Restoration of dynamic flood plain topography and riparian vegetation establishment through engineered levee breaching

JEFFREY F. MOUNT, JOAN L. FLORSHEIM & WENDY B. TROWBRIDGE

Center for Integrated Watershed Science and Management, University of California, Davis, California 95616, USA

e-mail: mount@geology.ucdavis.edu

Abstract Engineered levee breaches on the lower Cosumnes River, central California, create hydrologic and geomorphic conditions necessary to construct dynamic sand splay complexes on the flood plain. Sand splay complexes are composed of a network of main and secondary distributary channels that transport sediment during floods. The main channel is bounded by lateral levees that flank the breach opening. The levees are separated into depositional lobes by incision of secondary distributary channels. The dynamic topography governs distribution of dense, fast-growing cottonwood (*Populus fremontii*) and willow (*Salix* sp.) stands. In turn, establishment and growth of these plants influences erosional resistance and roughness, promoting local sedimentation and scour. Cottonwood and willow establishment is associated with late spring flooding and the occurrence of abundant bare ground.

Key words levee breach; flood plain; sedimentation; riparian vegetation; topography; Cosumnes River; California

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 have degraded ecosystem integrity and related ecosystem services in the world's river systems (Power *et al.*, 1995; Vitousek *et al.*, 1997; Benke *et al.*, 2000). In the past decade there has been an increasing emphasis on rehabilitation of flood plain ecosystems in large lowland rivers by re-establishing the key physical drivers that sustain ecosystem integrity (Galat *et al.*, 1998; Tockner *et al.*, 2000). This includes not only restoring the hydraulic connectivity between the river channel and its flood plain, but also promoting the processes of erosion and deposition that create dynamic flood plain topography (Stanford *et al.*, 1996; Florsheim & Mount, 2002).

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.

