Restoration of Dynamic Flood Plain Topography and Riparian Vegetation Establishment Through Engineered Levee Breaching

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ABSTRACT. The Cosumnes River watershed (3000 km^2) drains the western slope of the Sierra Nevada in California. The extensive flood plains of the lower Cosumnes occur in the Central Valley, just upstream of the San Francisco Bay-Delta The Cosumnes River and its flood plain have been managed for agricultural purposes for more than a century. The river channel is currently lined by close agricultural levees that restrict the river to a single, low-sinuosity channel that has incised as much as 5 m in some reaches. The goal of restoration efforts on the Cosumnes Preserve is to re-establish the physical processes that create and sustain flood plain and wetland ecosystems. Integral to this effort is the restoration of adequate duration, depth, frequency and timing of flood plain inundation. Engineered levee breaches on the lower Cosumnes River, Central California, appear to promote processes that replicate a network of main and secondary distributary channels (*crevasse splay complexes*) that transport sediment during moderate to low flood stages typical in large, lowland rivers. Depending upon geometry, location and sediment transport rates, engineered breaches create hydrologic and geomorphic conditions necessary to construct dynamic sand splay complexes on the flood plain adjacent to the breach opening. The main channel is bounded by lateral levees formed by deposition in the low velocity separation eddies that flank the breach opening. The levees decrease in elevation down-flood plain and are separated into depositional lobes by incision of secondary distributary channels. The lateral levees and depositional lobes of the sand splay complexes govern distribution of dense, fast-growing cottonwood (*Populus fremontii*) and willow (*Salix spp.*) stands. In turn, establishment and growth of these plants plays a major role in the dynamic topography of sand splay complexes. Where established, cottonwoodwillow patches increase erosional resistance and roughness, and promote local sedimentation. All cottonwoods and willows established in the first spring following construction of the nearest breach. Successful establishment may be controlled by late spring flooding, the presence of abundant bare ground prior to flooding, or both.

INTRODUCTION

With the exception of a handful of tropical and high latitude rivers, the hydrology and topography of flood plains of the developed and developing world have been extensively altered to support agriculture, navigation, and flood control. The loss of the seasonal flood pulse and the widespread conversion of riparian, wetland and flood plain habitats has degraded ecosystem integrity and related ecosystem services in the world's river systems (Toth et al., 1993; Cushing and Cummings, 1995; Power et al., 1995, Vitousek et al., 1997). In the past decade there has been an increasing emphasis on restoration, or more specifically rehabilitation of flood plain ecosystems in large, lowland rivers by reestablishing the key physical drivers that sustain ecosystem integrity (Galat et al., 1998). This includes not only restoring the hydraulic connectivity between the river channel and its flood plain, but promoting the processes of erosion and deposition that create dynamic flood plain topography (Stanford et al., 1996; Florsheim and Mount, in press).

In this paper we report on the use of engineered levee breaches to restore hydraulic connectivity and dynamic flood plain topography within an experimental restoration site on the Cosumnes River in the Central Valley, California, USA (Fig. 1). This work demonstrates the utility of engineered breaches in mimicking processes typically associated with avulsion and the formation of crevasse splays at natural levee breaches in anabranching rivers or delta systems (Boyer et al., 1997). Depending upon design and hydraulic conditions, sediment transport through the engineered breaches during floods creates prograding, dynamic sand splay complexes. The deposition and modification of the sand splay complexes promotes the establishment of riparian forests and strongly controls their growth rates.

COSUMNES RIVER FLOOD PLAIN

The Cosumnes River watershed (3000 km^2) drains the western slope of the Sierra Nevada in California. The extensive flood plains of the lower Cosumnes occur in the Central Valley, just upstream of the San Francisco Bay-Delta (Fig.1).

Prior to the arrival of European settlers in the mid-late 1800's, the lower Cosumnes River occupied a broad, low-energy cohesive flood plain with low-gradient, laterally stable anastomosing channels (Florsheim and Mount, in press). The river and flood plain supported a mosaic of successional cottonwood-willow (*Populus fremonti and Salix sp*) riparian forests, climax oak forests (*Quercus lobata*), and emergent wetland communities (reference TBI?). Flooding occurred annually between October and June, even during dry years. Large floods capable of significant sediment transport and flood plain scour and deposition occurred during winter months, typically December through February, in response to rainfall and rain-onsnow events. During years with above average snowpack, sustained low-intensity spring snowmelt floods inundated the flood plain between April and early June.

