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Geomorphology 44 (2002) 67–94

GEOMORPHOLOGY

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Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California

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Received 21 February 2001; received in revised form 15 August 2001; accepted 15 August 2001

Abstract

Restoration of sustainable geomorphic processes that create floodplain topography through development of sand-splay complexes at intentional breaches is one method to promote variability in physical structure needed for habitat restoration. The topography of splay complexes provides a range of floodplain elevations that creates local variability in (i) inundation duration and frequency and depth to ground water that influence riparian vegetation establishment; and (ii) flow depth and velocity that create refuge for fish. Two intentional levee breaches along the lowland Cosumnes River, Central Valley, CA, were evaluated during water years 1999 and 2000 in order to document changes in morphology and relief associated with deposition of sand-splay complexes. During the study period, annual peak-flow recurrence intervals ranged from ~1 to 3 years, and water flowed through the breaches for a minimum of 55 days during water year 1999 and 53 days during water year 2000. At the two study sites, rapid vertical accretion and scour occurred within the first several years after intentionally breaching the levee at the Accidental Forest floodplain (constructed in 1995) and at the Corps Breach floodplain (constructed in 1997). Splay complexes are organized into a variety of landforms, including lateral levees and lobes separated by new floodplain channels. Maximum deposition measured on the splay surface is 0.36 m/year, while maximum scour in channels is 0.27 m/year. Juxtaposition of floodplain splay deposition and adjacent channel scour creates relief ranging from ~1.6 to 0.25 m that decreases with distance from the breach and that becomes more pronounced over time as higher magnitude floods scour channels in the old floodplain sediment and deposit new sand and silt onto the surface of the splay. The ratio of splay complex height to depth of formative flow is estimated as ~0.4. Progradation of main and secondary splay channels takes place by down-floodplain sand transport (25 m/year maximum). Large wood recruited onto the floodplain through the breach promotes local scour and deposition that enhances topographic variability. At one of the study sites, initial grading of a low setback berm prior to opening the breach forced a change in floodplain flow direction and the geometry of the splay complex. Additionally, progradation of the complex is arrested by an excavated pond that creates a sediment trap. We present a conceptual model that describes the importance of floods in constructing and modifying sand-splay complexes that create floodplain topography. The potential habitat variability created as floodplain topography evolves is the linkage between physical and ecological processes that are critical for restoration.

Keywords: Floodplain; River; Sand-splay complex; Topography; Restoration; Levee breach

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0169-555X/02/$ - see front matter
PII: S0169-555X(01)00146-5

1. Introduction

Floodplain topography, the distribution and relief of floodplain landforms, constitutes the physical structure underlying floodplain ecosystems. As such, floodplain topography is an important consideration in the restoration of lowland rivers. In this paper, the use of the term "restoration" is not meant to imply full recovery to the predisturbance condition. Rather, it is intended to imply a trajectory toward sustainable physical processes consistent with the term "rehabilitation" (Federal Interagency Stream Restoration Working Group, 1998). Periodic erosion and sedimentation during floods sustain the health and productivity of floodplain river ecosystems (Junk et al., 1989; Bayley, 1991, 1995), while floodplain habitat plays a critical role in sustaining riparian ecosystem diversity (Ward and Stanford, 1995; Stanford et al., 1996). Thus, it follows that the dynamic geomorphic processes that form and modify floodplain topography are a fundamental component of riparian ecosystem ecology. Sand-splay and channel complexes, often called crevasse splays, create variability in floodplain topography by depositing sediment and cutting channels during avulsion at natural levee breaches in anabranching rivers (Smith et al., 1989; Richards et al., 1993). Over time, sand-splay complexes evolve toward a topographically diverse floodplain system containing channels, wetlands, and levees (Smith et al., 1989; Smith and Perez-Arlucea, 1994). Splay deposition also occurs at accidental breaches in engineered levees along channelized rivers, such as the Mississippi and Missouri Rivers, during the 1993 flood (Jacobson and Oberg, 1997; Schalk and Jacobson, 1997) or intentional breaches in engineered levees in Mississippi Delta distributary channels (Boyer et al., 1997).

This paper reports results of a field investigation during 1999 and 2000 documenting sand-splay complex deposition and scour and initial development of floodplain topography resulting from two intentional breaches in levees separating the Lower Cosumnes River, CA (Fig. 1), from its floodplain. Prior to anthropogenic disturbance, the lowland Cosumnes River was an anastomosing river that contained multiple channels, seasonal marshes, and "lagunitas," or perennial floodplain lakes. The dominant geomorphic process of change in this system was probably avulsion (Florsheim and Mount, 1999). Historical data

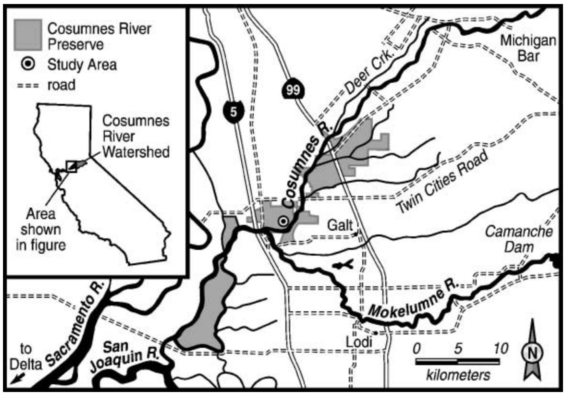


Fig. 1. Lower Cosumnes River from Michigan Bar to the confluence with the Mokelumne River showing the Cosumnes River Preserve study area.

suggest that most of the floodplain was covered by dense riparian forest patches or belts (Thompson, 1977; TBI, 1998), while tule marshes dominated lowest elevation areas (Commission of Public Works, 1861). Over the last 150 years, riparian forests were cleared, floodplain lakes, sloughs, and marshes were filled, and topography was graded to support agriculture. At present, much of the lower Cosumnes River is concentrated into a single channel constrained by levees, agriculture dominates the floodplain, and only isolated remnants of the former aquatic-terrestrial ecotone remain. In this paper, a "level floodplain" is defined as a floodplain lacking topographic relief, but which still has a gradient in the downstream direction.

The Cosumnes River is the largest river lacking large dams draining the west slope of the Sierra Nevada, and because flow is not regulated, the lower Cosumnes River floodplain is an ideal location to test methods to restore floodplain habitat. As part of a long-range watershed plan (TNC, 1992), the first intentional breach was completed in the Cosumnes River Preserve at the "Accidental Forest" floodplain in the fall of 1995, and the second was completed in the fall of 1997 at the "Corps Breach" floodplain (Fig. 2). The 1999–2000 study period reported in this paper represents the fourth and fifth year of sand-splay complex evolution at the Accidental Forest and second and third year of evolution at the Corps Breach study areas. The impetus for these restoration activities on the Cosumnes River Preserve arose after an uninten-

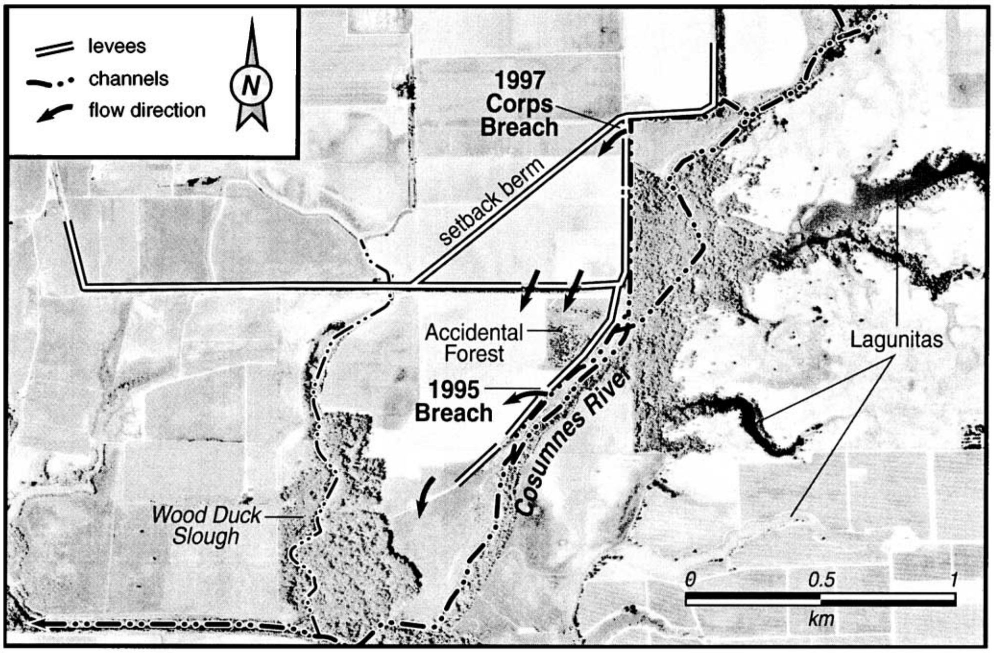


Fig. 2. Two intentional levee breaches at the Cosumnes River Preserve study area: Corps Breach and Accidental Forest Breach. Wood Duck Slough is a remnant of an abandoned channel segment of the predisturbance anastomosing Cosumnes channel network. The 90° bend in the main Cosumnes River upstream of the Corps Breach resulted from avulsion into a levee borrow ditch at some point between 1968 and 1980.

