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Elevation adjustments of paired natural levees during flooding of the Saskatchewan River

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Earth Surface Processes and Landforms

ABSTRACT: Natural levees control the exchange of water between an alluvial channel and its floodplain, but little is known about the spatial distribution and evolution of levee heights. The summer 2005 flood of the Saskatchewan River (Cumberland Marshes, east-central Saskatchewan) inundated large areas of floodplain for up to seven weeks, forming prominent new deposits on natural levees along main-stem channels. Measurements of flood-deposit thickness and crest heights of 61 levee pairs show that the thickest deposits occur on the lower pre-flood levee in 80% of the sites, though no clear relationship exists between deposit thickness and magnitude of height difference. Only 16% of the pairs displayed thicker deposits on the higher levee, half of which occurred at sites where relatively clear floodbasin waters re-entered turbid channels during general flooding. Difference in crest elevation (ΔE) between paired levees is approximately log-normally distributed, both before and after the flood, though with different mean values. Supplemental observations from tank experiments indicate that during near-bankfull flows, temporally and spatially variable deposition and erosion occur on levees due to backwater effects associated with nearby channel bars and irregular rises of the channel bed forced by channel extension. During floods, preferential deposition in lows tends to even out crest heights. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: natural levees; Saskatchewan River; flood-deposit thickness; crest heights; Cumberland Marshes

Introduction

Natural levees are low wedge-shaped ridges that border channels in most of the world's alluvial and deltaic floodplains. They are composed of mainly channel-borne sediment laid down during overbank flood events, typically highest and coarsest at the channel margins and gradually tapering and fining towards the adjacent floodbasin. The morphologies of natural levees vary considerably, both between and within floodplains (Brierley *et al.*, 1997). Widths vary from a fraction to over 10 times the channel width, with variations attributed to such factors as floodbasin width, floodbasin hydraulics, relative rates at which the basin and channel become flooded, sediment grain size, stage of development, and whether channel-to-basin dispersal is predominantly diffusive or advective (Cazanacli and Smith, 1998; Hudson and Heitmuller, 2003; Adams *et al.*, 2004; Filgueira-Rivera *et al.*, 2007; Pizzuto *et al.*, 2008). Levee height appears to develop independently of width (Filgueira-Rivera *et al.*, 2007) and is limited by the maximum water height attained during flooding. Because natural levees separate channels from their floodbasins, they affect hydrological connectivities and interactions within floodbasin-channel flow systems, including the routing of sediment, nutrients, and pollutants during flood events. Natural levees significantly influence alluvial soil development and the composition of floodplain biota (Wolfert *et al.*, 2002).

From the viewpoint of floodplain flow dynamics, crest height (and height distribution) relative to water stage is arguably the most important morphologic feature of natural levees. Low points in levees are sites of initial bank spilling, and each increment of deposition added to the levee raises the threshold of overtopping for the next flood. Continued upward growth of levees by repeated flooding may alter channel shape (Xu, 2002) and provide changing floodplain relief that continually modifies flood-flow patterns (Lewin and Hughes, 1980; Nicholas and Mitchell, 2003; Pizzuto *et al.*, 2008). On close inspection, opposing levees are rarely symmetrical, and topographic profiles of paired levees commonly show that one levee is higher than the other, though such discrepancies are rarely noted or discussed.

While examining geomorphic effects of the severe 2005 flood of the Saskatchewan River (Smith and Pérez-Arlucea, 2008), we noted (the following year, 2006) that in several surveyed channel cross-sections, thicker flood deposits tended to favor the lower of paired levees. While not unreasonable, this observation leads to a paradox – if flood deposition generally reduces elevation differences between paired levees, why were they different in the first place? After all, natural levees are