The Cosumnes River and its flood plain have been managed for agricultural purposes for more than a century. The river channel is currently lined by close agricultural levees that restrict the river to a single, low-sinuosity channel that has incised as much as 5 m in some reaches. The levees are capable of containing moderate flood flows with exceedance probabilities of approximately .2 or higher. The historic flood plain has been cleared, graded and leveled for agriculture purposes, eliminating the original flood plain topography and plant communities. Discontinuous, remnant oak and cottonwoodwillow riparian forests occur in areas of limited agricultural activity close to the river and along sloughs.

The Cosumnes River is distinguished from all other large Sierra Nevada rivers by its lack of large water retention structures and limited number of surface diversions. The winter and spring flow regime on this river remains largely unregulated and intact, with significant seasonal flooding. The flood of record on the Cosumnes occurred in January of 1997 and reached 2346 m^3/s (exceedance probability of <.01: Guay et al., 1998); the mean annual flood is 43 m^3/sec.

RESTORATION OF FLOOD PLAIN ECOSYSTEM ATTRIBUTES

The California Nature Conservancy, along with its partners in the Cosumnes River Preserve, have been conducting an extensive restoration program in the lower Cosumnes River that focuses on wildlife-friendly agriculture and restoration of riparian, flood plain and wetland habitats (Andrews, 1999; TNC 2000). Based on observations of successful establishment of riparian forests on sand splay deposits formed by historic levee failures, the Preserve partners experimented with intentional levee breaching. To date, two engineered breaches have been constructed on the lower Preserve. The first breach, termed the Accidental Forest Breach (for a nearby forest formed by an earlier levee breach) was constructed in October 1995. The second, termed the Corps Breach (for the US Army Corps of Engineers) was completed during October of 1997. Both breaches discharge water and sediment onto former agricultural fields that have been graded and leveled. However, the flood plain at the Corps Breach has a low setback berm that deflects flows away from adjoining rice fields, and an excavated 2 m deep "wildlife pond" (Fig. 2).

Hydraulic Connectivity

The goal of restoration efforts on the Cosumnes Preserve is to re-establish the physical processes that create and sustain flood plain and wetland ecosystems. Integral to this effort is the restoration of adequate duration, depth, frequency and timing of flood plain inundation. Based on numerous field observations and

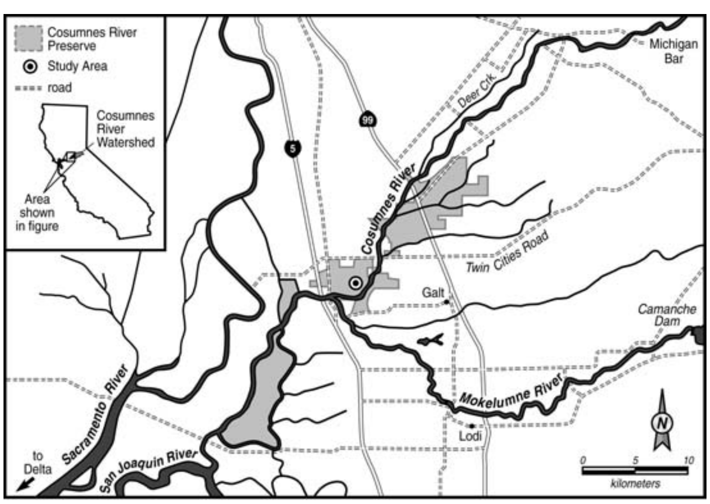

FIGURE 1. Lower Cosumnes River study area from Michigan Bar to the San Francisco Bay-Delta denoting levee breach study area.

FIGURE 1: Mount, Florsheim and Trowbridge.