tional levee breach in $\sim$1985 deposited a $\sim$0.06-km^2 sand splay on a farmed field adjacent to the river (Fig. 3). An "Accidental Forest" of cottonwood (*Populus fremontii*) and several species of willow (*Salix*) grew on the sand splay and demonstrated that in addition to restoring the hydrologic connectivity between the river

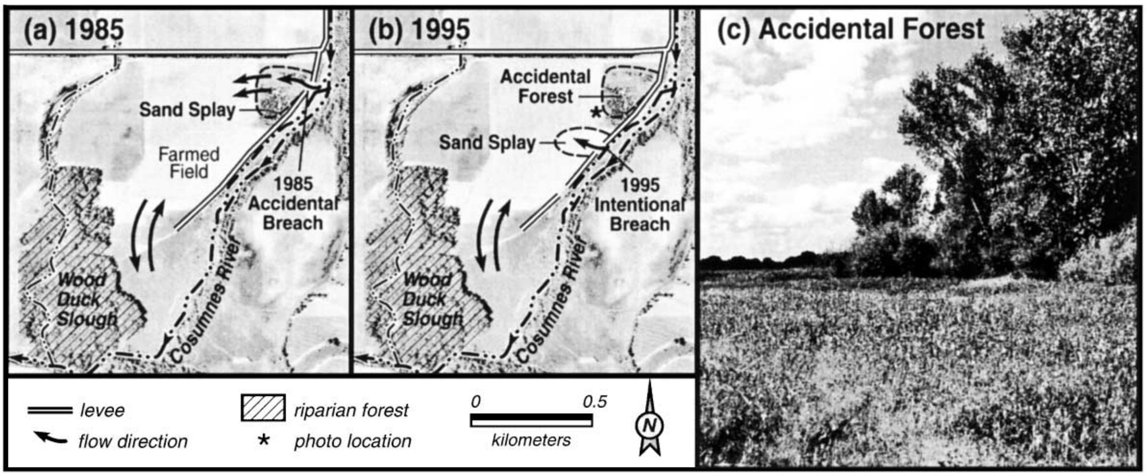


Fig. 3. General flow directions and spatial relationship of Accidental Forest floodplain breaches and resulting splays. (a) Accidental breach and sand splay deposited on farmed field occurred in 1985 prior to inclusion of area into Cosumnes River Preserve (Rich Reiner, TNC, personal communication, 2001). Although the levee breach was repaired, the floodplain flooded seasonally from a downstream connection to the Cosumnes River. (b) Intentional 1995 breach in the Cosumnes River Preserve. (c) The "Accidental Forest" established on the 1985 splay. Photo date: 1998.

and the floodplain, intentional levee breaches could be an effective method to promote floodplain revegetation.

The purpose of this field study was to document the geomorphology associated with the intentional levee breaches including (i) initial development of floodplain topography created by the morphology and relief of the sand-splay complexes; and (ii) changes in morphology resulting from processes such as sediment deposition, new floodplain-channel incision, breach scour, and progradation of the splay complex. Our results also analyze the effect of large wood recruited through the breaches that add variability to the splay complexes, sediment textures that compose the splay deposit, and the effect of initial grading on the morphology of the splay complexes. Based on this work, we present a conceptual model that illustrates the development of morphology and relief within the splay and channel complexes.

Sand-splay deposition in the previously level, tilled floodplain areas on the Cosumnes River Preserve is a first step in the development of floodplain topography needed to restore physical diversity to the floodplain restoration areas following reintroduction of water to the floodplain. Pervasive floodplain land uses often level floodplain topography and construct levees that inhibit floodplain inundation, erosion, and sedimentation. Consequently, the results presented in this paper are significant for potential floodplain restoration and management initiatives in other lowland river systems in California's Central Valley and in other floodplain river systems with levees.

2. Floodplain topography

The complex arrangement of landforms and sedimentary deposits that create floodplain topography record past river processes (Nanson and Croke, 1992; Smith and Perez-Arlucea, 1994; Brown, 1996) that vary temporally and spatially depending on climate, geology, drainage basin area and structure, vegetation, and land uses. Sediment deposits that build floodplain topography include numerous features besides level layers of fine sediment deposited by overbank flows. Numerous studies show that natural floodplains are not typically level, rather they contain a diverse range of subtle but distinctive topographic features (Happ et al., 1940; Wolman and Leopold, 1957; Leopold et al., 1964; Lewin, 1978; Kellerhals and Church, 1989; Smith et al., 1989; Nanson and Croke, 1992; Ritter et al., 1995; Brown, 1996; Schalk and Jacobson, 1997). The misperception that natural floodplains are level is influenced by human activities, which over the past centuries have leveled floodplain topography throughout most of the developed world. For example, in the lower Cosumnes River floodplain, current agricultural practices laser-level fields using graders to promote efficient irrigation and tilling and leave a level plain that masks the assemblage of vertically and laterally accreted sediment deposits that formed the floodplain. In contrast, natural floodplain relief associated with avulsion and splay deposition is typically formed by deposits that are 1 to 3 m thick but that may exceed 7 m in some systems (Perez-Arlucea and Smith, 1999).

3. Link between floodplain topography and ecology

Floodplains were first described as a relatively level and low relief landform periodically inundated by flow from the adjacent river (Wolman and Leopold, 1957). While floodplain topography is subtle relative to main channel cross-section geometry in large alluvial rivers—especially in incised or otherwise altered fluvial systems—its structure forms local variability and gradients in floodplain water depth, flow velocity, and shear stress, as well as fluctuations in elevation and relief of floodplain landforms relative to the ground water table. The variation of riparian plant species and associations with distance from the main river is linked in part to floodplain inundation duration and frequency (Naiman et al., 1988; Junk et al., 1989; Hupp and Osterkamp, 1996; Petts, 1996; Mahoney and Rood, 1998) and to height above the water table (Stromberg et al., 1991; Marston et al., 1995) that depend on the variability in floodplain topography. Additionally, the variability in floodplain elevation and sediment size related to the range of morphologic features and processes of formation affects substrate character. Thus, an association exists between establishment and viability of vegetation patches and floodplain topography. This has important implications for plant productivity and spatial heterogeneity in riparian wetland habitat on floodplains (Nilsson et al., 1989; Pollock et al., 1998), although substrate particle size may not be as important a factor for riparian vegetation as the elevation of the geomorphic feature (Hupp and Osterkamp, 1985). Floodplain topography may create depressions that retain water during the dry season and thus benefit wildlife. Finally, floodplains influence the temporal and spatial diversity that affect food and area available to fish in large rivers (Welcomme, 1994) and at the scale of a reach, the floodplain offers refugia to fish (Sedell et al., 1990).