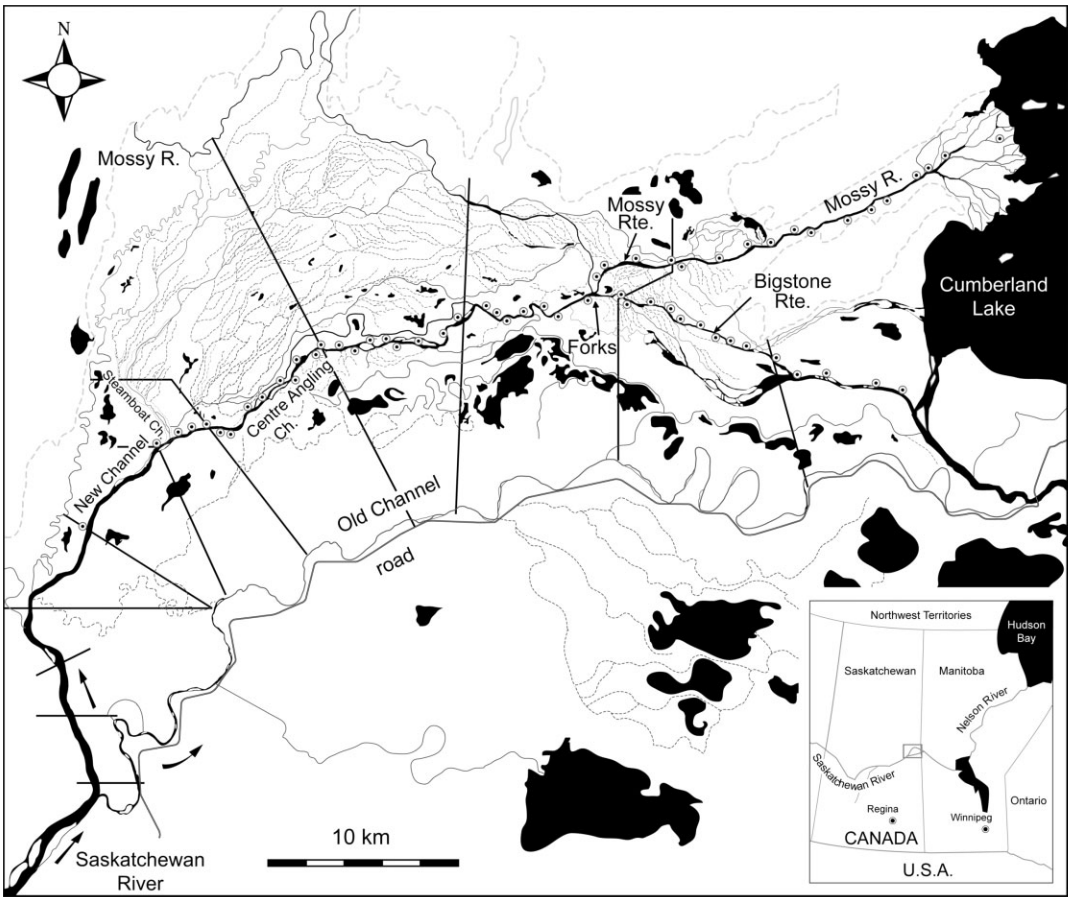

Figure 1. Map showing location of study area. The 1870s avulsion belt is the multi-channeled area north of the Old Channel, many channels of which are now abandoned or only seasonally active (dashed). Dark areas are shallow lakes. Dark straight lines indicate the Prairie Farm Rehabilitation Administration (PFRA) survey transects of the 1950s. Locations of levee pairs examined for deposits of the 2005 flood are shown in circled dots. Other survey sites used to construct Figure 4 are scattered through the avulsion belt and not shown. Flow is generally left to right.

generally thought to be formed predominantly by deposition during repeated flood events. In the following year (2007), we therefore expanded the investigation to include a larger area and larger number of paired levees to focus on three questions of natural levee development: (1) what is the normal variation of elevation differences between paired levees and what are its causes; (2) to what degree, if any, is new levee deposition affected by such differences in pre-flood elevation; (3) if deposition is affected, what are possible implications for long-term levee development and their roles in controlling channel-floodbasin interactions?

Location and the 2005 Flood

The area of investigation lies in the north-west portion of the Cumberland Marshes (also known as the Saskatchewan River delta), a large floodplain in east-central Saskatchewan and western Manitoba in south-central Canada (Figure 1). The physical setting and alluvial history of the region are described elsewhere (Kuiper, 1960; Dirschl, 1972; Morozova and Smith, 1999). The area of this study is located within the belt of alluvial deposition initiated by a northward avulsion of the Saskatchewan River from its former channel (today known as the Old Channel) in the 1870s. Accounts of the geomorphology, alluvial deposits, and avulsion evolution are given elsewhere (Smith *et al.*, 1989, 1998; Smith and Pérez-Arlucea, 1994, 2004; Pérez-Arlucea and Smith, 1999; Farrell, 2001; Morozova and Smith, 2003; Davies-Vollum and Smith, 2008). The area directly affected by the avulsion (termed avulsion belt) currently comprises ~500 km^2 of active and abandoned channels, floodbasins, and shallow lakes. Today, most of the discharge in the proximal two-thirds of the avulsion belt is carried by the contiguous New Channel and Centre Angling Channel (Figure 1). Fifty kilometers downstream from the New Channel/Old Channel bifurcation, the flow splits into two channel systems informally termed the Mossy and Bigstone routes. Avulsion-belt channels are predominantly unbraided with generally low sinuosities. Well-defined natural levees are present along nearly all channels, most of which are densely vegetated. These levees have evolved concurrently with other alluvial components of the avulsion belt and thus display a range of morphologies, sizes, and growth stages reflecting different stages of avulsion history (Cazanacli and Smith, 1998).

In June 2005, heavy rains in the upper reaches of the drainage basin in Alberta forced large releases of the E.B.Campbell Dam, located on the Saskatchewan River 31 km upstream from the Old/New Channel bifurcation, producing a controlled flood whose peak (2960 m^3/s) exceeded the annual mean discharge of the Saskatchewan River (~450 m^3/s) by over six-fold. It was the second highest flood for this reach since discharge records were begun in 1962. Except for relatively high-banked upper reaches of the New Channel, the flood inundated the entire avulsion belt, in some areas for up to seven weeks (Figure 2). After flows returned to normal in mid-August, new natural levee deposits (Figure 3A) were prominently displayed on the tops of channel banks from mid reaches of the New Channel to Cumberland Lake along both the Bigstone

Figure 2. South-eastward view of the Bigstone Route on June 25, 2005, several days before the flood maximum in this region of the floodplain. Photograph was taken from approximately the location of the Forks (out of view beneath camera), and Cumberland Lake lies just beyond view in background (Figure 1). Dark lines across principal channel (center right) indicate locations of six sampled levee pairs (dark forested areas along channel margins). Flow is generally away from observer (arrow).

