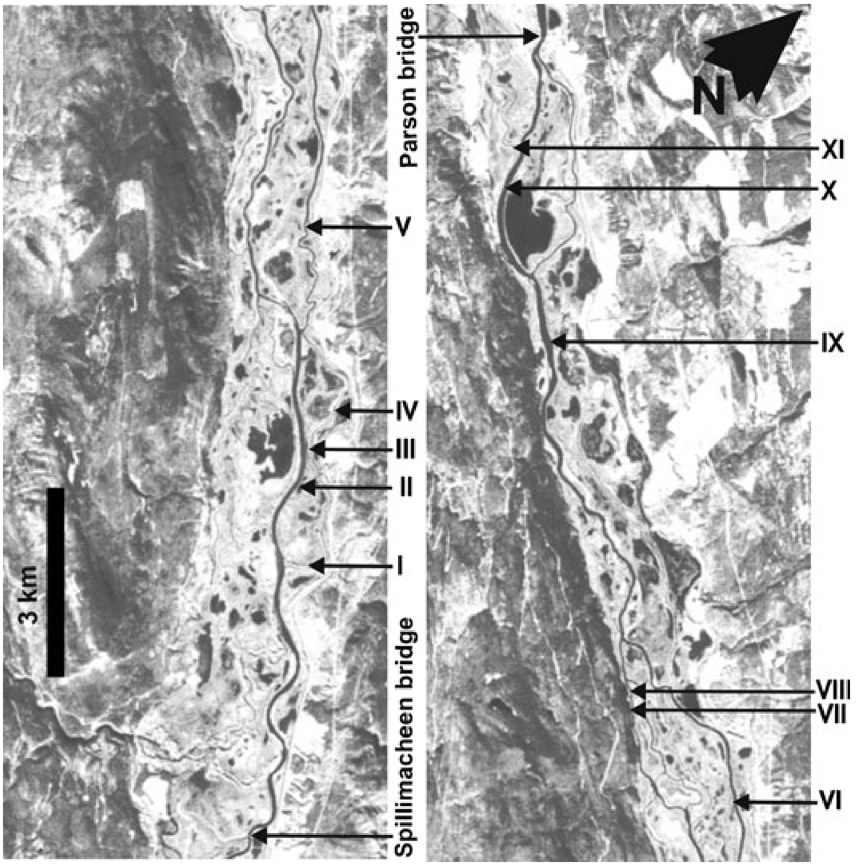

Fig. 2. Image showing study reach of upper Columbia River and location of survey transects. The two parts of the image overlap at Transect VI.

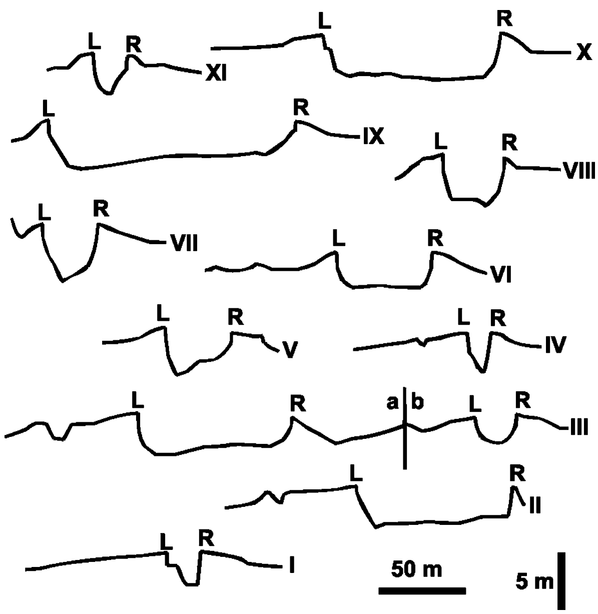

Fig. 3. Topographic profiles of surveyed transects showing left (L) and right (R) levées investigated in this study. Flow is away from viewer. See Fig. 2 for locations.

the narrow downstream section of Soles Basin and its two confining channels. In this case, the transect was divided into two contiguous segments, IIIa (main channel) and IIIb (secondary channel; Fig. 3). Water elevations, with repeatable precisions of 5 mm or less, were measured daily at each staff gauge for each transect from 7 June to 22 July 2000, covering most of the flood period. For the three transects that included Soles Basin (I, II and III, Fig. 2), water-surface elevations were combined with data from Abbado (2001) to obtain floodbasin longitudinal profiles.

For morphometric measurements, levée width is defined as the horizontal distance from the channel margin to the point on the surface where the average slope becomes less than 0·01 (Cazanacli & Smith, 1998). If a marked change in slope was apparent where the slope decreased rapidly and the levée surface became nearly flat, levée width was considered as the horizontal distance between the channel edge and the point of significant change in average slope. Levée height is defined as the difference in elevation between the highest point of a levée and the elevation of the levée–floodbasin transition as defined by levée width. Levée slope is taken as the ratio of height to width. Levée cross-sectional areas were calculated by comparing the weights of paper tracings of cross sections to the paper weight of a reference area. Individual levées are identified by transect number (I–XI) and the letters R and L for, respectively, right and left levées as observed facing downstream.

When levée crests were overtopped by flood waters, water velocities were measured along levée portions of transects from channel edge to flood-basin using a Price pygmy current meter. Velocities were measured at 0·4 depth and averaged over 1 min using a digital readout module. Velocity measurements at each site were combined with simultaneous measurements of surface turbidity and flow direction using a portable LaMotte 2020 turbidimeter (LaMotte Company, Chestertown, MD, USA) and Brunton compass respectively. Flows over levées were sufficiently shallow and clear that near-bottom particle transport could be observed to correspond to surface flow directions. Measurement sites were selected to reasonably represent changes in velocity along each levée transect; therefore, sites at each transect commonly differed on different days as flood stages changed. All measurements were made by wading.

Overbank sedimentation rates were measured with sediment traps constructed of framed 18×18 cm squares of astroturf with 0·5 cm blades, similar to those of Asselman (1997), Middelkoop (1998) and Makaske (1998). All traps were placed between 29 May and 6 June and collected between 26 July and 29 July 2000, depending on when they became exposed by the receding flood. This sampling period included most of the seasonal flood interval. In most cases, traps were placed before inundation, and only a few were placed at already submerged locations in the floodbasins. Following collection, sediment was rinsed from the traps, dried and weighed. Grain-size distributions were determined with a Coulter LS 100Q laser particle analyser (Beckman Coulter Inc., Fullerton, CA, USA). The total sediment weight for each sediment trap was converted to thickness assuming a 1016 kg m^{-3} bulk density (Makaske *et al.*, 2002). To allow for compaction after burial and for comparison with previous work, sample weights also were converted to aggradation thickness by assuming 30% porosity and 2·6 g cm^{-3} sediment density.