4. Study area

4.1. Cosumnes basin

The Cosumnes River basin ($\sim$3000 km^2) drains two geomorphic provinces, the mountainous Sierra Nevada and the lowland Central Valley, before entering the Sacramento–San Joaquin River Delta (Fig. 1). The Lower Cosumnes River valley incised into Plio-Pleistocene glacial outwash fans (Wahrhaftig and Birman, 1965; Bateman and Wahrhaftig, 1966; Shlemon, 1995; Harden, 1998) and partly refilled as climate changed and sea level rose during the late Pleistocene and Holocene (Atwater and Marchand, 1980; Shlemon, 1995), thus forming the modern floodplain. Flood basin sediment mapped in the lower Cosumnes River valley downstream of Twin Cities Road, in the vicinity of the Cosumnes River Preserve (Atwater and Marchand, 1980; Wagner et al., 1981), suggests that floods from the Sacramento, Mokelumne, Dry Creek, and Cosumnes River seasonally inundated the lowland area. The flood basin deposits are predominantly fine silty clay and clayey silt. In the study area, the grayish basin deposits are overlain by a veneer of reddish silt and fine sand up to 1.5 m thick attributed to anthropogenic disturbances since 1850 (Atwater and Marchand, 1980). These layers provide identifiable markers that are easily distinguished from the postbreach sandy floodplain sedimentation documented in this study. The lowland Cosumnes River floodplain can be classified as a low-energy cohesive floodplain (Nanson and Croke, 1992) typical of floodplains formed along low gradient laterally stable anastomosing channels. Organized levee construction along the lower Cosumnes River started in 1907 (R. Bauer, Reclamation District 100, personal communication, 1999) and, at present, moderate floods are concentrated into a single channel confined by levees and separated from its floodplain.

4.2. Cosumnes River hydrology

Seasonal flow in the Cosumnes River occurs between October and May, and because $<20\%$ of the basin is above the snow line, the majority of stream flow results from rain fall. The hydrograph for the Cosumnes River at Michigan Bar (USGS gaging station 11335000), for the initial period of formation of the Accidental Forest (1995–2000) and Corps Breach (1998–2000) splay complexes, illustrates episodic, short duration winter storm peaks and smaller spring floods (Fig. 4a). The January 1997 event produced one of the largest regional floods on record and reached 2346 m^3/s in the Cosumnes River at Michigan Bar (recurrence interval>100 years; Guay et al., 1998). Subsequent winter flood peaks had recurrence intervals up to 3 years and spring floods had recurrence intervals of $\sim$1 year. Fig. 4b shows a detail of the hydrograph during the study period for water years 1999 and 2000.

When river stage becomes high enough for water to flow from the channel through the intentional breaches, floodplain connectivity is achieved. Based on field observations, we estimate the discharge at Michigan Bar that corresponds to floodplain connectivity at the Cosumnes River Preserve study sites as betwee $\sim$23.5 and 25.5 m^3/s. During water year 1999, floodplain connectivity first occurred in January and recurred intermittently through April for a minimum of 55 days at the Corps Breach, with continuous floodplain flow lasting $\sim$42 days during February and March. The duration of inundation at the Corps Breach was similar in 2000 with a minimum of 53 days of intermittent floodplain inundation between January and May and $\sim$40 days of continuous flow. Connectivity at the Accidental Forest floodplain occurred at a slightly lower corresponding discharge than at the Corps Breach. Water drains the floodplain restoration areas and returns to the Cosumnes River at the downstream end of the Accidental Forest floodplain, where the levee ends (Fig. 2).

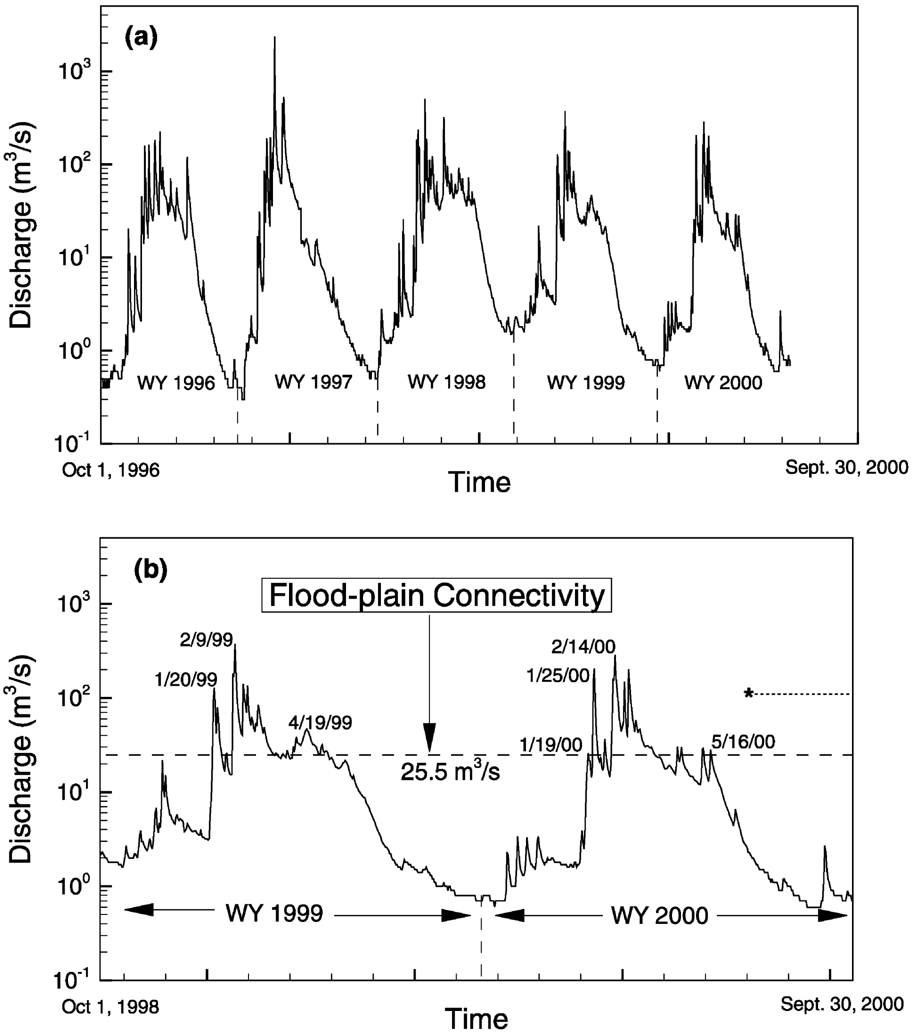


Fig. 4. (a) Hydrograph for USGS gaging station Cosumnes River at Michigan Bar for water years 1996 through 2000. Seasonal flow is dominated by winter storm peaks. (b) Detail of hydrograph for study period between water years 1999 and 2000 illustrating duration of floodplain connectivity when the corresponding river discharge is $\sim$25.5 m^3/s. Star symbol indicates corresponding river discharge of $\sim$110 m^3/s when flow through Corps Breach overtops setback berm.

4.3. Cosumnes River Preserve field study sites

Two levees were intentionally breached in the Cosumnes River Preserve in an effort to restore floodplain hydrology (Fig. 2). In October 1995, a breach was excavated in the levee separating the Accidental Forest floodplain from the Cosumnes River ($\sim$0.5 km downstream of the 1985 accidental breach). In this reach, the thalweg of the main Cosumnes River channel is $\sim$1.5 m below the elevation of the adjacent floodplain. Preliminary measurement of sand capped by silt in distinct layers (J. DeCarlo, University of California, Davis, personal communication, 1999) represents the first 3 years the site was open to flow including the great flood of January 1997 and subsequent smaller floods. This paper describes results of the field investigation on the Accidental Forest floodplain and some of the changes that occurred during the winter and spring of water years 1999 and 2000, 4 and 5 years after the breach was opened.

The Corps Breach was excavated in October 1997 in the main levee along the Cosumnes River (Fig. 2). Other site grading that affected the development of floodplain topography included (i) excavation of a 2.0-m-deep mitigation pond; and (ii) construction of a relatively low setback berm ranging in height from ~0.5 to 2.0 m above the elevation of the floodplain. Prior to restoration activity by TNC, the former farmer lowered the elevation of the triangular shaped floodplain restoration area ~0.15 to 0.60 m below the floodplain elevation on the opposite bank. In this reach, the thalweg of the main Cosumnes River channel is ~3.0 to 5.0 m below the adjacent floodplain elevation. Sediment analysis reported in this study suggests that some sand capped by silt was deposited on the floodplain during the first winter and spring after the levee breach (water year 1998), prior to our study. This paper reports results of field surveys on the Corps Breach floodplain conducted during the dry season in 1999 and 2000, 2 and 3 years after the breach was opened.