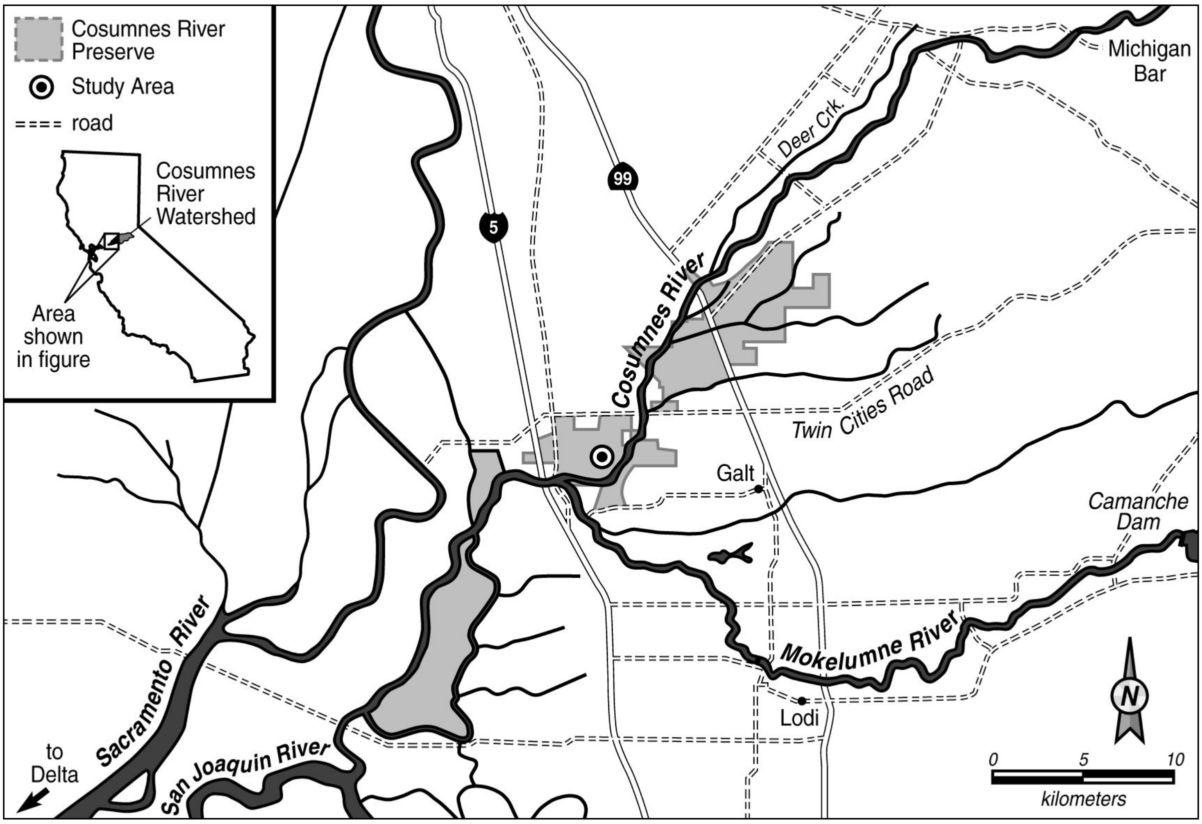

Fig. 1 Lower Cosumnes River study area from Michigan Bar to the San Francisco Bay–Delta denoting levee breach study area.

COSUMNES RIVER FLOOD PLAIN

The Cosumnes River basin (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 1800s, the lower Cosumnes River occupied a broad, low-energy cohesive flood plain with low-gradient, anastomosing channels (Florsheim & Mount, 2002). 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.

The Cosumnes River channel is currently lined by close agricultural levees that restrict the river to a single, low-sinuosity incised channel. The levees are capable of containing moderate floods with exceedance probabilities of 0.2 or higher. The historic flood plain has been cleared, graded and levelled for agriculture, eliminating the original flood plain topography and plant communities. Discontinuous, remnant oak and cottonwood–willow riparian forests occur in areas of limited agricultural activity along the river and its 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.

RESTORATION OF FLOOD PLAIN ECOSYSTEM ATTRIBUTES

The Nature Conservancy (TNC), along with its partners in the Cosumnes River Preserve, are conducting an extensive management and restoration programme 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 in two locations: the Accidental Forest Breach, constructed October 1995, and the Corps Breach, constructed October 1997. Both breaches discharge water and sediment onto former agricultural fields that were graded and levelled prior to restoration. At the Corps Breach, a low set-back berm that deflects flows away from adjoining rice fields, and an excavated 2-m-deep "wildlife pond" were graded as part of the restoration project (Fig. 2).