RESULTS

Water-surface elevation

Of the 24 surveyed levées, the crests of 10 were overtopped during the 2000 flood peak and, of these, six were overtopped sufficiently to allow flow measurements over the entire transect. The maximum water depth measured over a levée crest was 36 cm at Transect VR on 2 July 2000. Changes in water-surface elevations in channels and their adjacent floodbasins were in phase throughout the entire period of observation (Fig. 4); however, differences in water-surface elevations were often significant as the basins filled and emptied at different rates. Regardless of whether water-elevation differences were large or small (e.g. Fig. 4A and B), there was clear evidence of advective transfer between channel and floodbasin over levées during flooding. Advective flow was most commonly observed from channel to floodbasin, but occasional floodbasin-to-channel advection was also observed, as is expected to conserve mass. Table 1 gives the water-surface slopes for flooded cross sections at peak discharge.

At Soles Basin, projection of water-surface elevations from various measurement points to the main axis of down-basin flow (Fig. 5) yields approximate longitudinal water-surface slopes for the floodbasin that can be compared with successive water-surface slopes in the adjacent main channel (Fig. 6). The profiles, measured at different discharges, show that the water surface of the floodbasin is not flat, although the average water-surface slope in the basin is similar to that of the channel. The profiles in Soles Basin show two distinct areas: a wide and nearly flat upstream portion where the local slope is lower than that of the main channel; and a narrow and relatively steep downstream portion (Figs 5 and 6). As both ends of Soles Basin are connected to the main channel, the average water-surface slope of the basin is controlled by the channel. Therefore, like the channel, the overall slope of Soles Basin reduces slightly with increasing water stage. For data in Fig. 6, channel slope changed from 0·000222 (18 June 2000) to 0·000210 (2 July 2000). This small overall decrease in slope is accentuated in the steeper parts of the Soles Basin, especially near the outlet. In contrast, the upper part of the basin becomes slightly steeper during higher water stages due to its proximity to the inlet connecting the basin with the main channel. Irregular water surfaces in floodbasins were also observed in the Ob River by Velinakova & Yarnykh (1970).

Levée morphology

All of the 11 surveyed transects show prominent levées associated with each channel (Fig. 3).

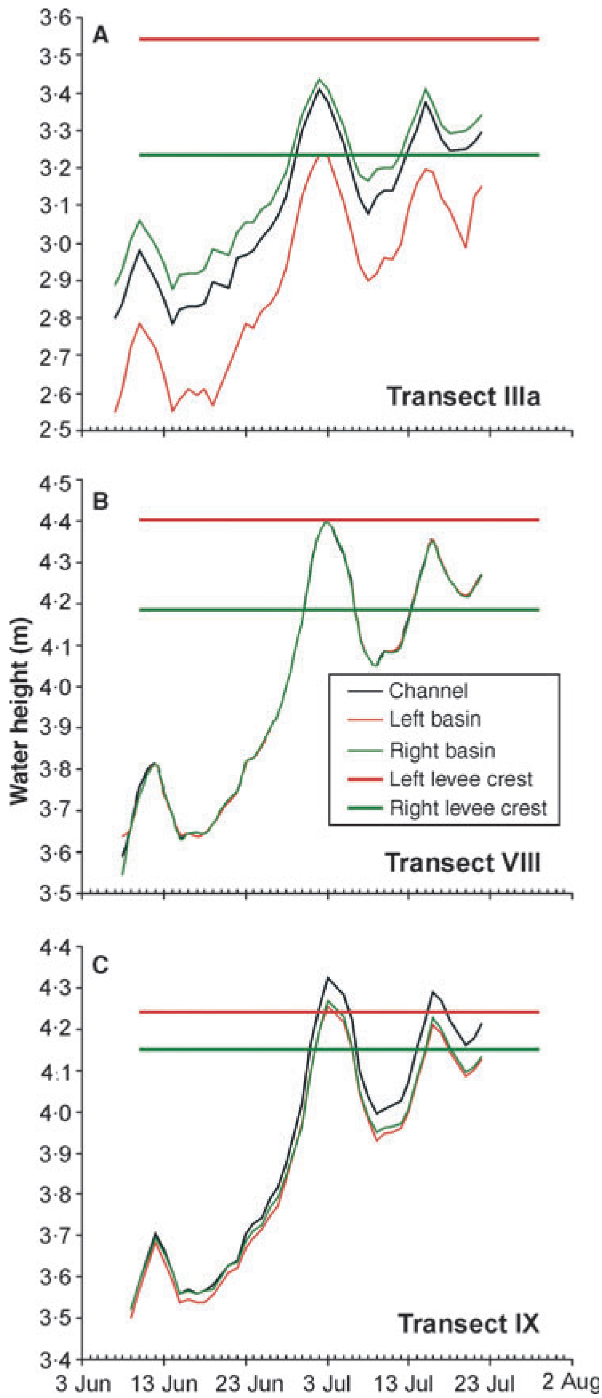

Fig. 4. Variations in water-surface heights of channel and adjacent floodbasins for three representative transects during changing discharges. (A) Water surface of right floodbasin remains higher than water surface of channel throughout flood event while left floodbasin remains lower; (B) all three water-surface heights remain virtually equal; (C) channel surface remains higher than either floodbasin. Levée crest heights are shown for reference.

Table 1. Water-surface slopes of flooded transects between channels and adjacent floodbasins during peak discharge.

Location	Distance between gauges (m)	Slope
IIIbL	24	0·00063
VL	19	0·00026
VIL	20	0·00075
VIIL	12	0·00067
VIIR	15	0*
VIIIR	14	0*
IXL	11	0·00636
IXR	23	0·00239
IIIaR	9·3	−0·00269
VR	18	−0†

Negative values represent floodbasin-to-channel flow; other values represent channel-to-floodbasin flow.
*Slope less than measurement accuracy; channel-to-floodbasin flow observed.
†Slope less than measurement accuracy; floodbasin-to-channel flow observed.

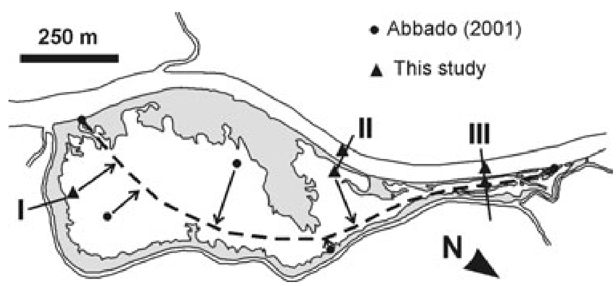

Fig. 5. Plan view of Soles floodbasin showing locations of water elevation measurements and their projection into the axis of basin flow (dashed line). Shaded pattern represents areas of levées and inactive splays separating channels from basin. For location see Figs 1 and 2 Transects I–III. Flow is left to right.

Levée widths range from 6 to 81 m, heights from 0·9 to 2·3 m and slopes from 0·018 to 0·259 (Table 2). Levée slopes are generally steep compared with those of most fluvial systems (Brierley *et al.*, 1997), a feature due more to the comparatively narrow widths of the Columbia levées than to unusually large heights. Adams *et al.* (2004) showed that within the same study reach, little or no correlation exists between levée slope and levée-crest grain size.