5. Methods

Surveys using a Leica Electronic Total Station (TC 800) provided the basis for documenting floodplain topography and geomorphic changes on the Accidental Forest and the Corps Breach floodplain restoration areas at the intentional levee breaches. Field investigations during 1999 and 2000 included surveying and sediment sampling in summer and documentation of high water marks in the inundated floodplain (Corps Breach) and flow directions during winter and spring. Elevations reported in this study are approximately referenced to NGVD 1929 (S. Blake, U.C. Davis, personal communication). Fifteen cross-sections surveyed at the Corps Breach floodplain and seven at the Accidental Forest floodplain illustrate the two-dimensional geometry of the splay complexes and are the basis for quantification of (i) maximum cross-section relief, measured as the difference between the maximum elevation on the crest of the splay surface and the thalweg elevation in the adjacent splay channel; (ii) maximum scour and deposition rates, measured as the maximum increase in height of deposition or depth of scour over the study period; (iii) change in scour and fill area between monumented cross-section endpoints, calculated using winscour (Madej et al., 1999); (iv) average scour and deposition rate, calculated as the scour or fill per cross-sectional area divided by cross-sectional width during the study period; and (v) total volume of sediment sequestered on or scoured from the floodplain, estimated as the product of the cross-sectional change in area and the length between the medial distances between adjacent cross-sections. Cross-section geometry prior to the breaches were estimated by averaging floodplain elevations at the margins of the splay deposit, assuming flat topography in the level agricultural fields prior to the breaches.

Surveyed splay boundaries show the pattern of landforms within the splay complexes. Elevation surveys of points between transects provided data to construct topographic maps of the splays. Surveys of splay-channel thalweg profiles illustrate changes in splay-channel morphology and local scour and deposition over the study period. Sediment deposited on the sand-splay complexes following the levee breaches was easily identified and differentiated from older floodplain deposits that contained reddish silt or blue-gray clay. Each year, the most recent deposition was recognized as the softer sediment deposited over harder sand capped by silt and clay or separated by a thin organic layer. Size distributions of splay sediment were investigated by sieving bulk sediment samples.

Table 1
Physical parameters of the Accidental Forest and Corps Breach sand-splay complexes

	Maximum length[a] (m)	Maximum width (m)	Planimetric area[b] (m^2)	Volume	
				1999–2000 (m^3)	Total (m^3)
Accidental Forest	387	207	6310	2145	10,980 (5 years)
Corps Breach	428	195	4460	3960	7560 (3 years)

[a] Measured as distance from breach to distal end of sand deposited in main floodplain splay channels in 2000.
[b] Areas planimetered from geomorphic map constructed using total station survey data.

6. Results

6.1. Sand-splay complex parameters

The sand-splay complex morphology and variation in the relief created by sediment deposition and channel incision creates floodplain topography on the formerly level agricultural fields at the Cosumnes River Preserve. Table 1 reports some physical parameters of the Accidental Forest and Corps Breach sand-splay complexes. The following sections describe the morphology and relief that comprise floodplain topography, splay-channel progradation, initial temporal and spatial changes in scour and fill, and the volume of sediment sequestered in the floodplain-splay complexes at both study sites.

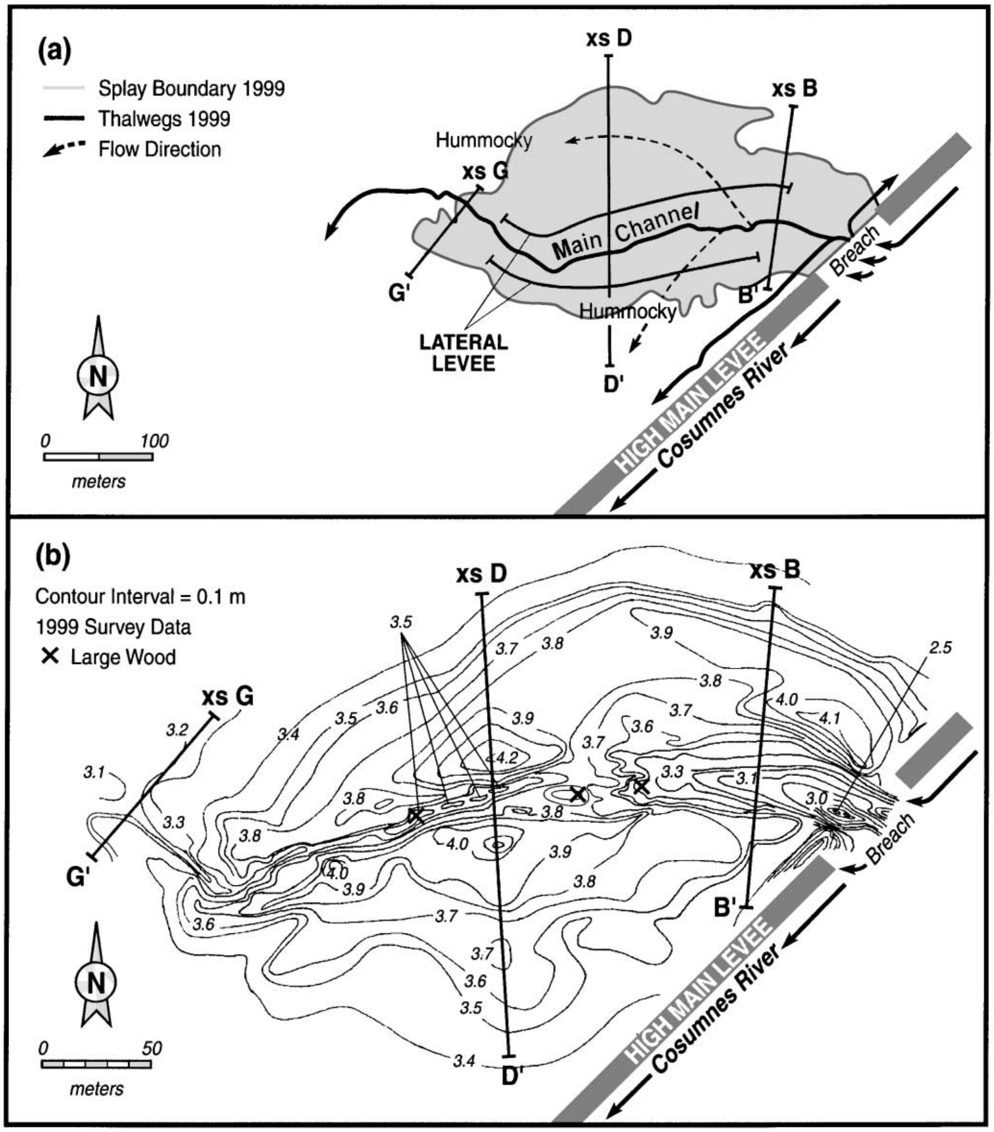


Fig. 5. (a) Accidental Forest floodplain geomorphic plan map showing surveyed boundary and pattern of splay lateral levees and main channel in 1999, locations of cross-sections (XS) B, D, and G, and main and two distributary channel thalwegs. (b) Topographic map illustrating variation in relief and morphology created by scour and deposition in the splay complex. Note difference in scale from Fig. 5a.