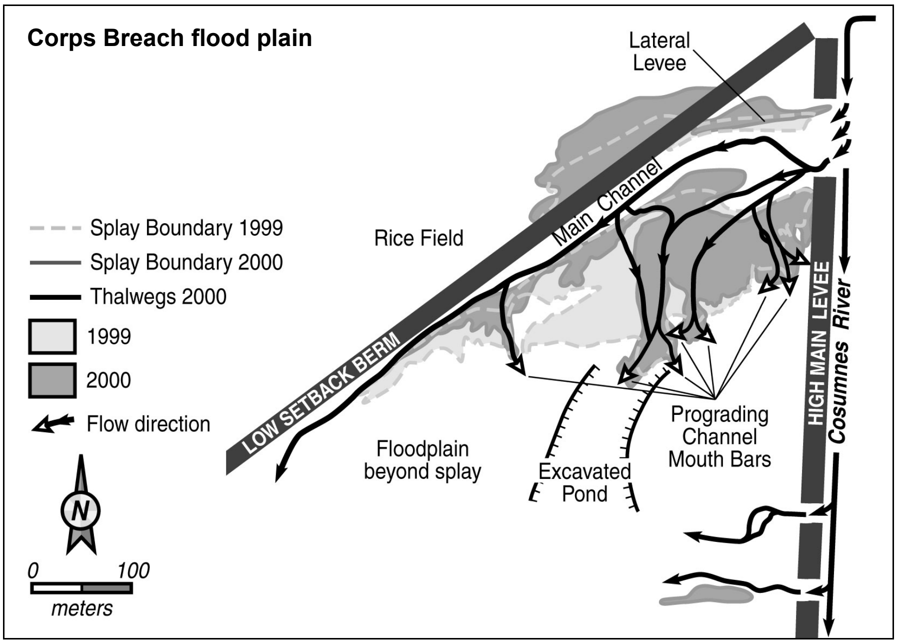

Fig. 2 Generalized geomorphic map of the Corps Breach constructed during fall of 1997. Note complex morphology and growth patterns of sand splay complex due to set back levee (modified from Florsheim & Mount, 2002).

Hydraulic connectivity

Integral to the restoration effort is the provision of adequate duration, depth, frequency and timing of flood plain inundation. Based on field observations and surveys during the winters of 1999, 2000 and 2001, we estimate that hydraulic connectivity through the breaches occurs when flows reach 20–25.5 $m^3 s^{-1}$ at an upstream flow gauge at Michigan Bar (exceedance probability of 0.95). 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 1995/96 and 1997/98. Both years had sustained flooding, coupled with unusually late spring snowmelt floods.

Table 1 Flood plain inundation of the lower Cosumnes River, 1996–2000.

Water year*	Date of first flood flows	Number of flood days	Peak Q†	Date of last flood flows
1995/96	18 December	117	224	30 May
1996/97	6 December	99	719	13 March
1997/98	9 December	163	504	25 June
1998/99	2 December	109	374	15 May
1999/2000	20 December	70	289	18 May

* Water years extend from 1 October to 30 September.
† Based on daily average discharge measured at Michigan Bar, $m^3\ s^{-1}$.

When flows recede to less than 20–25.5 $m^3\ s^{-1}$ 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 fall between 1 and 2 cm day^{-1} depending upon wind, temperature and soil moisture.

Sand splay complexes

At the two study areas, elongate sand splay complexes are developing adjacent to and down-flood plain from the breach openings (Figs 2, 3). The two complexes differ in geometry, thickness and complexity, reflecting differences in initial grading of the restoration sites prior to breaching. Both complexes are accumulating significant volumes of sediment, extending as much as 0.5 km down-flood plain from the breach.

Although the sand splay complexes differ in detail, they contain several geomorphic elements that are common to most crevasse splays seen in natural river