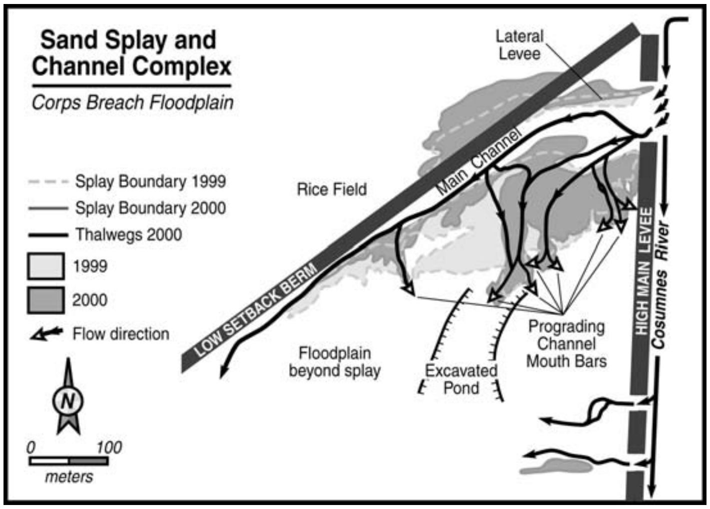

FIGURE 2. Generalized geomorphic map of the Corps Breach constructed during Fall of 1997. Note complex topography and growth patterns of sand splay complex due to set back levee (from Florsheim and Mount, in press).

FIGURE 2: Mount, Florsheim and Trowbridge.

TABLE 1: Floodplain inundation of the lower Cosumnes River, 1996-2000.

Water Year	Date of First Flood Flows	Number of Flood Days	Peak Q (cms)*	Date of Last Flood Flows
1995-1996	Dec 18	117	224	May 30
1996-1997	Dec 6	99	719	March 13
1997-1998	Dec 9	163	504	June 25
1998-1999	Dec 2	109	374	May 15
1999-2000	Dec 20	70	289	May 18

*Based on daily average discharge measured at Michigan Bar

surveys during the winters of 1999, 2000 and 2001, we estimate that hydraulic connectivity through the breaches occurs when flows reach 20 to 23 cms at an upstream flow gage at Michigan Bar. Flows in this range are approximately half of the mean annual flood and have an annual exceedance probability of greater than .95. The timing and duration of flood plain connectivity from water year 1996 through 2000 on the lower Cosumnes are summarized in Table 1. Of particular note are water years 1996 and 1998. Both years had sustained flooding, including 163 days in 1998, coupled with unusually late spring snowmelt floods.

When flows recede to less than 20 to 23 cms at Michigan Bar, the flood plain becomes disconnected from the channel within 24 h. Based on measurements taken in 2000, water depths on the flood plain appear to fall between 1 and 2 cm/day depending upon wind, temperature and soil moisture conditions. Highest rates of fall occur in the spring, when evaporation rates on the flood plain are highest.

Sand Splay Complexes

The two breaches examined for this study are developing elongate sand splay complexes adjacent to and down-flood plain from the breach openings (Figs. 2, 3). As described below, the complexes differ in geometry, thickness and complexity, reflecting differences in flood plain topography at the time of the breaching. Both complexes are accumulating significant volumes of sand and silt, extending as much as .5 km down-flood plain from the breach. By the end of water year 2000, the sand splay complex at the Accidental Forest Breach had accumulated approximately 11,000 m^3 of sediment, averaging 2200 m^3/year over a five year period with an areally-averaged vertical accretion rate of .04 m/yr. The Corps Breach accumulated approximately 7500 m^3 over a three-year period, averaging 2500 m^3/yr, with a vertical accretion rate of .08 m/yr.

Although the sand splay complexes differ in detail, they contain several geomorphic elements that are common to most crevasse splays seen in natural river systems (Lewin, 1973; Richards et al, 1993; Boyer et al, 1997), and where flood control levees have failed during high flows (Magilligan et al, 1998). These include distributary channels, lateral levees and depositional lobes.

Distributary Channels. A main distributary channel originates from the lowest elevation in both breaches and extends through the entire length of the sand splay complex. Each main channel contains a breach scour zone (Fig. 3) that is flanked by lateral levees. Sequential survey results indicate that the scour zone deepens following the initial opening of the breach and, over time, extends down-flood plain, maintaining a negative slope. The breach scour zone merges into a sand-bedded distributary channel.

Within the Corps Breach (Fig. 2), and to a lesser extent within the Accidental Forest Breach (Fig. 3), the main distributary channel bifurcates into one or more sand-bedded, secondary distributary or anastomosing channels, each containing a distributary mouth bar. Extension of the splay complex channels takes place through progradation of the distributary mouth bars.

Large woody debris (LWD) influences the growth and topographic diversification of the sand splay complexes. Large tree trunks and root wads transported through the levee breaches during high flow events strand within the main or distributary splay complex channels, causing local scour and deposition (Fig. 3).