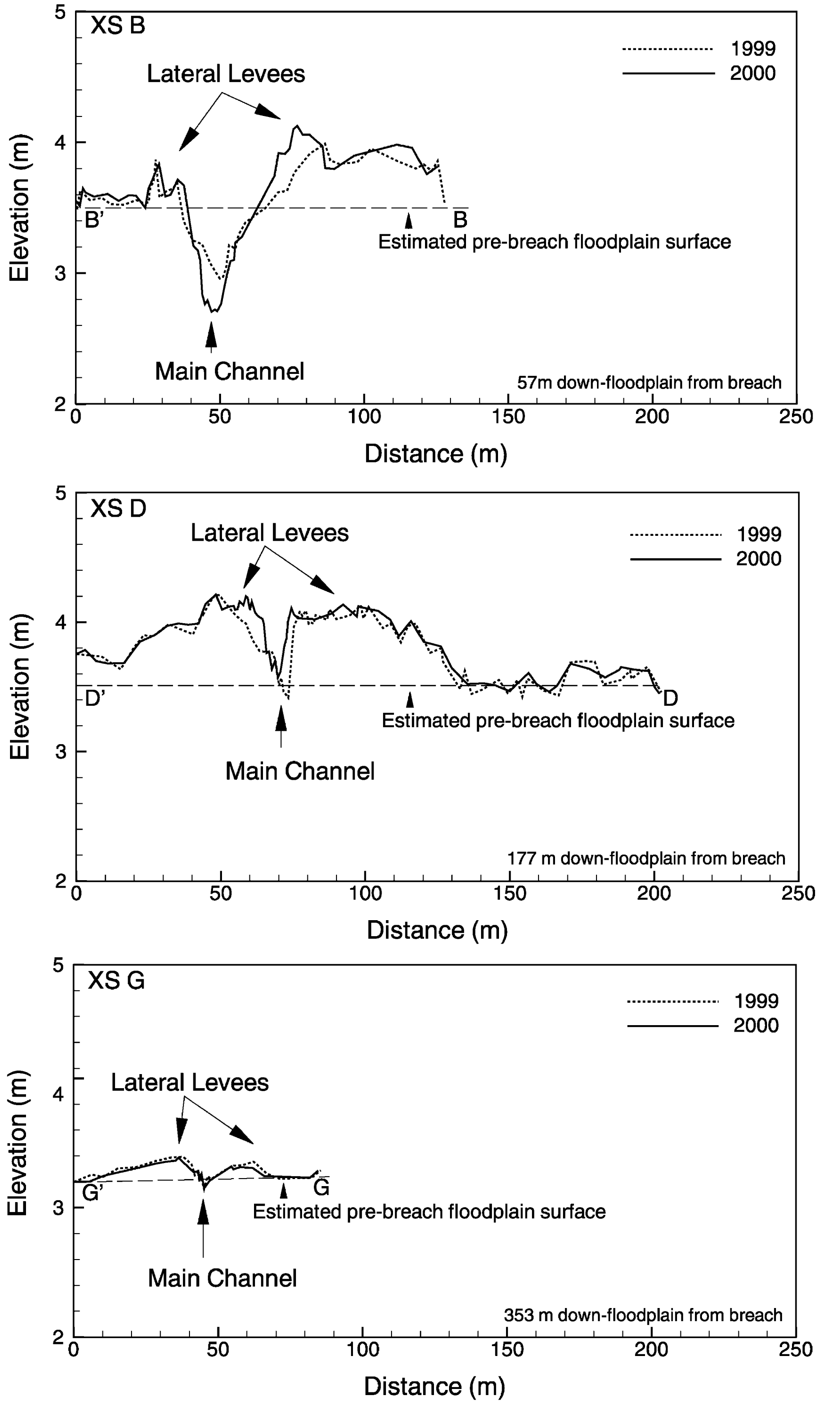
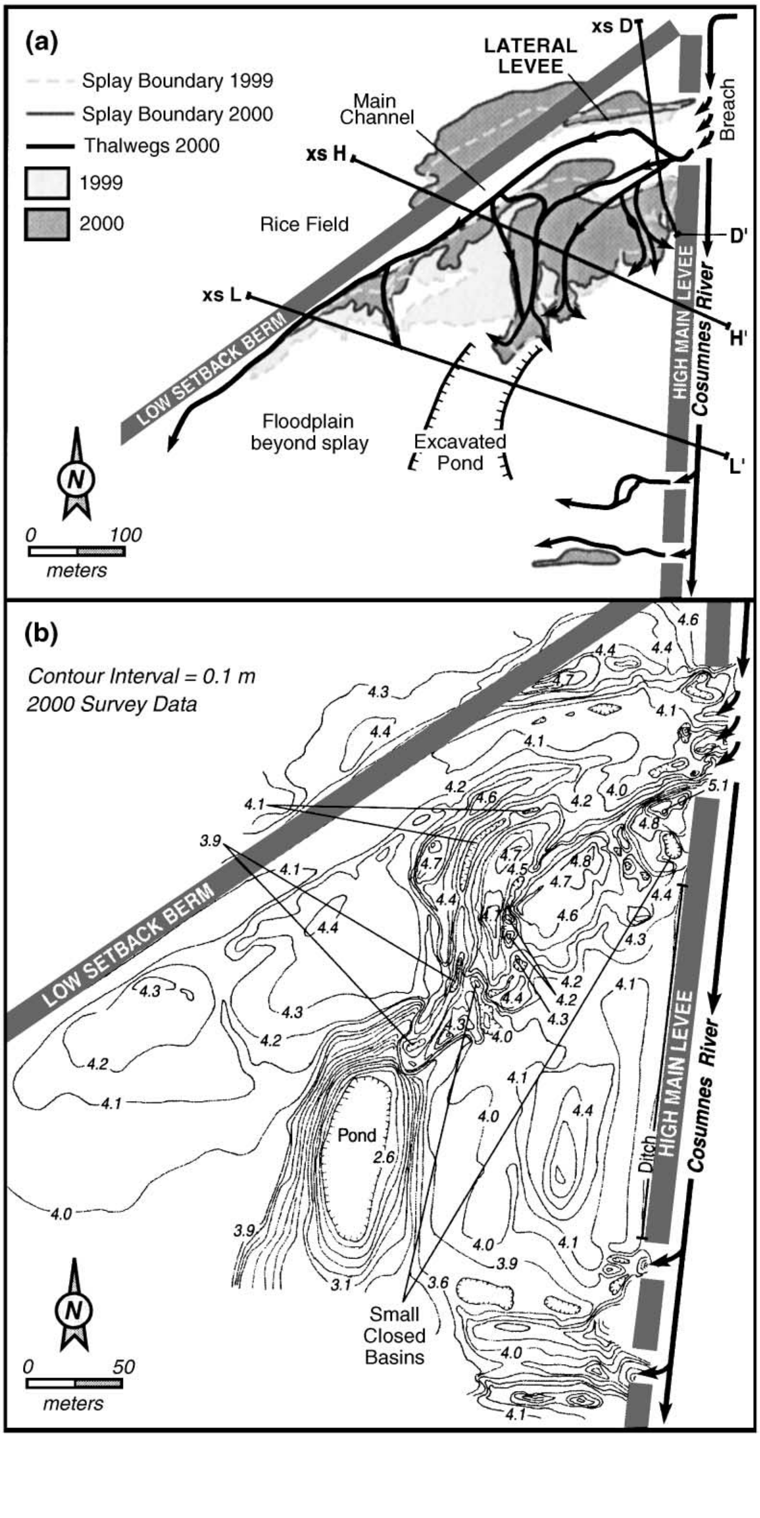


Fig. 6. Cross-sections surveyed in 1999 and 2000 at the Accidental Forest illustrate main channel contained between lateral levees. Scour depth is greatest near the breach (XS B), while the height and width of lateral levees is greatest in the mid portion of the splay (XS D). Splay dimensions decrease down-floodplain (XS G). Note vertical exaggeration.