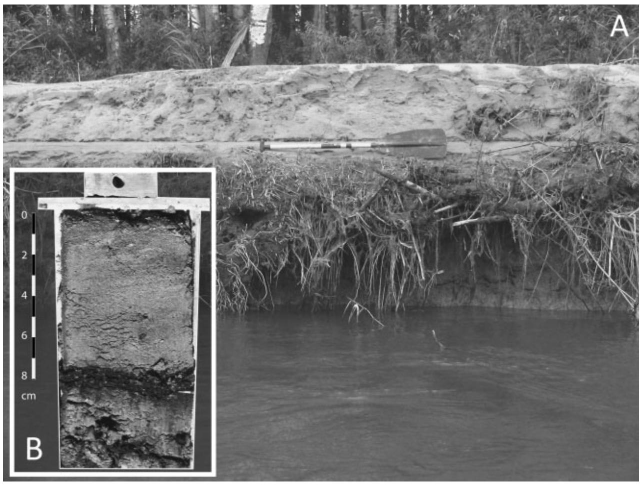

Figure 3. Photographs of 2005 flood deposits. (A) Thick deposit of fine and very fine sand overlying vegetated levee surface. Note dense tree cover in background. Paddle is 1·3 m long. (B) Upper portion of sampling device showing abrupt contact between coarse silt flood deposit (0–7 cm) and older levee sediment, including dark humic layer (7–8 cm) representing the pre-flood levee surface.

and Mossy routes, distances of approximately 50 and 55 km, respectively. A more detailed account of the flood is given by Smith and Pérez-Arlucea (2008).

Measurements

Flood-deposit thicknesses and relative heights were measured in the highest parts of opposing levees, usually occurring within 2–3 m of the channel banks, at 61 locations, most of which were spaced at ~1–2 km intervals (average 1·2 km) along the main-stem reaches between the New Channel and Cumberland Lake (Figure 1). All sample locations were inundated by the 2005 flood. At most sites, the flood deposits were sampled with a Turf-Tec™ soil profile sampler which returns a flat $18 \times 7 \times 2$ cm^2 rectangular slice of sediment (Figure 3B). Where flood-deposit thickness exceeded 18 cm, sampling was completed by gouge auger or trenching. Deposit thicknesses were averaged for four to seven measurements at each site. Height difference between paired levee crests was measured as their difference in heights above channel water surface, assumed to be a horizontal datum for that site. Pre-flood heights were determined by subtracting flood-deposit thicknesses from post-flood heights. Difference in paired levee heights was recorded as elevation difference (ΔE) in order to avoid confusion with the common practice of defining levee height as the vertical distance between levee crest and floodbasin surface (e.g. Adams *et al.*, 2004). The 2005 flood deposits were readily distinguished from older alluvium by their fresh appearance and sharp basal contacts with underlying material (Figure 3). Although sampling was done in July 2007, no significant flooding had occurred in the two-year interim to modify or disrupt the 2005 deposits.

To estimate the distribution of ΔE values for the entire avulsion belt, three sources of data were utilized: (a) topographic profiles surveyed by the Prairie Farm Rehabilitation Administration (PFRA) in the 1950s (PFRA, 1954) ($n = 80$); (b) topographic profiles surveyed in this and earlier investigations ($n = 98$), some of which appear elsewhere (e.g. Smith and Pérez-Arlucea, 1994; Cazanacli and Smith, 1998; Pérez-Arlucea and Smith, 1999; Lazar, 2002); (c) relative elevations of paired levee crests measured as height above water surface ($n = 64$), including most sites of the current investigation. From these three sources, ΔE values were obtained for 242 levee pairs within and bordering the avulsion belt. Channel widths at measurement sites ranged from 8 to 564 m, with the majority (77%) less than 150 m.

ΔE and Flood Deposits

Because large channels can normally be expected to have larger levees and therefore greater ranges of ΔE than small channels in the same floodplain, the 242 levee pairs were divided into four groups defined by channel width, and their ΔE frequencies were plotted in 10-cm class intervals (Figure 4). The distributions of the four width classes cluster at low ΔE values and skew toward higher values, with average ΔE increasing with channel size. The three smaller groups show quite similar distributions of ΔE, but because the largest class (>150 m) also comprises the greatest range of channel widths (150–564 m), its distribution is unsurprisingly the least regular. About one-quarter of the total population of paired levees display crest elevations within 10 cm of each other, and approximately half differ by more than 20 cm. The arithmetic mean value of ΔE for the whole population is 25 cm. Such differences assure that bank spilling and overbank returns are irregularly distributed during changing flood stages, and that intervals of levee-crest submergence are similarly varied.