Lateral Levees/Depositional Lobes. The most significant vertical accretion that occurs in sand splay complexes takes place on lateral levees that form adjacent to the main distributary channel and the breach scour (Fig. 2, 3). The levees are formed through turbulent diffusion of sand in secondary flow cells of the main distributary channel into the flow separation eddies that flank the breach opening. The construction of the lateral levees creates the maximum elevations within the splay complexes and, as is shown below, plays a key role in the

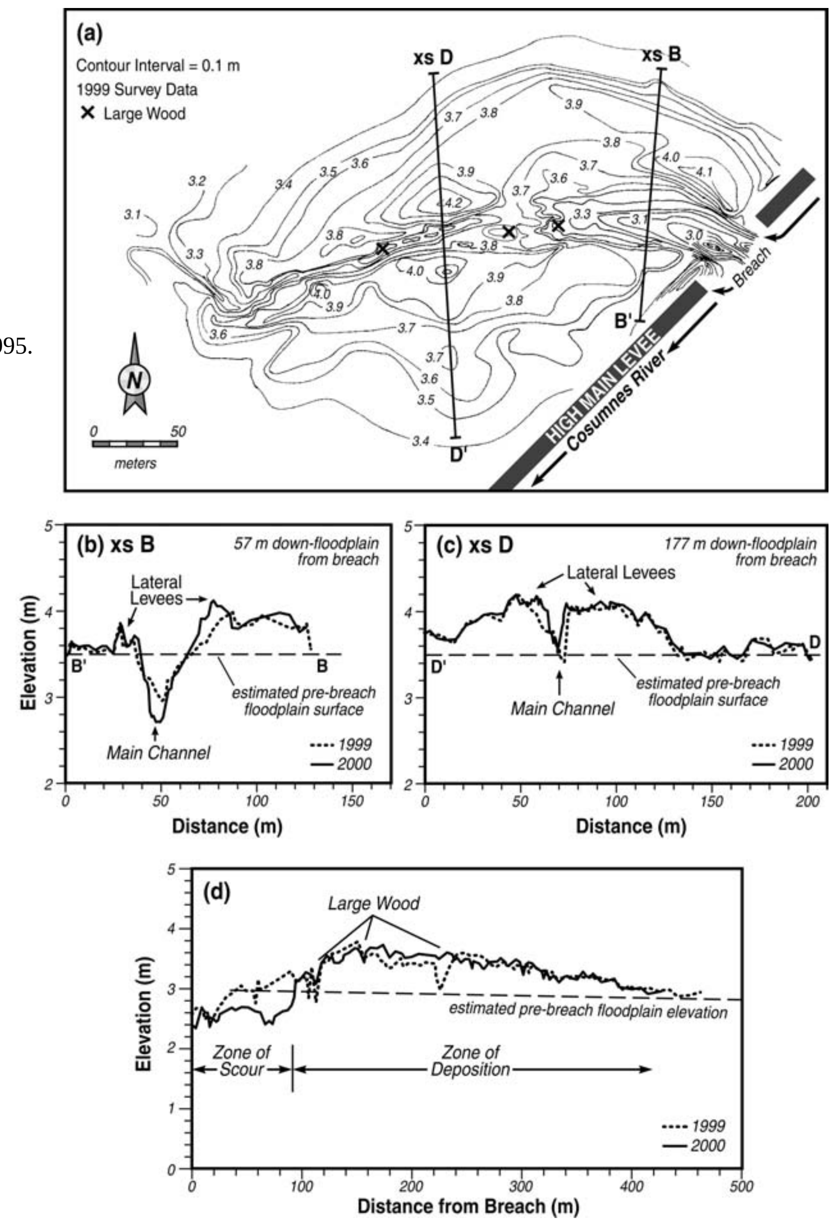

FIGURE 3. Geomorphology of sand splay complex at Accidental Forest, constructed during Fall of 1995.

establishment and growth of riparian vegetation. Based on field surveys of lateral levee elevations and high water marks, we estimate that the maximum height of accretion in lateral levees is approximately .4 the maximum depth of local flow. For this reason, the elevation and morphology of the lateral levees is strongly controlled by the maximum flood stage recorded since the opening of the breach.