Both levée slope and cross-sectional area correlate well with levée width (Fig. 7A and C), but neither show a significant relationship to height (Fig. 7B and D). This suggests that levée height and width behave quasi-independently of each other. The channels in the surveyed transects are all mature and relatively stable, as assessed from air photos and channel ages ranging from 600 to 3000 years (Makaske *et al.*, 2002). Considering that other workers (Smith & Pérez-Arlucea, 1994; Törnqvist *et al.*, 1996;

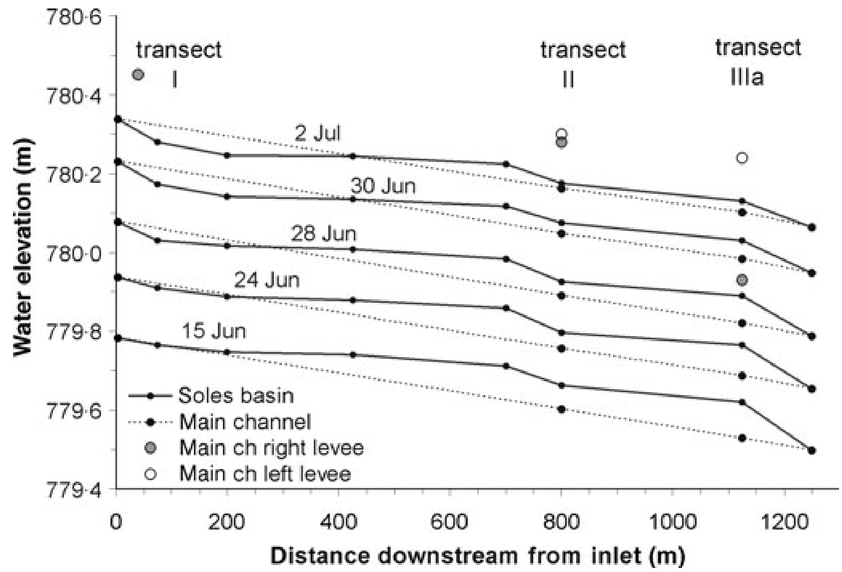

Fig. 6. Longitudinal water-surface profiles of parent channel and axis of Soles Basin during rising flow stages. Transect locations (Fig. 2) and levée crest elevations are shown for reference.

Table 2. Morphometric data for channel–levée–floodbasin transects.

	Levée				Floodbasin	Channel
Location	Width (m)	Height (m)	Slope	Area (m^2)	Width (m)	Area (m^2)
IL	81·0	1·44	0·0178	66·0	525	47·9
IR	38·5	1·34	0·0348	28·6	270	47·9
IIL	75·1	1·85	0·0247	75·0	660	255·2
IIR	6·0	1·55	0·2590	6·6	300	255·2
IIIaL	76·0	2·10	0·0276	76·7	600	264·0
IIIaR	25·5	2·28	0·0895	31·0	95	264·0
IIIbL	30·0	1·68	0·0560	20·7	95	69·0
IIIbR	24·4	1·20	0·0492	19·8	105	69·0
IVL	65·0	1·44	0·0222	46·9	330	47·9
IVR	28·7	1·19	0·0414	14·6	210	47·9
VL	26·6	1·32	0·0495	14·5	180	124·8
VR	25·3	1·53	0·0603	27·4	60	124·8
VIL	31·0	1·50	0·0484	16·5	105	93·0
VIR	30·5	1·90	0·0623	32·1	150	93·0
VIIL	12·2	1·12	0·0915	8·7	18	130·2
VIIR	30·0	1·49	0·0495	23·2	105	130·2
VIIIL	27·1	2·12	0·0782	33·5	30	133·0
VIIIR	7·6	0·92	0·1201	3·8	90	133·0
IXL	22·0	1·84	0·0836	18·3	150	470·9
IXR	27·0	1·38	0·0511	18·8	300	470·9
XL	33·0	1·15	0·0348	21·0	75	383·8
XR	32·4	1·91	0·0590	21·0	330	383·8
XIL	15·6	1·29	0·0823	16·8	315	67·2
XIR	40·0	1·55	0·0386	20·1	45	67·2

Moody *et al.*, 1999) have shown that levée heights may grow quickly as they strive towards equilibrium with the hydraulic regime, it may be inferred that the levées of this study are mature, asymptotically approaching a steady-state height, with morphologies in dynamic equilibrium with the fluvial system.

Flow velocity and turbidity

Flow velocity, flow direction and turbidity values along transects of overtopped levées are shown in Fig. 8. Flow was clearly advective in all cases. Net water movement in Transects IIIaR and VR is towards the channel, whereas in Transects IIIbL,

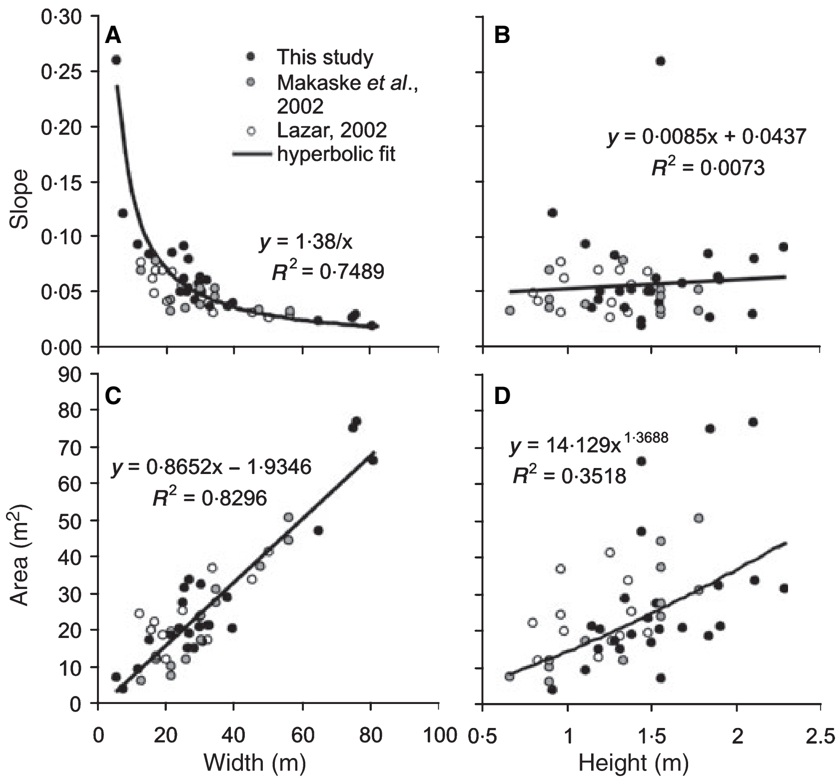

Fig. 7. Plots of morphometric data for levées of the upper Columbia River. Note that reasonable correlations exist for levée slope vs. width (A) and levée area vs. width (C), but not for slope or area vs. levée height (B, D).

VIIL, VIIIR and IXR, flow is towards the floodbasin. Velocity tends to decrease and becomes less variable away from the channel regardless of flow direction, and its values tend to be more similar between different days of measurement than between different transects. Flow direction tends to be more perpendicular to the channel close to the channel edge, regardless of whether the water exits or enters the channel. Down-floodbasin flows become more apparent in middle and distal portions of the levées.