(a)
Splay Boundary 1999
Splay Boundary 2000
Thalwegs 2000
1999
2000
LATERAL LEVEE
Main Channel
Breach
Rice Field
xs D
xs H
xs L
D'
H'
L'
LOW SETBACK BERM
HIGH MAIN LEVEE
Cosumnes River
Floodplain beyond splay
Excavated Pond
0 100
meters
(b)
Contour Interval = 0.1 m
2000 Survey Data
LOW SETBACK BERM
HIGH MAIN LEVEE
Cosumnes River
Pond
Ditch
Small Closed Basins
0 50
meters

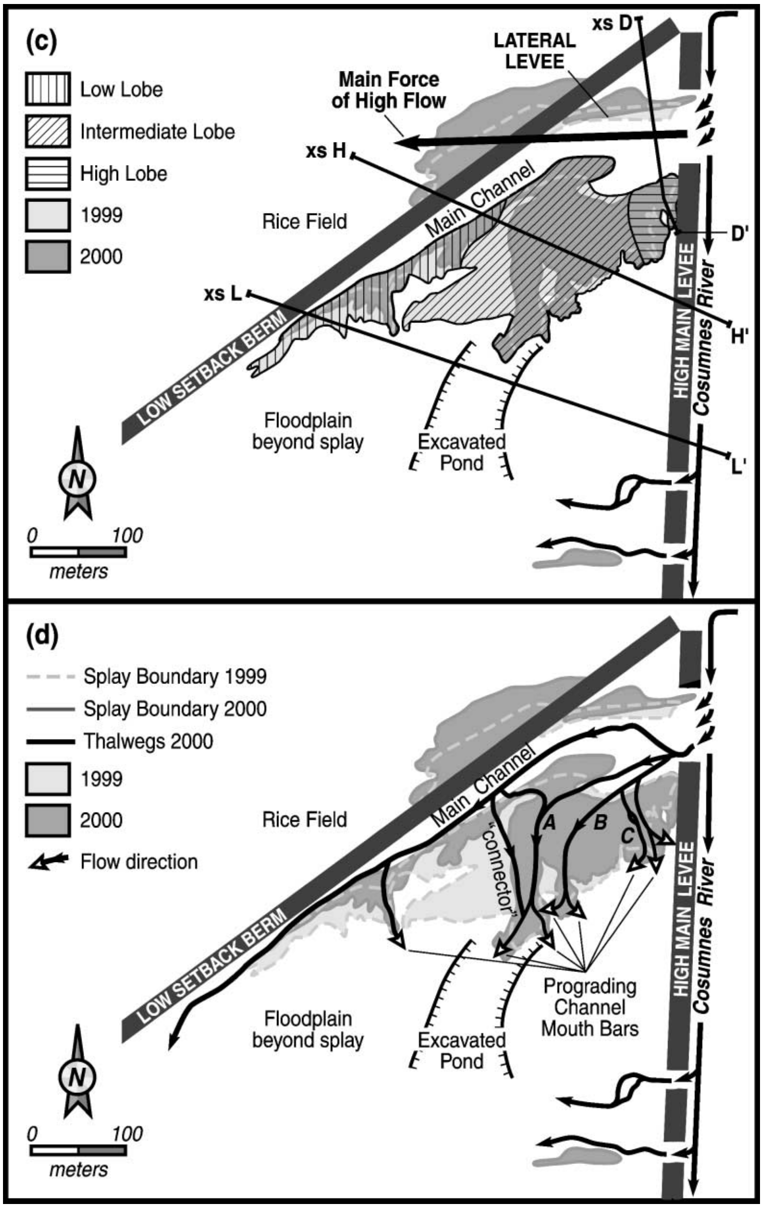


Fig. 7. (a) Corps Breach floodplain geomorphic plan map showing pattern of splay landforms and boundaries surveyed in 1999 and 2000, locations cross-sections (XS) D, H, and L, and surveyed locations of main and secondary floodplain-channel thalwegs, lateral levee, lobes, rice field fan, and two small splays at breaches downstream of main breach. (b) Topographic map illustrating variation in morphology and relief created by scour and deposition in the splay complex. Note difference in scale from this figure. (c) High, intermediate, and low lobes and lateral levee. During high flow, the main force of flow is directed over the setback berm into the rice field. (d) During lower flow, the setback berm diverts flow and causes incision in secondary channels. Flow directions along surveyed thalwegs are based on field observation.

6.2. Floodplain-splay-complex morphology

Five years after the intentional breach, the Accidental Forest sand-splay complex consisted of a main channel that flowed between two lateral levees (Fig. 5a,b). The two lateral levees are relatively symmetrical, with the south (down-floodplain) levee ~ 0.1 m higher than the north (up-floodplain) levee (Fig. 6).

The shape of the deposit is elliptical, with hummocky areas along the splay boundary where overflow from the main channel and a distributary channel reworked the margins of the lateral levees. Two additional distributary channels that emanate from the main channel flow against the inside of the main levee separating the Cosumnes River from the Accidental Forest floodplain. The splay boundary at the margins of the lateral levees did not appear to change between 1999 and 2000.

Three years after the intentional breach at the Corps Breach floodplain, the sand-splay complex consisted of numerous depositional and erosional features, including a relatively small lateral levee north (up-floodplain) of the breach that is separated from the majority of the sediment deposited south (down-floodplain) of the breach by a main splay channel. A fan-shaped deposit consisting of sediment that overtopped the low setback berm formed in the adjacent rice field (Figs. 7a,b,c,d and 8). Fig. 9 illustrates a splay lobe and a secondary channel. The morphology of the main portion of the splay deposit on the south side of the breach includes a "high" lobe just inside the breach, a broad "intermediate" lobe incised by secondary channels, and a relatively narrow "low" lobe that parallels the setback berm adjacent to the main channel (Fig. 7b,c). This morphology reflects depositional and erosional processes dependent on flood stage and the influence of the low setback berm on flow direction. Initial deposition of lateral levees north and south of the breach occurs during relatively high flood stage (Fig. 7c). The north lateral levee extends for ~ 100 m before it is blocked by the setback berm. During these high flows ($> \sim 110$ m^3/s), water flows westward over the low setback berm into the adjacent rice field. A low-pressure wake produced as turbulent flow overtops the setback berm leads to accumulation of a fan shaped deposit in the rice field. Incision of secondary channels that separate the deposit into distinct lobes occurs at lower flood stage when flow impinges on the setback berm and is directed toward the southwest (Fig. 7d). While flow direction on the Corps Breach floodplain may also depend on flood duration and timing, the setback berm appears to be a dominant factor controlling splay complex morphology.

The zone of splay deposition extends 428 m beyond the Corps Breach. The distal margin of the sand splay complex is highly irregular with lobes and stringers that extend from the main body of the deposit. Both the high and intermediate lobes of the sand splay have slip faces along most of their distal ends with maximum height above the old floodplain surface of 0.58 m. The west side of the low lobe has a discontinuous slip face with a maximum height of 0.46 m. Numerous small overwash channels escaping from the main channel erode sand from the low lobe and deposit it further on the floodplain forming sand distributary channels as much as 50 m long. The boundaries of the splay margin varied between 1999 and 2000 with the downstream extent of sand further down-floodplain in 2000 than in 1999 in some locations (Fig. 7a). Progradation of sand lobes formed complex topographic features, including a small closed basin around a patch of the former floodplain surface that remains free of sand.

6.3. Floodplain-splay-channel morphology and progradation

The mechanism for floodplain-channel development at the intentional levee breaches includes breach scour as the channel head incises toward the lower base level elevation of the adjacent Cosumnes River—and down-floodplain deposition and scour of sand through progradation. Longitudinal profiles of the main splay-channel thalweg surveyed at the Accidental Forest floodplain in 1999 and in 2000 illustrate a strongly convex shape caused by scour and incision near the breach and deposition further down-floodplain (Fig. 10; Table 2). Topographic variability in the splay-channel profile is dominated by (i) a downstream-migrating breach scour step, a feature that is currently 0.76 m in height; and (ii) three pieces of large wood recruited through the breach during water year 1999—a tree trunk (0.6 m in diameter and almost 10 m in length; Fig. 11) and two large root wads. Average channel relief formed by turbulence that locally scours and deposits sand associated with the large wood was 0.63 m in 1999, or about six times greater than the average relief between low points and adjacent downstream high points (0.11 m) in the sand bed. During water year 2000, the large tree trunk was transported out of the main channel to a new position near the crest of the southern lateral levee and the main channel incised through the sand