The lateral levees of the splay complex decrease in elevation down-flood plain, and are separated into depositional lobes incised by distributary channels. The lobes have highly irregular topographic surfaces that are extensively modified by small overwash channels and by high velocity flows that exceed distributary channel capacity

Cottonwood-Willow Forest Establishment

The primary goal of the levee-breaching project was to re-introduce the proper hydrologic conditions and disturbance regimes necessary to promote establishment of riparian forests. Establishment, density and growth rates for three typical riparian trees—Gooding's willow (*Salix sp.*), Sandbar willow (*Salix sp.*) and Fremont cottonwood (*Populus fremonti*)—were monitored within the splay complexes and on the adjacent flood plain. Detailed results of these surveys are described in Trowbridge et al. (in prep.) and are summarized here.

The age of cottonwoods and willows at both breaches were measured during 1999 and 2001. Regardless of location, all trees sampled appear to have established during the spring following the opening of the adjacent breach: trees on the Accidental Forest splay complex established in the spring of 1996, trees on the Corps Breach complex established in spring of 1998. Highly selective recruitment is a commonly recognized characteristic of cottonwood-willow forests (Braatne et al., 1996) and is tied to their unique phenology. As Scott et al. (1996), Rood and Mahooney (1998) and others have noted, recruitment and survival of riparian trees occurs when several key factors coincide. These include: presence of exposed soil or sediment to limit competition; coincidence of declining river stage with seed dispersal (typically in late May and June, depending upon temperature); gradual decline in stage to allow roots to maintain contact with moisture zone (4–12 mm/day); sustained soil moisture over the length of the growing period (June through September); and protection from scour during subsequent flood events.

Several factors that support establishment of cottonwoods and willows appear to have cooccurred during and immediately following construction of both breaches. Both breaches were constructed during the late Fall, leaving bare, disturbed soil immediately prior to winter flows. During spring of both 1996 and 1998, the first years following the breaches, the Cosumnes River experienced unusual late season floods that coincided with the timing of seed dispersal for riparian trees (Table 1). In contrast, during 1997, 1999, and 2000, when little or no cottonwood and willow establishment occurred, spring floods did not occur past mid-May. Based on later measurements, the rate of water surface lowering is presumed to have been approximately 1-2 cm/day, supporting late spring and early summer germination and growth of the cottonwoods and willows near the breaches. Areas of moderate elevation, including areas of sand deposition in the splay complex and higher flood plain elevations near the breaches, appear to have promoted early germination and extended growth of the trees. Lower elevations of the flood plain, which remained under water during the critical seed dispersal and viability period, had limited establishment.

It should be noted that although spring 1998 had optimal conditions for dispersal and germination, there appears to have been no significant new establishment on the Accidental Forest sand splay complex (originally formed in 1996). New deposition occurred within the complex during the extended flooding of 1998, which should have promoted establishment. However, deposition took place principally within already vegetated sites where shading and competition would have limited establishment. In addition, new deposition at distal mouth bars remained submerged or continuously reworked by flows during the extended June flooding of that year, further limiting establishment

Cottonwoods and willows exhibit a range of adaptations to cope with episodic sedimentation (Braatne et al., 1996; Scott et al., 1996) that make them effective competitors in riparian and flood plain settings. These traits create a strong feedback between cottonwood-willow growth and the geomorphic evolution of the splay complexes. The patch density, distribution and growth rates of cottonwoods and willows were surveyed on selected transects of the splay complexes and the surrounding flood plain. In addition, we identified and monitored growth rates of willows and cottonwoods within 19 vegetation patches on the Corps Breach splay complex at various elevations and geomorphic conditions (Fig. 4). Although establishment occurred in a range of settings, we found that density and frequency was substantially higher within the splay and channel complex, with most growth occurring on lateral levees and depositional lobes. Local scour and/or poor soil conditions appears to reduce establishment or survivorship within the distributary channels and on the flood plain. Where establishment was successful, annual growth rates varied considerably (Fig. 4). Cottonwoods and willows average 50-75% higher annual growth rates on the sandy lateral levees and depositional lobes than in distributary channels and flood plain sites.

The higher rates of establishment and growth on the lateral levees and depositional lobes influence the hydraulics of the sand splay complex and its topographic complexity. Where sand cover is sufficient and growth rates high, we noted the development of mats of adventitious roots. These root networks act to stabilize the sand splay complex, increasing local erosional resistance. In addition, the emergent vegetation of cottonwoods and willows create substantial local drag roughness. This promotes localized sediment deposition within vegetation patches, increasing their elevation and enhancing their overall growing conditions.