When overbank flows enter the floodbasin from the channel (Fig. 8 IIIbL, VIIL, VIIIR and IXR), turbidity values are at a maximum at the channel edge and tend to remain steady or decrease slightly away from the levée crest. When flows enter the channel from the floodbasin (IIIaR and VR), turbidity remains constant along the transect length. At both of the latter locations, however, a slight increase in turbidity was measured at the channel edge where floodbasin waters mixed with suspended-sediment-rich channel waters. In general, however, turbidity varies little with distance from the channel, even for different floodbasins and days.

Sedimentation patterns and rates

Sediment traps showed considerable variability in sediment accumulation, both along and between transects (Fig. 9). High variability was also observed in studies of the Rhine River by Asselman (1997) and Middelkoop (1998). Transects that were not completely flooded, or those where water flowed from floodbasin to channel, showed trends of increasing accumulation away from the channel, partly related to submersion time (e.g. Transects IIIaL, IIIaR and VIIIL). In those transects where flood water flowed from channel to floodbasin for significant time periods, sediment accumulation decreased away from the channel (e.g. Transects VIIIR and IXR). However, levées overtopped for only short periods with channel-to-floodbasin flow show increasing sediment accumulation away from the channel, probably related to longer inundation times (e.g. Transects IIIbL and IXL). In transects where flow is from channel to floodbasin, grain size tends to decrease away from the channel, but where flow is from basin to channel (e.g. Transect IIIaR, ≈170 m in Fig. 9, or VR in Fig. 8), grain size varies little.

From the trap recoveries, average uncompacted aggradation on all levée surfaces was estimated as 0·9 mm for the 2000 flood season, with a maximum observed value of 3·7 mm. Average floodbasin aggradation during the period of measurement was 1·1 mm (calculated using the most distal floodbasin sediment traps in each transect). On completely flooded levées, average levée-crest aggradation was 1·3 mm. Assuming

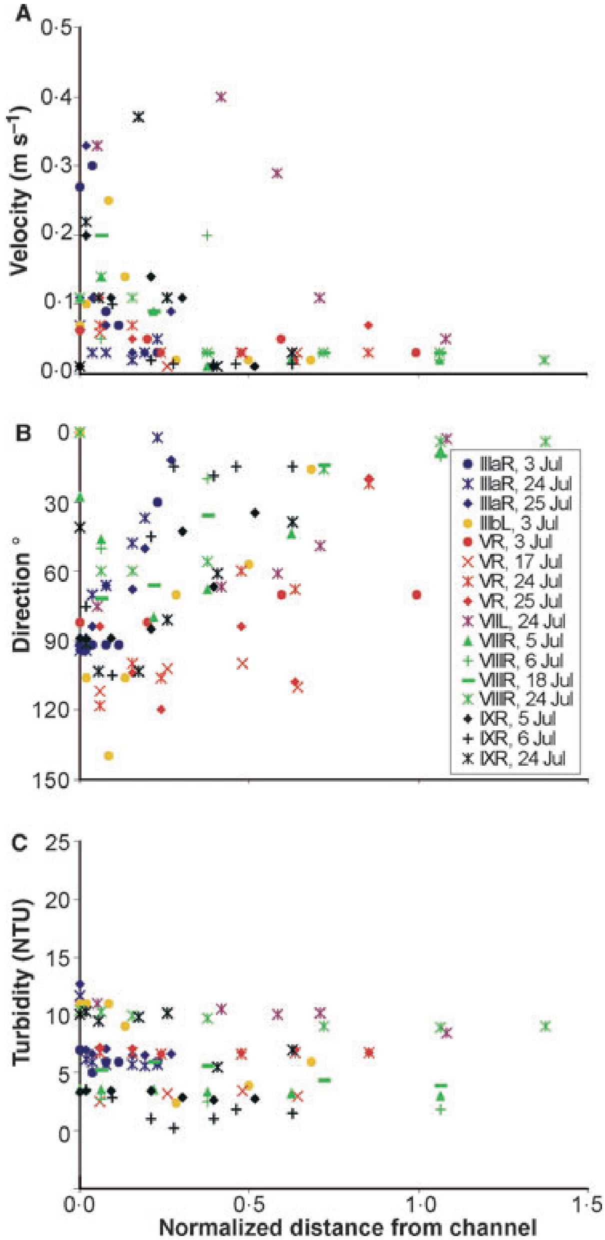

Fig. 8. Flow data for inundated levées. (A) Mean velocity at 0·4 depth (m sec^{-1}); (B) flow direction (degrees relative to channel orientation where 0^0 is the down-channel direction); (C) turbidity of near-surface sample (NTU). The data represent different days and water stages for each levée. Distance from channel is normalized where 0 represents the channel edge and 1 the levée width for each location. Data plotted to the right of 1 represents floodbasin beyond the levée. Although not distinguishable in the figure, Transects IIIaR and VR showed net flow from floodbasin to channel, whereas Transects IIIbL, VIIL, VIIIR and IXR showed channel-to-floodbasin flow.

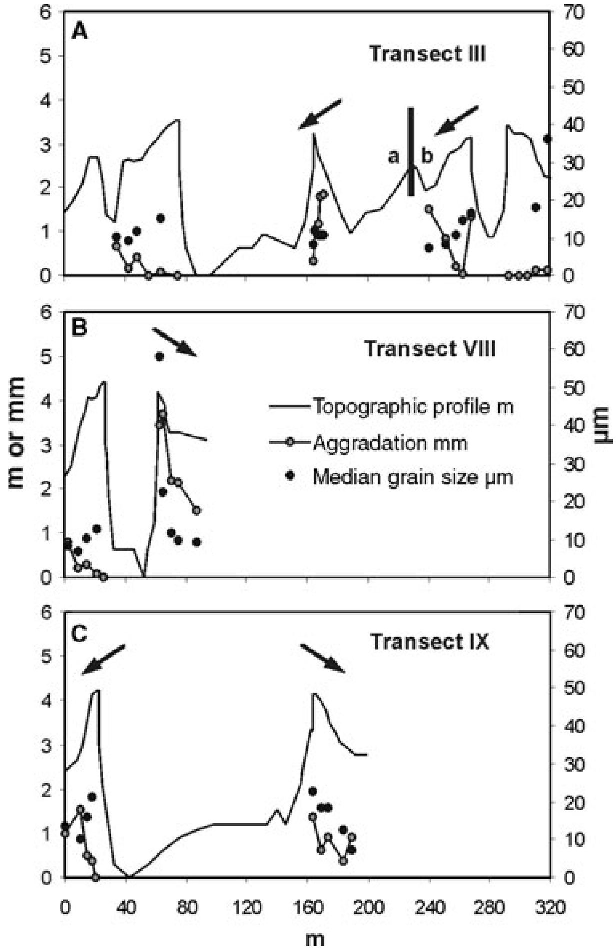

Fig. 9. Topographic profiles (m), aggradation inferred from sediment trap catches (mm) and median grain size in sediment traps (µm) along Transects III, VIII and IX. Arrows indicate direction of flow over levée during flood discharges.