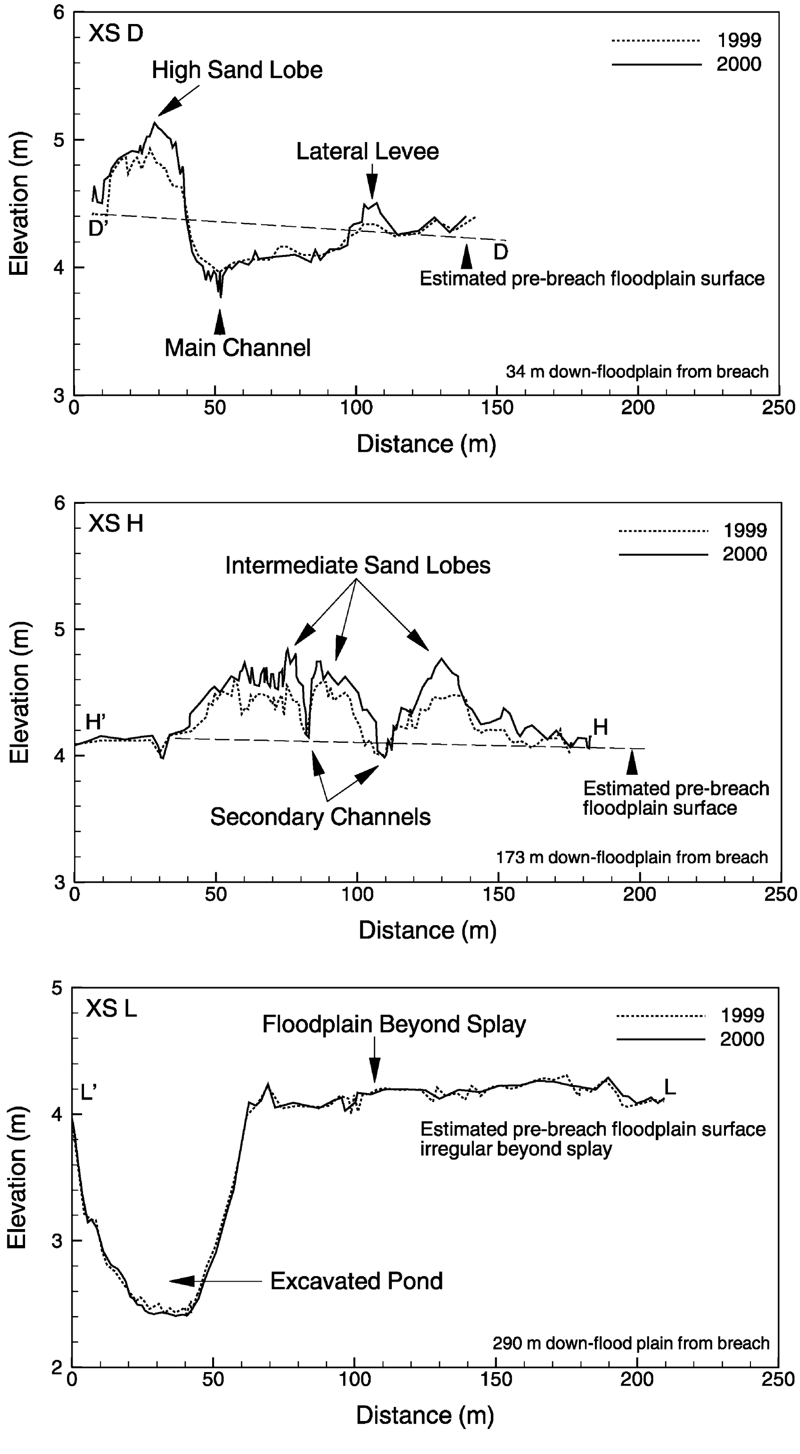


Fig. 8. Examples of cross-sections surveyed at the Corps Breach in 1999 and 2000 illustrate main and secondary channels between lateral levee and lobes (representative segments shown). Scour depth is greatest near the breach (XS D), while lateral levee height and width are greatest in the mid portion of the splay (XS H). Beyond the splay (XS L), relatively little deposition or scour occurs on the floodplain. Note vertical exaggeration.

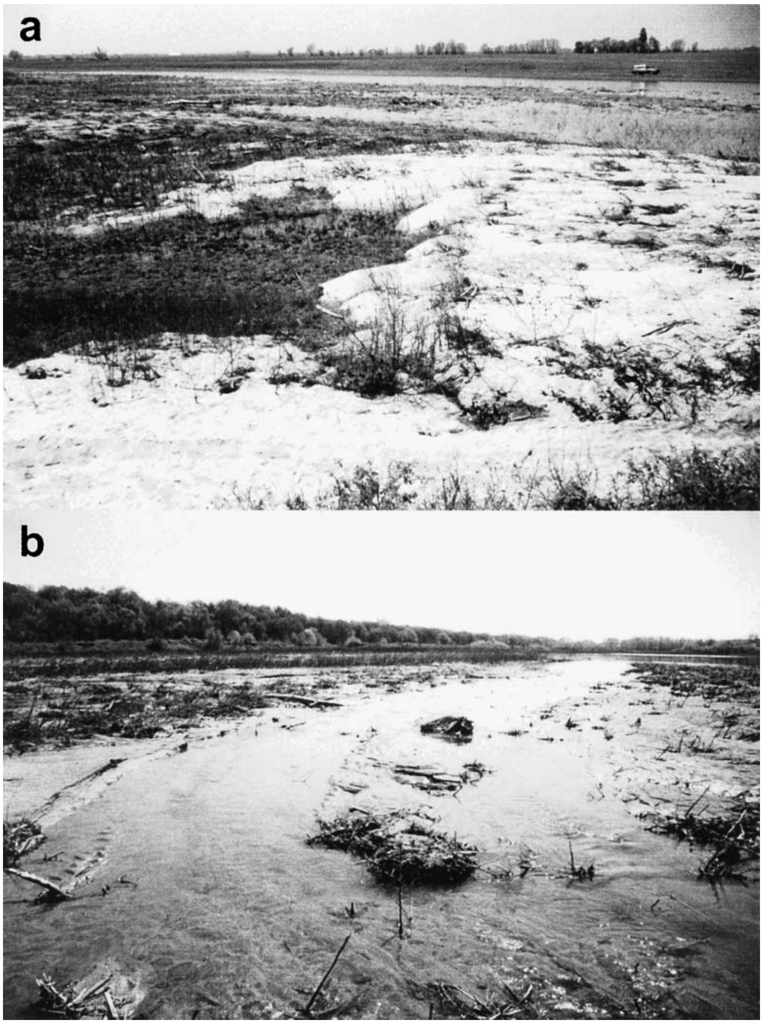


Fig. 9. Photos illustrate Corps Breach floodplain-splay complex morphology. (a) Sand lobe deposited on level floodplain surface. (b) Secondary channel incised into splay.

bar previously associated with the log. Additional–ly, scour associated with the downstream root wad was partially filled during water year 2000 (Fig. 10). Progradation of the main splay channel at the Accidental Forest splay complex was measured ~25 m beyond a marker during water year 1999 and an additional 8.0 m in 2000. In 2000, the zone of sand-splay complex deposition in the main floodplain channel beyond the breach reached an extent of 387 m.

At the Corps Breach, water in the "main" splay complex channel flows between the lateral levee and main splay deposit for the first 100 m after flow enters the floodplain through the breach, similar to the pattern at the Accidental Forest (Fig. 7c). However, after impinging on the setback berm, lower stages of main channel flow changes direction and flows between the margin of the sand deposit and the setback berm (Fig. 7d). The combination of incision in the 175-m-long scour zone at the main channel head and some incision at the distal end, with a small amount of deposition extending for almost 200 m in the middle, forms a weakly convex shaped profile with much less curvature than that at the Accidental

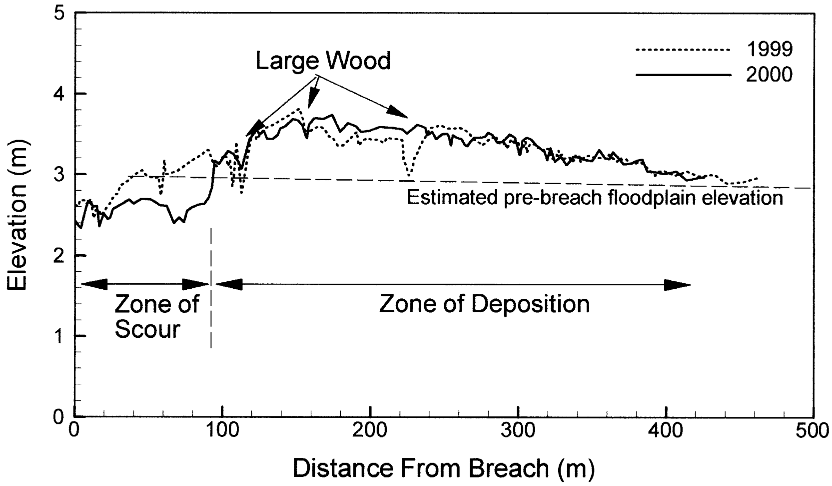


Fig. 10. Convex shaped main channel longitudinal profile surveyed at the Accidental Forest is created by the breach scour zone followed by deposition farther down-floodplain. Thalweg location shown on Fig. 5a. Large wood promotes local scour and deposition and enhances topographic variation in sand bed channel.