The 2005 flood deposits on the 61 sampled levee pairs (122 individual levees) along the main-stem reaches (Figure 1) ranged from predominantly fine silt to fine sand. Most deposits appeared massive or faintly laminated, but some sandy deposits contained ripple laminations or small-scale cross stratification. Flood-deposit thickness for each levee site was plotted against pre-flood ΔE and identified as either the lower or the higher member of the pair (Figure 5). Three features of the plot are notable:

(1) Mean thickness varies widely for both higher and lower levees of pairs, including 10 individuals (8%) with zero thickness.

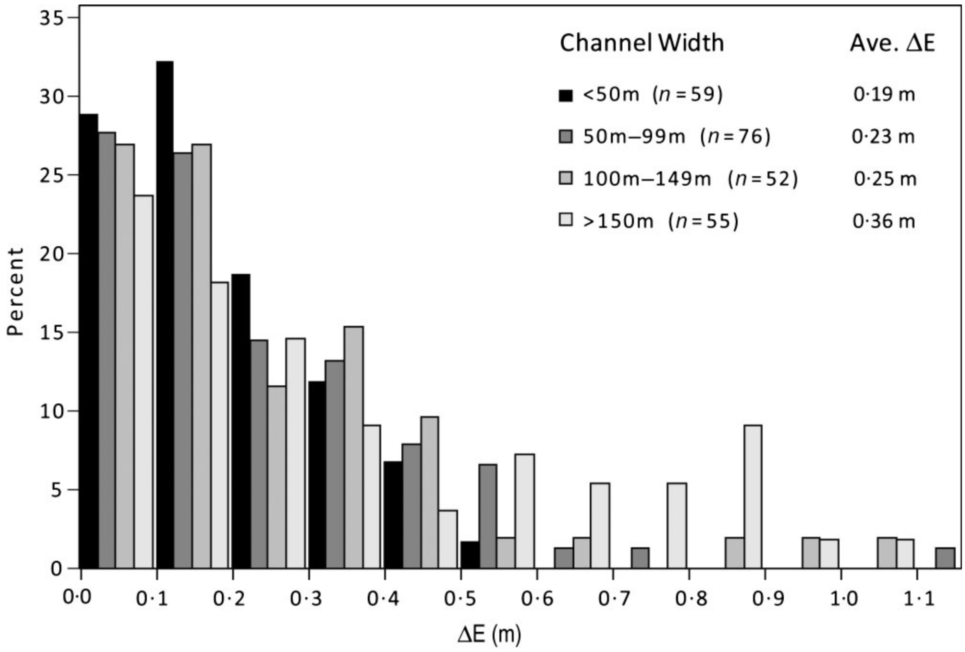

Figure 4. Distribution of elevation differences (Δ*E*) between crests of opposed levees of variously sized channels in the Cumberland Marshes avulsion belt. Note that average Δ*E* increases with channel size.

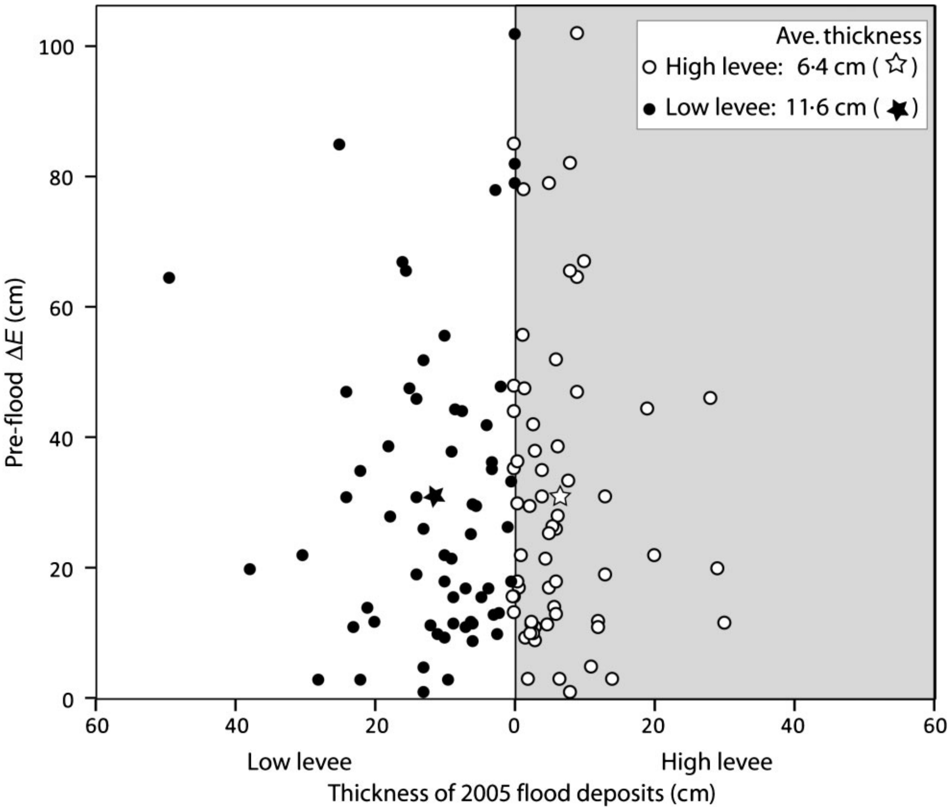

Figure 5. Distribution of pre-flood elevation differences (Δ*E*) and flood-deposit thicknesses for lower versus higher levees of 61 pairs (total 122 points). Note that magnitude of pre-flood Δ*E* appears to have little influence on flood-deposit variations or differences, but that the lower levees of pairs tend to accumulate thicker deposits than their higher opposites.