30% porosity and 2620 kg m^{-3} mineral density, compacted aggradation for the 2000 flood was 0·5 mm overall average, 2·0 mm maximum, 0·6 mm floodbasin average and 0·7 mm average for overtopped levée crests. Considering that most of the flood event occurred during the period of measurement, these rates can be interpreted as reasonable approximations for aggradation rates of average floods, representing at least a minimum for the year.

DISCUSSION

Water surface slopes

The measurements during the 2000 flood show that water-surface elevations between channels and adjacent floodbasins were usually unequal, and channel-to-floodbasin slopes for most of the flooded channel/floodbasin pairs were significant (Fig. 4, Table 1). Given the anastomosed nature of the floodplain, local floodbasins could be expected to fill and empty at different rates through a flood cycle, depending on their relative sizes and the nature and efficiency of their connections to main channels. Some of the observed dissimilarity in local water-surface elevation is probably due to the pattern of filling and emptying. When flooded, advective flow across the levées was nearly always evident, even in cases where differences in water-surface elevations fell below the limits of detectability (Table 1). Under the conditions of this average flood, advection rather than diffusion was the dominant transfer process during overbank flooding. Field observations, however, confirmed the presence of turbulent shear layers at interface zones between channel and overbank flow at several different locations and flood stages, but significant diffusion of turbulent eddies away from this zone into the floodbasin as described by several authors (Sellin, 1964, 1995; Knight & Shiono, 1996) could not be verified.

The Soles floodbasin, with both its inlet and outlet connected to the same parent channel, showed irregular longitudinal water-surface profiles that did not parallel the longitudinal profiles of the parent channel during changing discharges (Fig. 6). This difference in hydraulic behaviour between the floodbasin (non-uniform flow) and its parent channel (≈uniform flow) provides another possible explanation for dissimilar water-surface elevations across levée-channel transects in the study area (Figs 4A and 6). Although longitudinal profiles were not measured for other floodbasins, an inference of non-uniform flow behaviour seems reasonable because down-valley conveyance of water through floodbasins and channels will necessarily be different, given differences in cross-sectional area and roughness, thereby creating variations in water-surface elevations at different stages of flow. The flow constriction imposed by converging levées of the main and secondary channels in the lower portion of the Soles Basin (Fig. 5) could explain the low elevation of the levée crest in Transect IIIaR compared with that of IIIaL and others bordering the main channel (Fig. 6). At this location, observed return flow from the Soles Basin imposed on the IIIaR levée under current hydraulic conditions has inhibited levée growth. Note that levée crests along the main channel (Fig. 6, Transects I, II and IIIaL) indicate a longitudinal slope similar to that of the channel water surface. In addition to varying filling and emptying rates of local floodbasins during flood events, therefore, differences in elevations between channel and adjacent floodbasin water elevations may arise from non-parallelism of their down-valley water surfaces.

Flow over levées

During flooding, all observed cross-levée flows over mature levées were decidedly unidirectional, non-uniform and unsteady. This was true whether flow was channel-to-floodbasin or floodbasin-to-channel, and regardless of the degree of flooding or magnitude of the water-elevation differences. In general, levées were not observed to be areas where turbulent eddies diffused and attenuated away from the channel, gradually transferring momentum and mass to floodbasin waters, but instead were areas where advective flows connected broadly parallel down-valley channel and floodbasin flows. The major source of variability in flow velocities along the levée transects, including the general reduction of velocity away from the channel (Fig. 8), was due to differences in local depth – in general, the deeper the flow, the lower the velocity. Another source of variability was heterogeneity of roughness elements (obstacles, ground relief and vegetation) that vary across a levée. Differences arising from different days of measurement were due to changes in the water stage and its relationship to changes in relative roughness. All flows observed along transects of overtopped levées were unidirectional over the duration of flooding and controlled mainly by floodplain topography.

Sediment accumulation

Spatially averaged sediment accumulations measured from traps over the period of observation (average 0·5 mm after compaction) agree roughly with previous estimates for the Columbia River floodplain during a single flood (Locking, 1983; Makaske, 1998; Makaske *et al.*, 2002), but fall below the long-term aggradation rate of 1·75 mm year^{-1} estimated by Makaske *et al.* (2002). The difference can be attributed to dominant sedimentation occurring during larger floods and probably also to deposition during the rest of the year for floodbasin areas that contain water year-round. The estimate presented here is a minimum and applies only to levées. Lower-lying floodbasin areas probably experience additional sediment accumulation through the remainder of the year.

Results of this study suggest that levées do not aggrade evenly across their entire surface during a

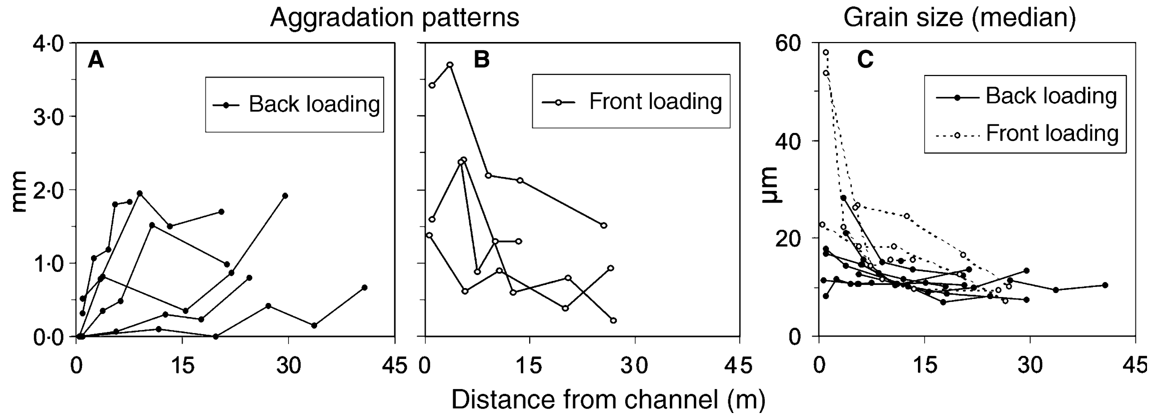

Fig. 10. Aggradation and grain-size patterns resulting from front and back loading of upper Columbia levées during the 2000 flood. Back loading is represented by Transects IIIaL, IIIaR, VIL, VIIR, VIIIL and IXL; front loading is represented by Transects VIR, VIIL, VIIIR and IXR.

flood event and instead respond differently to different flood magnitudes and degrees of levée submergence. Because they remain partially exposed, the crests of many levées do not aggrade during average floods such as the 2000 event; this was also observed for the 1994 flood by Makaske *et al.* (2002). During such partially submergent conditions, the distal levée and floodbasin are preferentially aggraded with fine suspended sediment supplied by floodbasin flow, a process termed *back loading* here (Fig. 10A), which tends to reduce levée slope. During larger floods when levée crests are inundated, *front loading* increases levée height and slope by preferentially aggrading the proximal portions of the levée with coarser sediment supplied directly from the channel and producing grain-size fining towards the basin (Fig. 10B and C). To sustain steep levée shapes for long time periods, larger floods than that experienced in this study are required. During such floods, it is possible that turbulent diffusion, as suggested by Adams *et al.* (2004), plays a more significant role in the front loading process than observed in this study. This possibility awaits observations during flood events greater than the 2000 flood.