During moderate to low flood stages, flow concentration in distributary channels is enhanced by the erosionally resistant, hydraulically rough vegetation patches. The increased bed shear stress and transport capacity within the distributary channels maintains or enlarges the channels through incision and, where vegetation is lacking, bank erosion. This acts to increase topographic complexity and relief within the splay complex. Additionally, the high bed load transport rates of the distributary channels promote progradation of the splay and channel complex through deposition at distributary mouth bars (Florsheim and Mount, in press).

Long-term Evolution of Splay Complexes. With the limited number of years of monitoring, it is difficult to predict the sustained evolution of the engineered breach sand splay complexes. In the near-term, the complex feedback between patterns of sedimentation and growth of riparian vegetation will presumably lead to continued vertical accretion near the breach opening and

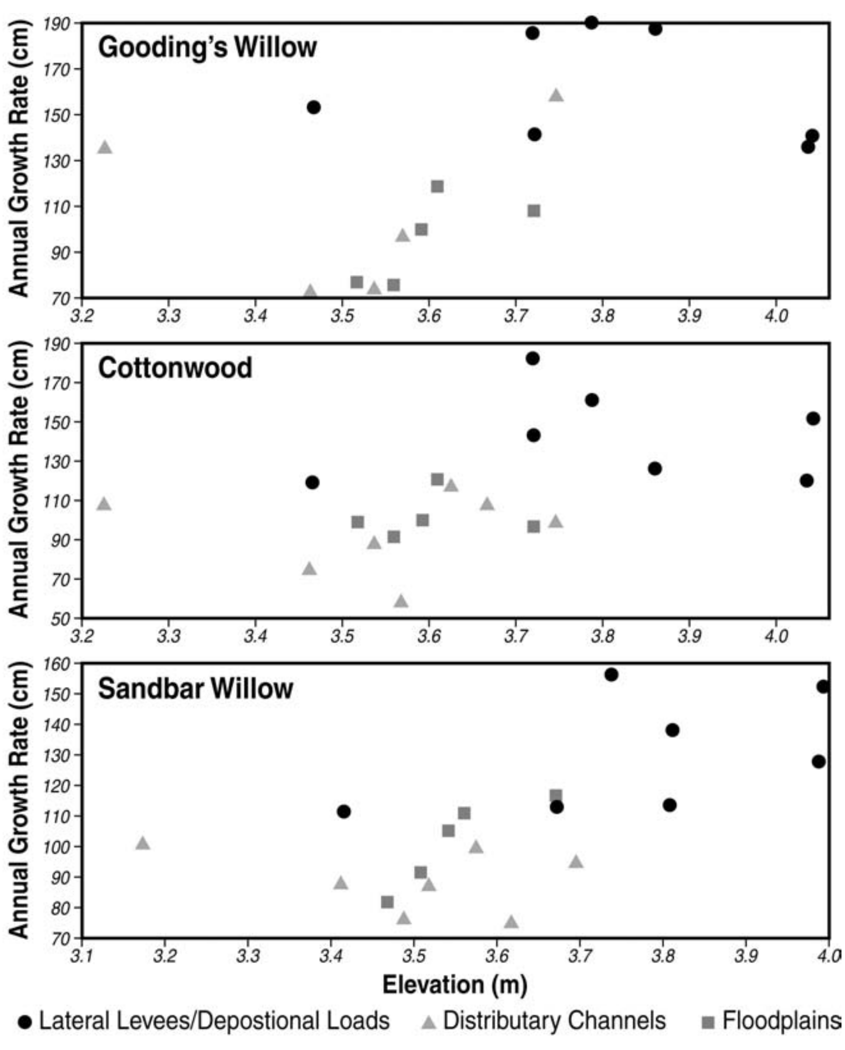

FIGURE 4. Elevation vs growth rates of cotton woods and willows within sand splay complex and adjacent floodplain. Note higher rates of growth for all three plants when located within lateral levees and depositional lobes.

down-flood plain expansion of the complex through progradation of distributary channel mouth bars. Over the long-term, depth controls on the maximum elevation of lateral levees will lead to progressive increases in progradation and lateral expansion of the complex. As overall roughness of the complex increases due to growth of vegetation sedimentation may effectively block the breach, restoring a natural levee. Conversely, continued down-flood plain expansion of the breach scour may narrow the elevational difference between the distributary channels and the main channel. This, coupled with aggradation in the main channel may promote avulsion and the establishment of a new main river channel though the splay complex.

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