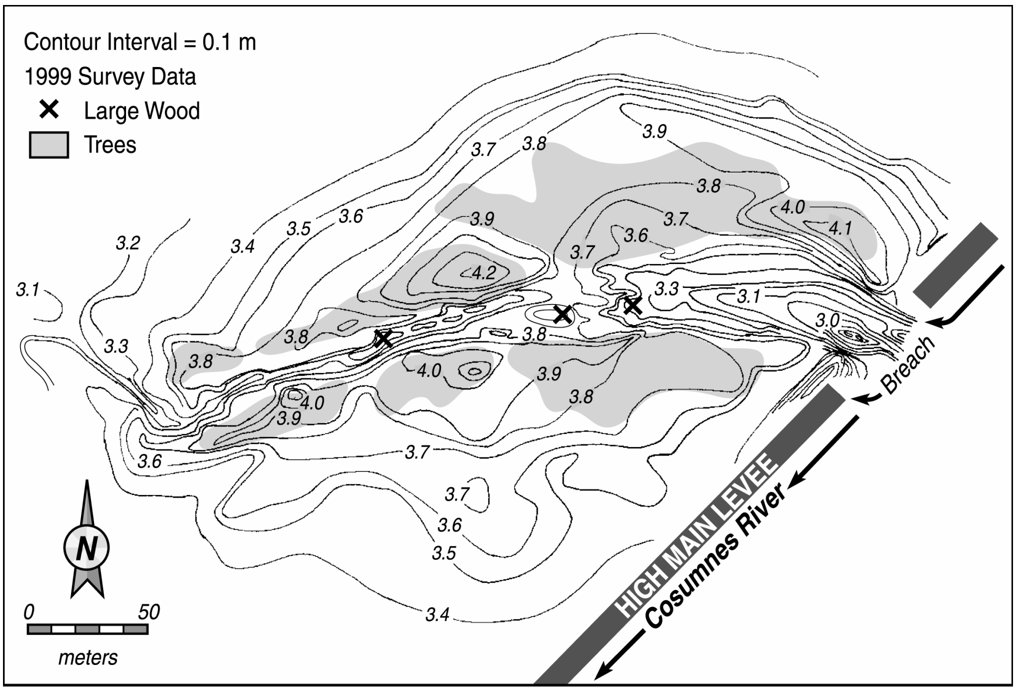

Fig. 3 Topography of sand splay complex at Accidental Forest, surveyed in September 1999. Pattern indicates areas of dense cottonwood and willow establishment and growth.

systems (Lewin, 1973; Richards *et al.*, 1993; Boyer *et al.*, 1997), and where flood control levees have failed during high flows (Gomez *et al.*, 1997; 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 surveys indicate that the scour zone deepens following the initial opening of the breach and, over time, extends down-flood plain, maintaining a negative slope. 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 channel mouth bar. Extension of the splay complex channels takes place through progradation of distributary mouth bars.

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 (Figs 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 establishment and growth of riparian vegetation. The lateral levees of the splay complex 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 hydrological conditions and disturbance regimes necessary to promote establishment of riparian forests. Establishment, density and growth rates for three riparian trees—Gooding's and Sandbar willows (*Salix* sp.) and Fremont cottonwood (*Populus fremonti*)—were monitored during 1999 and 2000 within the splay complexes and on the adjacent flood plain. Detailed results of these surveys are described in Trowbridge *et al.* (in preparation) and are summarized here.

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), Mahooney & Rood (1998) and others have noted, recruitment and survival of riparian trees occurs when several key factors coincide, including:

- the presence of exposed soil or sediment to limit competition;
- the coincidence of declining river stage with seed dispersal;
- a gradual decline in stage to allow roots to maintain contact with moisture zone;
- sustained soil moisture over the length of the growing period, June–September;
- protection from scour during subsequent flood events.

Several of these factors that support establishment of cottonwoods and willows appear to have occurred during and immediately following opening of both breaches. Both breaches were constructed during the late fall, leaving bare, disturbed soil immediately prior to winter flows. During spring of 1996 and 1998, the first years following the breaching of the levees, the Cosumnes River experienced 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 is recorded, spring floods did not occur after mid-May. Based on measurements made during water years 1999 through 2001, the rate of water surface lowering in spring floods is approximately 1–2 cm day^{-1}, supporting germination and growth of the cottonwoods and willows near the breaches. 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 elevation areas, which remained under water during the critical seed dispersal and viability period, had limited 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. 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 measured growth rates of willows and cottonwoods within 19 vegetation patches on the Corps Breach splay complex at various elevations and geomorphic conditions. Although establishment occurred in a range of settings, we found that density and frequency were substantially higher within the splay and channel complex, with most growth occurring on lateral levees and depositional lobes. Cottonwoods and willows average 50–75% higher annual growth rates on the sandy lateral levees and depositional lobes than in distributary channels and the flood plain beyond the splay.

The higher rates of establishment and growth on the levees and 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 stabilize the sand splay complex by increasing local erosional resistance. In addition, the emergent vegetation of cottonwoods and willows create substantial local drag roughness. This may promote localized sediment deposition within vegetation patches, increasing elevation and enhancing overall growing conditions. During moderate to low flood stages, the flow concentration in distributary channels is enhanced by the erosionally resistant, hydraulically rough vegetation patches, increasing topographic complexity and relief within the splay complex.

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