(2) In most pairs, the lower levee has the thickest flood deposit. This is shown both in their greater mean thickness (11·6 versus 6·4 cm) and in their larger range of thickness values (e.g. 12 of the lower levees have thicknesses exceeding 20 cm compared to only three of the higher levees).

(3) No clear relationship exists between deposit thickness and magnitude of pre-flood Δ*E*. Simply being higher or lower appears to affect relative thickness more than how much higher or lower a levee lies.

The effects of deposition on relative levee elevation are illustrated by a plot of pre-flood versus post-flood Δ*E* (Figure 6). Only two of the 61 pairs experienced equal deposition (nearest centimeter) on both levees and thus fall on the diagonal $x = y$ line. The majority of pairs (46, or 75%,) plot

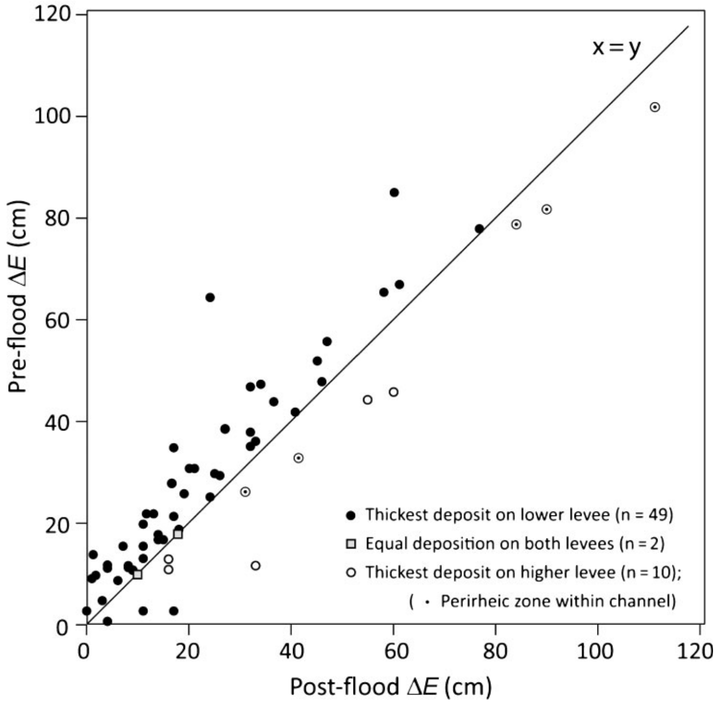

Figure 6. Plot of pre-flood versus post-flood ΔE showing tendency for thicker flood deposits to occur on lower levees and overall reduction of ΔE (i.e. most points lie above line of equality). Only 10 sites show thickest deposits on the higher levee, five of which occurred where turbid flood water overlaid only one levee due to channelward intrusion of clear water from the adjacent floodbasin (circled dots).

above the line of equality, representing thicker deposits on the lower levee and reduced ΔE after the flood. Thirteen pairs (21%) plot below the line, indicating that ΔE was increased by flood deposition. Of these 13, however, three points actually represent pairs with thicker deposits on lower pre-flood levees except that deposition exceeded the pre-flood ΔE enough to create a larger post-flood ΔE that reversed the order of relative elevation. In all, the thickest flood deposits occurred on the lower pre-flood levee in 49 (80%) of the 61 pairs.

Only 10 pairs (16%) contained thickest deposits on the higher pre-flood levee. Of those 10, five are explainable from observations made during a reconnaissance overflight of the avulsion belt on June 25, 2005, two days after inflow discharge had peaked and floodplain inundation was general. In each of the two reaches, one in the Bigstone route (5 km long, three consecutive sample sites) and the other in the Mossy route (3 km long, two consecutive sites), we observed relatively clear floodbasin water entering the turbid channel across one of the flooded banks along a linear front parallel to the channel axis. The zone of intermixing of the two water masses was situated close to the entry bank but positioned within the channel so that the entry bank was covered by clear water while the opposite bank laid under turbid water displaced from the channel by the intruding clear-water mass (Smith and Pérez-Arlucea, 2008). Analogous situations are described by Mertes (1997, 2000, her perirheic zone) and Aalto *et al.* (2003). In each of the five levee pairs later sampled and measured in these two reaches, the clear-water bank was observed to be the lower levee and displaying the thinnest deposits (1, 1, 0, 0, 0 cm for the five low levees; 6, 8, 5, 8, 9 cm, respectively, for the high opposing levees). Post-flood ΔE thus increased in each of these five sites (tagged points in Figure 6). [Note: In the previous field season, 2006, we measured flood-deposit thickness in three additional levee pairs in these two reaches, confirming the same relationship between turbidity and flood-deposit thickness (Smith and Pérez-Arlucea, 2008: figure 11), but did not measure levee heights because we were unaware of its significance at that time.] Mean values of pre- and post-flood ΔE for the 61 levee pairs are as follows: pre-flood = 30·7 cm; post-flood = 26·9 cm, a reduction of 12%. A simple *t*-test shows that the probability of the difference between the two mean values (3·8 cm) being random is $p < 0{\cdot}002$. If the five sites involving channelward intrusion of clear floodbasin water are removed, mean post-flood decrease in ΔE for the remaining 56 levee pairs is 17%.