Levée morphology

Figure 7 supports the hypothesis that levée height and width behave quasi-independently in the Columbia River and may be controlled by different mechanisms. Neglecting the influence of crevasse splays in some floodbasins, levée height is ultimately limited by the maximum water elevation during flooding, whereas width is affected more by the hydraulic characteristics of the floodbasin, which determine sediment transport capability and extent of deposition away from the channel. If sufficient growth space were available, width could hypothetically increase indefinitely after a levée has grown to near its maximum elevation permitted by flood regime. As such, if channel aggradation is negligible and maximum flood elevations do not increase through time, levée slopes would be gradually reduced by preferred deposition in their distal portions (back loading) during non-levée-topping floods. However, if channel aggradation is significant and overall floodbasin aggradation keeps pace with channel aggradation, levée slope could remain virtually constant through episodic alternations of front loading and back loading.

The shape of mature levées is interpreted here to be governed predominantly by channel-to-floodplain flow combined with hydraulic characteristics of the floodbasin. The rapid rates of water-elevation change in the floodbasins, comparable with those of the channels (Fig. 4), combined with the similar velocities and turbidities measured at the distal portions of levées for different stages and locations (Fig. 8), suggest that the Columbia floodbasins behave as efficient hydrodynamic systems; that is, they convey water down-valley efficiently during high water stages, thus behaving more as alternative water pathways to the existing channels than as water storage features. This characteristic is enhanced by the confined nature of the whole floodplain, as narrow floodbasins can be expected to have greater competence during equal discharge floods than wider ones. Because individual Columbia floodbasins tend to be small and interconnected due to the anastomosed character of the channel system, they tend to fill and empty quickly in an overall down-valley direction, producing relatively efficient floodbasin through-flow. This is shown in the observed change of flow direction from high-angle at the channel edge to channel-parallel within the floodbasin (Fig. 8).

In the study reach, floodbasin flows are inferred to be sufficiently competent to shape levée morphology. High floodbasin flow velocities will retard deposition by keeping fine sediment in suspension. Furthermore, suspended sediment exiting the channel over the levée and into the floodbasin changes direction and moves parallel to the channel rather than further away into the basin. This effect limits basinward progradation and enhances development of narrow levées.

During large floods when levée crests are inundated and floodbasin flows are most competent, suspended sediment is introduced to levées directly from the channel, the coarser fractions depositing quickly because flow competence decreases abruptly at the overbank edge (Knight, 1989; Sellin, 1995). Early in their development, levée heights increase rapidly while flooding is more frequent due to low banks (low levée crests), but basinward growth of the levée reduces floodbasin cross-section area, thus constricting floodbasin flows and increasing velocities that impede further deposition. This introduces a feedback system that helps to sustain narrow and steep levées wherever floodplain widths are constricted by levées of nearby channels and/or valley walls. This feedback mechanism may be enhanced by the stabilizing effects of trees and deep roots in the higher portions of levées which more effectively resist erosion during large floods in comparison with less robust seasonal vegetation in the floodbasins and distal levée areas. Increasing flow velocity due to floodbasin constriction might also explain the presence of floodplain channels adjacent to levées and near valley walls in some of the Columbia floodbasins, e.g. Transect VIIL (Fig. 3). The meandering Tuross (Ferguson & Brierley, 1999a,b) and Powder Rivers (Moody *et al.*, 1999) and the anastomosing Bani and Niger Rivers (Makaske, 1998) also show narrow and steep levées associated with narrow floodbasins as well as floodbasin channels similar to those of the Columbia River.

To further test the hypothesis that steep narrow levées are caused by competent floodbasin flows, heights and widths of Columbia River levées were compared with those from the lower Saskatchewan River at the Cumberland Marshes (Fig. 11). The two fluvial systems have important similarities: both are multichannelled, aggradation rates are similar (Morozova & Smith, 1999; Makaske *et al.*, 2002); vegetation patterns along the levées and floodbasins are not greatly different; both include levées and channels of different sizes; and levée grain sizes are similar. In contrast, the Columbia River floodplain is constricted by high valley walls and displays small, well-defined floodbasins, whereas the Saskatchewan River floodplain is less confined and displays larger and less well-defined floodbasins. The data show that levée width and height broadly covary in the Saskatchewan River, whereas the same range of levée heights observed in the Columbia River

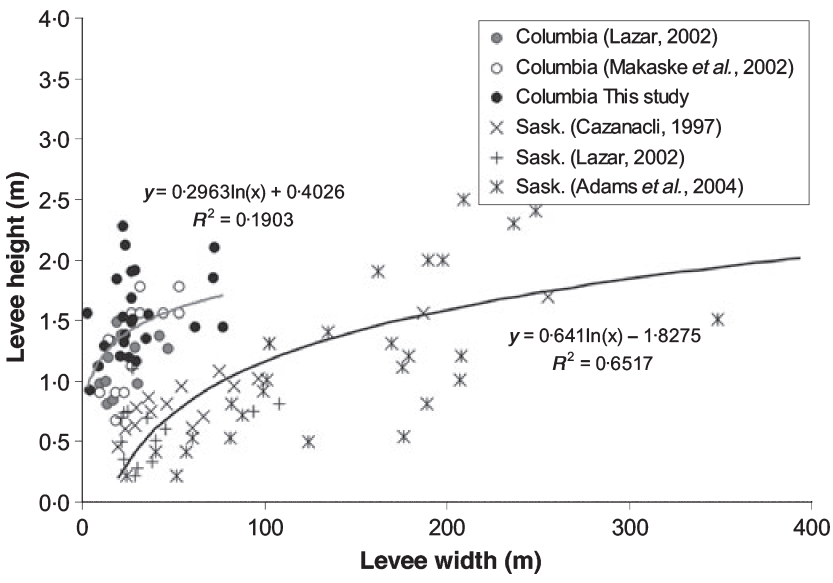

Fig. 11. Comparison of heights and widths of levées from the upper Columbia River and the Saskatchewan River at the Cumberland Marshes. The Columbian levées show little relationship between height and width whereas the Saskatchewan levées show broad covariation between height and width.

shows little or no covariance with width. This suggests that, unlike the Columbia River, levée width in the Saskatchewan River is not as limited by the hydraulics of the wider floodbasins, allowing levées to extend well away from their channels as they develop. The logarithmic fit of the Saskatchewan levées is interpreted as reflecting rapid initial growth of levée height and a later asymptotic approach to a steady-state height as crest elevation approaches dynamic equilibrium with the flood regime.