To better understand the causes of levee height variation, we also analyzed elevations of levees constructed in physical modeling experiments of delta systems in a 3 m by 5 m tank of standing water approximately 4 cm deep and with no allogenic forcing. This is an appropriate analog to the Cumberland Marshes field area because most levees in the Marshes were initiated during progradational phases of an avulsion wedge into relatively free-standing water ponded on a floodplain (Smith *et al.*, 1998; Pérez-Arlucea and Smith, 1999). A steady uniform mixture of water and sediment was introduced through a fixed 0·038 m wide channel located at the center of a wall. The sediment mixture ranged from bentonite clay to coarse sand and was combined with a small amount of stabilizing polymer to reproduce the dynamics of fine-grained, cohesive deltas. For fuller discussion of the methodology and scaling issues, see Hoyal and Sheets (2009). Delta lobe growth in these experiments consisted of two stages – an initial stage of extension (Stage I) in which flows in the channel are routinely at bankfull or slightly higher, and a later stage of stagnation (Stage II) when a morphodynamic backwater traveled upstream and produced generalized overbank flooding. A morphodynamic backwater is similar to an ordinary hydrodynamic backwater except that it propagates upstream due to sediment deposition [see Hoyal and Sheets (2009) for more details].

Values of ΔE were calculated for 236 levee pairs measured instantaneously at different times and locations during Stages I (~bankfull) and II (general flooding), then normalized by

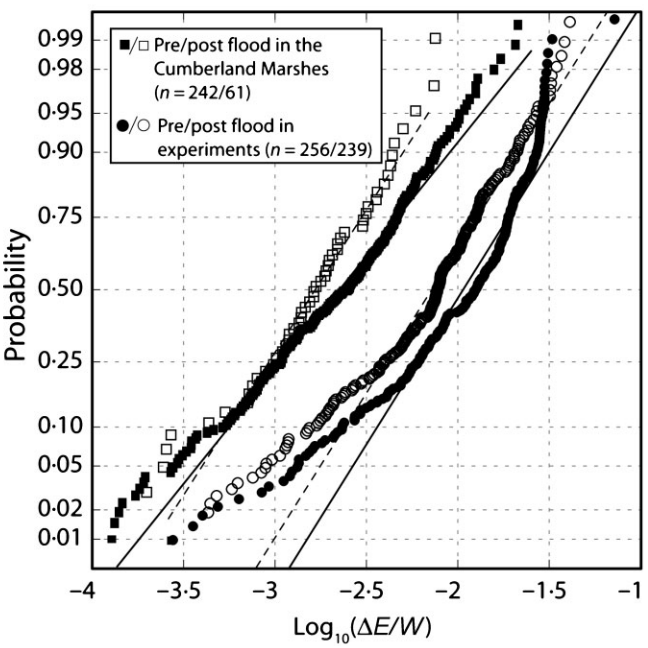

Figure 7. Probability plot of elevation differences (ΔE) between paired levees normalized by local channel width (W). Squares represent Cumberland Marshes field observations; circles represent data from tank experiments. Both datasets show similar deviations from log normality, being over-represented in the tails. Both also show that floods tend to reduce ΔE values.

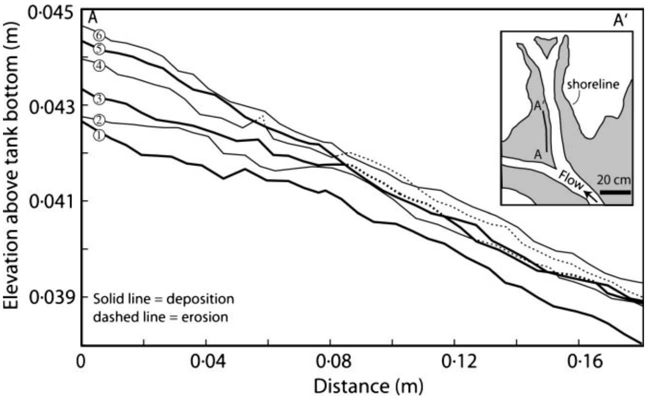

Figure 8. Topographic profiles along one levee (A–A′, inset) of a distributary channel during progradation of experimental delta. Profiles 1–6 are numbered consecutively through time with Δt intervals of approximately 40 min. Every other profile has a thicker line weight to make it easier to follow through. Note that levee alluviation is not uniform but instead experiences periods of increasing relief, then relief reduction, through combinations of preferential deposition and erosion. See text for more details.