Model of levée evolution

A conceptual model for the growth and evolution of mature Columbia River levées is presented in Fig. 12. During early levée growth, following the formation of a new channel, levée heights are thought to reach near-equilibrium with the flooding regime in a relatively short time, producing initially narrow and steep morphologies. It is possible that diffusion plays an important role in this early stage of levée development, before the levées become established as efficient barriers that significantly impede the transfer of flow between the channel and floodbasins. As height and along-channel continuity of developing levées increase, however, differences in water surface elevations between channel and floodbasins during floods become potentially larger, and channel-to-floodbasin transfer becomes more advective. In wide floodbasins, such increasingly advective flow will lead to wider levées. In the Columbia River, however, the levées remain narrow and steep during subsequent aggradation of the floodplain because the competence of floodbasin flows limits their widths by preventing distal levée progradation into the floodbasin. Levée shape is then determined by the relationship between floodbasin discharge and topography, which conditions the floodbasin flows. Considering that channels are actively aggrading in the Columbia valley (Makaske *et al.*, 2002; Abbado *et al.*, 2005), maximum water elevation during flooding consequently rises with time. Accordingly, levée crests will continually grow upwards to maintain equilibrium with flood stages for as long as the channels remain active. The floodbasin floor will also aggrade following a similar equilibrium between total discharge and cross-section topography. During a single flood event, the levée surface does not aggrade evenly because front loading dominates during above-average floods (increasing height and slope) and back loading dominates during average and below-average floods (reducing slope). Ultimately, the relationship between discharge regime and floodplain aggradation will maintain the levée shape for as long as the channel remains active. This suggests that the morphology of mature levées is in quasi-equilibrium with hydraulic characteristics and aggradation rate of the system. This conceptual model presumes that, once the levées have been formed, aggradation rates of the channel floor, levée crest and floodbasin floor remain equal; otherwise, levée shape will change with time. If channel aggradation exceeds floodbasin aggradation, levées will steepen due to domination of front loading; conversely, levée slopes will reduce if floodbasin aggradation exceeds that of the channel. Moreover, if the channel becomes abandoned altogether, back loading will dominate as the channel fills, discharge is redirected elsewhere, and subsequent deposition on the levée (and ultimate burial) is provided by flooding of active channels located elsewhere on the floodplain.

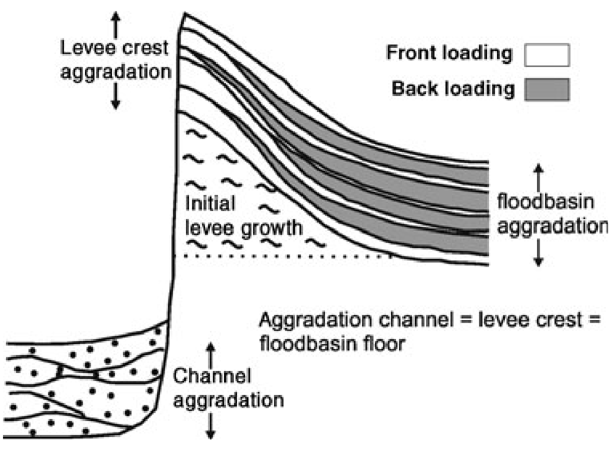

Fig. 12. Model of levée evolution for the upper Columbia River following initial levée growth. The balance between front and back loading deposits maintains a consistent levée shape in equilibrium with flood regime and floodbasin hydraulic conditions during overall aggradation of the floodplain.

CONCLUSIONS

1 In the anastomosed reach of the upper Columbia River during an average flood, water-surface elevations of channels and their adjacent floodbasins were usually unequal during changing discharges. This inequality was due to both the varying efficiencies at which local floodbasins fill and empty and also to uneven water-surface elevations caused by non-uniform flow through floodbasins, as exemplified by the Soles floodbasin.

2 Advection was the only observed mechanism of sediment transfer from channel to floodbasin. Flow velocities across levées tended to decrease away from the channel, whereas turbidity remained approximately constant, regardless of flow direction. Channel-to-floodbasin overbank flows tend to turn down-valley at short distances away from the channel.

3 Aggradation rates measured in sediment traps on levée surfaces suggest two different modes of levée aggradation – front loading and back loading. Front loading occurs when levée crests are overtopped and relatively coarse sediment is delivered directly from the channel to the floodbasin, preferentially aggrading the levée crest and increasing levée slope. When floodbasins and levée toes are inundated but levée crests remain exposed, back loading preferentially aggrades the distal levée with fine sediment delivered by floodbasin flows, reducing levée slope.

4 The floodbasins of this study, localized by anastomosing channels and valley walls, behave more as efficient water pathways than as water storage features during flooding. They are characterized by competent down-valley flows capable of shaping levée morphology, resulting in steep and narrow levées. Floodbasin hydraulics determine levée width by controlling sediment delivery and deposition in distal levée areas. Levée height is controlled more by maximum flood stage.

5 Levées included in this study respond differently to different flood magnitudes, but mature levées sustain consistent morphometries by a balance that is maintained between channel aggradation and floodbasin flow competence. This account is expressed as a long-term balance between front loading and back loading after initial levée growth, sustaining the narrow and steep morphologies that characterize this reach of the Columbia River.

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REFERENCES

Abbado, D. (2001) *The origin of anastomosis in the upper Columbia River, British Columbia, Canada*. Unpublished MS Thesis. Pennsylvania State University, 88 pp.

Abbado, D., Slingerland, R.L. and **Smith, N.D.** (2005) The origin of anastomosis in the upper Columbia River, British Columbia. In: *Fluvial Sedimentology VII* (Eds M.B. Blum and S.B. Mariott), *Spec. Publ. Int. Assoc. Sedimentol.*, **35,** 3–15.

Adams, P.N., Slingerland, R.L. and **Smith, N.D.** (2004) Variations in natural levée morphology in anastomosed channel flood plain complexes. *Geomorphology*, **61,** 127–142.

Asselman, N.E.M. (1997) Suspended sediment in the river Rhine. *Ned. Geogr. Stud.*, **234,** 257.

Axelsson, V. (1967) The Laiture delta: a study of deltaic morphology and processes. *Geogr. Ann.*, **49A,** 1–127.

Brierley, G.J., Ferguson, R.J. and **Woolfe, K.J.** (1997) What is a fluvial levée? *Sed. Geol.*, **114,** 1–9.

Cazanacli, D. (1997) *Morphology and evolution of natural levées: Cumberland Marshes, Saskatchewan River, Canada*. Unpublished MS Thesis. University of Illinois at Chicago, 74 pp.

Cazanacli, D. and **Smith, N.D.** (1998) A study of morphology and texture of natural levées – Cumberland Marshes, Saskatchewan, Canada. *Geomorphology*, **25,** 43–55.

Ferguson, R.J. and **Brierley, G.J.** (1999a) Levée morphology and sedimentology along the lower Tuross River, south-eastern Australia. *Sedimentology*, **46,** 627–648.

Ferguson, R.J. and **Brierley, G.J.** (1999b) Downstream changes in valley confinement as a control on floodplain morphology, lower Tuross River, New South Wales, Australia: a constructivist approach to floodplain analysis. In: *Varieties of Fluvial Forms* (Eds A.J. Miller and A. Gupta), pp. 377–406. John Wiley and Sons Ltd, London.

Guccione, M.J. (1993) Grain-size distribution of overbank sediment and its use to locate channel positions. In: *Alluvial Sedimentation* (Eds M. Marzo and C. Puigdefabregas), *Int. Assoc. Sedimentol. Spec. Publ.*, **17,** 185–194.

Howard, A.D. (1996) Modelling channel evolution and floodplain morphology. In: *Floodplain Processes* (Eds M.G. Anderson, D.E. Walling and P. Bates), pp. 16–62. John Wiley and Sons Ltd, London.

Hudson, P.F. and **Heitmuller, F.T.** (2003) Local- and watershed-scale controls on the spatial variability of natural levées in a large fine-grained floodplain: Lower Pánuco Basin, Mexico. *Geomorphology*, **56,** 255–269.

Hughes, D.A. and **Lewin, J.** (1982) A small-scale floodplain. *Sedimentology*, **29,** 891–895.

James, C.S. (1985) Sediment transfer to overbank section. *J. Hydraul. Res.*, **23,** 435–452.

Kesel, R.H., Dunne, K.C., McDonald, R.C. and **Allison, K.R.** (1974) Lateral erosion and overbank deposition on the Mississippi River in Louisiana caused by 1973 flooding. *Geology*, **2,** 461–464.

Knight, D.W. (1989) Hydraulics of flood channels. In: *Floods: Hydrological, Sedimentological and Geomorphological Implications* (Eds K. Beven and P. Carling), pp. 83–105. John Wiley and Sons Ltd, London.

Knight, D.W. and **Shiono, K.** (1996) River channel and floodplain hydraulics. In: *Floodplain Processes* (Eds M.G. Anderson, D.E. Walling and P. Bates), pp. 139–181. John Wiley and Sons Ltd, London.

Lazar, O.R. (2002) *The origin of natural levées: a field study*. Unpublished MS Thesis. University of Nebraska-Lincoln, 177 pp.

Locking, T. (1983) *Hydrology and sediment transport in an anastomosing reach of the upper Columbia River, B.C.* Unpublished MS Thesis. University of Calgary, 107 pp.

Mackey, S.D. and **Bridge, J.S.** (1995) Three-dimensional model of alluvial stratigraphy, theory and applications. *J. Sed. Res.*, **65,** 7–31.

Makaske, B. (1998) Anastomosing rivers: forms, processes and sediments. *Ned. Geogr. Stud.*, **249,** 287 pp.

Makaske, B., Smith, D.G. and **Berendsen, H.J.A.** (2002) Avulsions, channel evolution and floodplain sedimentation rates of the anastomosing upper Columbia River, British Columbia, Canada. *Sedimentology*, **49,** 1049–1071.

Marriott, S.B. (1992) Textural analysis and modeling of a flood deposit: River Severn, UK. *Earth Surf. Proc. Land.*, **17,** 687–697.

Marriott, S.B. (1996) Analysis and modeling of overbank deposits. In: *Floodplain Processes* (Eds M.G. Anderson, D.E. Walling and P. Bates), pp. 63–93. John Wiley and Sons Ltd, London.

Middelkoop, H. (1998) *Embanked floodplains in the Netherlands*. Faculteit Ruimtelijke Wtenschappen Universiteit Utrecht, 341 pp.

Moody, J.A., Pizzuto, J.E. and **Meade, R.H.** (1999) Ontogeny of a floodplain. *Geol. Soc. Am. Bull.*, **111,** 291–303.

Morozova, G.S. and **Smith, N.D.** (1999) Holocene avulsion history of the lower Saskatchewan fluvial system, Cumberland Marshes, Saskatchewan-Manitoba. In: *Fluvial Sedimentology VI* (Eds N.D. Smith and J. Rogers), *Int. Assoc. Sedimentol. Spec. Publ.*, **28,** 231–249.

Narinesingh, P., Klaassen, G.J. and **Ludikhuize, D.** (1999) Floodplain sedimentation along extended river reaches. *J. Hydraul. Res.*, **37,** 827–845.

Nicholas, A.P. and **McLelland, S.J.** (1999) Hydrodynamics of a floodplain recirculation zone investigated by field monitoring and numerical simulation. In: *Floodplains; Interdisciplinary approaches* (Eds S.B. Marriot and J. Alexander), *Geol. Soc. Lond. Spec. Publ.*, **163,** 12–26.

Nicholas, A.P. and **McLelland, S.J.** (2004) Computational fluid dynamics modeling of three-dimensional processes on natural floodplains. *J. Hydraul. Res.*, **42,** 131–143.

Nicholas, A.P. and **Mitchell, C.A.** (2003) Numerical simulation of overbank processes in topographically complex floodplain environments. *Hydrol. Proc.*, **17,** 727–746.

Pizzuto, J.E. (1987) Sediment diffusion during overbank flows. *Sedimentology*, **34,** 301–317.

Rajaratman, N. and **Ahmadi, R.** (1981) Hydraulics of channels with floodplains. *J. Hydraul. Res.*, **19,** 43–60.

Rameshwaran, P. and **Willetts, B.B.** (1999) Conveyance prediction for meandering two-stage channel flows. *Proc. Inst. Civ. Engrs Wat. Marit. Energy*, **136,** 153–166.

Schumm, S.A., Erskine, W.D. and **Tilleard, J.W.** (1996) Morphology, hydrology and evolution of the anastomosing Ovens and King Rivers, Victoria, Australia. *Geol. Soc. Am. Bull.*, **108,** 1212–1224.

Sellin, R.H.J. (1964) A laboratory investigation into the interaction between the flow in channel and that over its flood plain. *La Hoille Blanche*, **7,** 793–801.

Sellin, R.H.J. (1995) Hydraulic performance of a skewed two-stage channel. *J. Hydraul. Res.*, **33,** 43–64.

Sellin, R.H.J., Ervine, D.A. and **Willets, B.B.** (1993) Behavior of meandering two-stage channels. *Proc. Inst. Civ. Engrs Wat. Marit. Energy*, **101,** 99–111.

Smith, D.G. (1983) Anastomosed fluvial deposits: modern examples from western Canada. In: *Modern and Ancient Fluvial Systems* (Eds J. Collinson and J. Lewin), *Int. Assoc. Sedimentol. Spec. Publ.*, **6,** 155–168.

Smith, N.D. and **Pérez-Arlucea, M.** (1994) Fine-grained splay deposition in the avulsion belt of the lower Saskatchewan River, Canada. *J. Sed. Res.*, **B64,** 159–168.

Tabata, K.K. and **Hickin, E.J.** (2003) Interchannel hydraulic geometry and hydraulic efficiency of the anastomosing Columbia River, southeastern British Columbia, Canada. *Earth Surf. Proc. Land.*, **28,** 837–852.

Törnqvist, T.E., Kidder, T.R., Autin, W.J., van der Borg, K., de Jong, A.R.M., Klerks, C.J.W., Snijders, E.M.A., Storms, J.E.A., van Dam, R.L. and **Wiemann, M.C.** (1996) A revised chronology for Mississippi River subdeltas. *Science*, **273,** 1693–1696.

Velinakova, Z.M. and **Yarnykh, N.A.** (1970) Field investigations of the hydraulics of a flood plain during a high flood. *Trans. State Hydrol. Inst.*, **183,** 33–53.

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