local channel width (W). To compare field with tank measurements, data depicted in Figures 4 and 6 were recast and likewise normalized by channel width. The normalized ΔE distributions of both plots are roughly log-normal for both pre- and post-flood conditions (Figure 7). Their shapes are similar, although the means of the tank distributions are larger, possibly due to scaling factors or material property differences. The origin of the ΔE distributions in the tank experiments is revealed in a plot of longitudinal profiles along a segment of a levee crest as a function of time (Figure 8). Initially, deposition is continuous but non-uniform along the levee ($t_1 < t < t_2$), then fills upstream lows ($t_2 < t < t_3$), and then becomes continuous again ($t_3 < t < t_4$). This is followed by a period of upstream deposition and downstream erosion ($t_4 < t < t_5$) and finally ($t_5 < t < t_6$), a thin cap is deposited almost everywhere along the crest. Simultaneous observations of the water surface show that the causes of this temporally and spatially variable deposition and erosion are a combination of backwaters from in-channel bar growth and removal, super-elevations of the water surface from flow curvature around bars (e.g. location of levee profile in Figure 8), and irregular rises of the channel bed necessitated by channel extension. After general flooding during Stage II, the experimental levees also experienced a reduction in mean normalized ΔE (Figure 7) similar to the field observations. In the tank experiments, this occurred because low points in the levee crests tap waters from deeper in the channel containing higher sediment concentrations.

Discussion

Unequal elevations of paired levees are commonly depicted in topographic cross-sections (e.g. Wolman and Leopold, 1957; Speight, 1965; Coleman, 1969; Iseya and Ikeda, 1989; Brizga and Finlayson, 1990; Makaske, 1998; Makaske *et al.*, 2002; Adams *et al.*, 2004), but rarely pointed out or discussed. We do not know if ΔE distributions for levees in other regions or floodplains resemble those of Figures 4–7, but in any case, it is likely that significant elevation differences between paired levees are common features of alluvial floodplains and are likely to behave in similar ways. The results herein indicate a tendency for the lower levee of a pair to preferentially aggrade during a single large flood and thus reduce the elevation difference between them. If this is a characteristic result of all floods, the anticipated outcome would be a general evening-out of crest elevations as levees mature, in some cases ‘over-evening’ as suggested by three sites in Figure 6 (solid points below line), but nevertheless tending toward elevations that differ only slightly within pairs. Such trends would tend to modify the spatial patterns of floodplain inundation through time as well as affect the interactions between channel and floodbasin water masses during floods.

As we did not make on-site measurements during the 2005 flood, we can only speculate on the cause of the low-levee/high-deposition association which to our knowledge has not been previously reported for levee pairs where both crests were inundated. A simple explanation is that the lower levee is submerged for a longer interval and thus able to receive water-borne sediment for a longer time. Also, because the lower levee is the first to overspill during rising stages, it is more likely to receive early peaks of high suspended sediment concentrations which commonly precede discharge peaks on rising limbs of flood hydrographs (Wood, 1977; Bogen, 1980; Sidle and Campbell, 1985; Iseya, 1989). Neither mechanism, however, explains why some lower levees aggrade to heights that exceed their opposite, nor why magnitude of ΔE appears to have little effect on deposit thicknesses (Figure 5). Clearly, other processes are involved.

In contrast to this ‘smoothing’ tendency of flood deposition to reduce ΔE, other factors must have operated to create unequal pre-flood elevations in the first place. For convenience of discussion, such ΔE-increasing factors can be cast into two groups: (A) those that operate during major flooding, particularly preferential deposition on higher levees, and (B) those not confined to major flood events, such as observed in the tank experiments. Of the first group, one process observed herein – intrusion of clear overbank floodwater across one levee into a turbid channel – favors deposition on the opposing levee, and repeated flooding under similar conditions would continually increase the relative height of the higher levee. Of the 10 pairs (16%) that displayed thicker flood deposits on the higher pre-flood levee, half can be explained, at least partially, by this mechanism. For the remaining five pairs (8%), other factors that might lead to preferential deposition on higher levees include: (1) fluctuations in in-channel sediment sourcing accompanying channel deepening or widening (Smith and Pérez-Arlucea, 2008), (2) fluctuations in flow velocity and/or eddying near levee/channel interfaces, resulting in momentarily higher suspended sediment loads; (3) effects of varying channel geometries, especially at or near bends; (4) varying baffling effects resulting from different patterns and densities of bank vegetation; (5) floodplain topography that draws more flow off one side of a channel than the other regardless of relative levee height; (6) lodgment of large woody debris on bank tops that traps and mounds suspended sediment (McCloy, 1970). In addition, increased ΔE could arise simply from surficial erosion of the lower levee.

Although these (or other) flood-related processes increased ΔE for a few levee pairs during the 2005 event, their average effects on the whole system of levees were surpassed by the far greater proportion of thicker deposits left on lower levees. In the long term then, average ΔE will become smaller with time if levee heights are modified mainly during large floods. What factors (group B) may have operated to increase differences in paired levee heights at other times, i.e. between major floods? Using the tank experiments as a guide, we conjecture that many years of bankfull or slightly greater than bankfull discharge may increase ΔE by either erosion or deposition (Figure 8) through a combination of backwaters from in-channel bar growth and removal, super-elevations of the water surface from flow curvature around bars, and irregular rises of the channel bed necessitated by channel extension. There are other possible mechanisms as well. One is differential compaction beneath paired levees (van Asselen and Stouthamer, 2008), especially since most of the avulsion belt overlies easily compacted peat deposits representing the floodplain surface prior to the 1870s avulsion (Smith *et al.*, 1989; Morozova and Smith, 2003; Smith and Pérez-Arlucea, 2004). Another possibility is the varied erosional and depositional effects of ice drives and ice jams on channel and floodplain morphology (Smith, 1979, 1980; Smith and Pearce, 2002), which have occurred frequently in the Saskatchewan River, though have become less effective in recent years due to effects of hydroelectric power dams. Large differences in heights of paired levees can also result from eolian deposition where nearby sand bars are exposed (McCloy, 1970), though its effect on Saskatchewan River levees is uncertain. Another non-flood process that potentially increases ΔE, one that we have observed directly, results from lateral channel erosion – because levees are typically highest at channel margins, lateral erosion (by channel migration or simple widening) exposes progressively lower portions of a levee surface, thereby altering height difference with its opposite. This process is particularly common in the Centre Angling Channel which in places has more than doubled in width in the past several decades due to flow capture from the Steamboat Channel (Figure 1).

The most likely factor that yields unequal levee heights on temporally and spatially larger scales, however, is that in an evolving alluvial landscape like that of the 1870s avulsion belt, evolving topography provides a continually changing surface on which natural levees initiate, develop, and in most cases eventually become abandoned (e.g. most of the levees intersected by the PFRA survey lines in Figure 1). For example, a previously stable channel with well-developed levees of near-equal heights may at some point begin to shift laterally, cutting into one levee and essentially abandoning the other as a lateral or side bar develops in the widened channel space. In time, the bar may become stabilized by vegetation and a new levee initiated. At that time, ΔE of the then-current levee pair would likely be larger than that of the original pair. If the observations of this study generally apply, the new levee on the vegetated bar will preferentially aggrade, reducing ΔE with successive floods. Many variations of scenarios involving lateral erosion, bar formation/stabilization, and development of new levees are possible, and so any survey involving a sample of randomly selected levee pairs is likely to include some in which the paired levees have different heights that reflect substantially different histories. An analogous situation is described by Moody *et al.* (1999) in a study of floodplain development following the 1978 flood of the Powder River, USA. The channel was significantly widened by the flood, and new vertically accreted floodplain deposits, including natural levees, are presently developing in different locations and at different rates on the flood-widened channel surface.

While the 2005 flood resulted in overall reduction of ΔE between paired levees, we do not know if this is part of a consistent trend toward increasing uniformity in levee height throughout the avulsion-affected floodplain (i.e. Figure 4 continually shifts towards lower ΔE values with time) or whether flood-induced reductions in ΔE are continuously countered and balanced by other factors that increase ΔE at other times (i.e. Figure 4 approximately represents ΔE distribution through time). Both interpretations bear on the character of the still-evolving avulsion belt, now active for over a century but winding down and approaching a quasi-stable single-channel stage (Smith *et al.*, 1989, 1998). The choice, namely, whether the levees are still evolving toward further minimization of ΔE or whether a balance between ΔE-increasing and ΔE-decreasing processes is already attained, cannot be made at this time. A perturbing factor of unknown significance is the E.B.Campbell Dam, which impounds most river-borne sediment that would ordinarily be carried into the New Channel. Resulting sediment deprivation has caused widening and deepening of some downstream channel reaches whose erosion in turn have provided much of the sediment for present-day levee deposition (Smith and Pérez-Arlucea, 2008, and unpublished data). We do not think, however, that such in-channel sediment sourcing has affected the main observations of this study.

Conclusions

Whereas natural levees are ubiquitous features of alluvial floodplains and known to occur in a great variety of sizes and shapes, details of their morphologic development are comparatively scarce. We have shown that during a single large flood of the Saskatchewan River, 80% of the levee pairs sampled along active channels displayed thicker flood deposits on the lower of the two opposed levees, resulting in an average reduction of ΔE of 12%. If levee sites characterized by floodbasin return flows are omitted, average post-flood ΔE is 17% lower than the pre-flood average. Such changes are likely to affect patterns of spilling thresholds and channel-floodbasin interactions for subsequent flood events. It cannot be ascertained, however, whether the observed one-flood reductions in levee-height differences represent part of a continuous trend toward minimizing ΔE or whether it is more of a ‘steady-state’ process in which, on the longer term, increases and decreases of ΔE are roughly balanced, especially by processes that occur at times other than major floods. Tank experiments appear to support the latter view in that repeated flows at or near bankfull stage tended to amplify differences in ΔE.

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