Forest splay (Fig. 12a). While sediment deposition in secondary channels was greater than in the main channel, the main channel appeared to carry the majority of flow during the study period. The lower base level and greater volume of sand deposited at the downstream end of secondary channel A (that terminates in a delta in the excavated pond) suggests that the proportion of flow carried by the main channel and secondary channels on the dynamic splay complex may vary over time.

Secondary channels incised in the main splay deposit on the south side of the breach have a distributary or anastomosing pattern. Morphologic characteristics of secondary channels at the Corps Breach are reported in Table 3. Secondary channel A, the lowest elevation and dominant secondary channel, prograded 8.0 m into the excavated mitigation pond during water year 2000; secondary channel B, the intermediate elevation-splay channel, did not prograde; while secondary channel C, the highest elevation secondary channel, prograded 17.3 m (Fig. 12b).

Topographic variability in secondary splay channels at the Corps Breach results from the same mechanism that drives progradation of sand across a floodplain. Sand eroded from upstream portions is transported and deposited at the distal ends of splay channels and in channel mouth bars. Mouth bars are higher elevation mounds of sand that sometimes spread at the distal edge of the splay and form a slip face at the boundary with the old floodplain surface. The increase in elevation of the channel bed at their distal end reflects the mechanism for down-floodplain

Table 2
Main channel characteristics 1999 to 2000

	Length of scour zone (m)	Maximum scour depth (m/year)	Maximum deposition (m/year)	Scour zone slope (m/m)		Maximum width/depth (m/m)
				1999	2000	
Accidental Forest	93	0.25	0.15	– 0.008	– 0.0008	520[a]
Corps Breach	175	0.19	0.10	– 0.008	– 0.012	230[b]

[a] Range varies from maximum mid splay, where channel margin is poorly defined, to 14 at distal end of splay where the narrow channel is well defined.

[b] Ranges from ~ 90 to 230 in main channel up-floodplain of bifurcation into secondary channels.

Fig. 11. Large log that entered Accidental Forest floodplain breach deposited in main splay complex channel in 1999. Photo looking toward breach, shows scoured area that remains wet for longer periods than higher depositional area associated with the log.

extension of channels and progradation of the sand-splay complexes, with the mound of sand at the terminus of the channels as a result of progradation of sand into standing water (a mechanism suggested by Smith et al., 1989) or as a response to the higher resistance of the old floodplain surface relative to that of the sand channel. The height of the channel mouth bars (measured on the downstream side), slope, and length of each channel measured in 2000 are reported in Table 3. During water year 2000, progradation of secondary channel A through its mouth bar created new distributary channels. The buildup of sand at the distal end of some of the secondary splay channels leads to reverse bed slopes, and could eventually lead to their abandonment.

6.4. Topographic relief

Topographic relief is created by deposition of sand on lateral levees and lobes and scour in the breach zones and channels. At both study sites, maximum relief occurs near the upstream end of the splay complexes due to the juxtaposition of breach scour through the silt and clay of the former floodplain and adjacent deposition on the lateral levees and lobes (Figs. 13a and 14a). Relief decreases in the down-floodplain direction as the magnitude of both scour and deposition decrease. Maximum relief at the Accidental Forest floodplain is 1.42 m and is slightly higher at the Corps Breach splay complex (1.62 m). Portions of the lobes have a relatively flat surface, while other portions are extremely variable. Irregular lateral levee and lobe surfaces with micro-relief (<0.2 m) reflect local scour and deposition associated with small woody debris and young trees and reworking of the sand by flow that overtops the deposit.

The general trend of a down-floodplain decrease in splay complex relief is altered where a combination of deposition in channel mouth bars and excavation of the adjacent pond increases relief to 0.90 m at the distal end of the Corps Breach splay complex (Fig. 14a). On the relatively level floodplain beyond the margin of the splay, relief is comparatively low (0.20 m). The ratio of splay complex height to depth of formative flow (h/H) is estimated as 0.4, based on measurements of splay height and high water marks at the Corps Breach.

6.5. Temporal and spatial changes in scour and fill area and cumulative volume

Total lateral levee thickness at the Accidental Forest floodplain, measured as the elevation change between

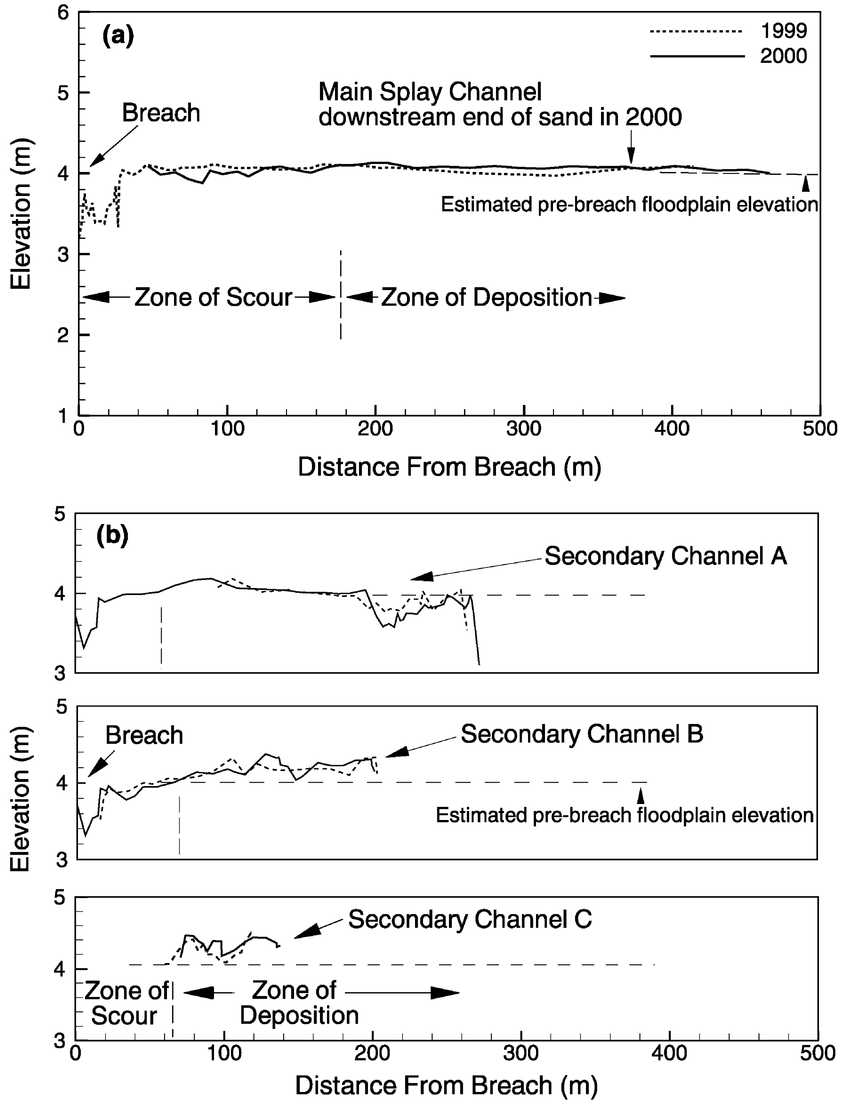


Fig. 12. (a) Longitudinal profile of main channel at the Corps Breach floodplain. Scour occurs near the breach; however, little sediment is deposited downstream. (b) Longitudinal profiles of three secondary channels (A, B, and C) form in sand deposited on the splay complex and terminate in channel mouth bars. Deposition dominates changes in secondary channels between 1999 and 2000, except for a 45-m reach of secondary channel A where the channel bed incised by 0.2 m upstream of the mouth bar/delta prograding into the excavated pond. Thalweg locations shown on Fig. 7a.

the floodplain surface at the margin of the splay complex and the splay surface at the crest, ranges from ~ 0.8 m at the proximal end to ~ 0.1 m at the distal end. Maximum rates of splay deposit accretion over the study period and estimated average rates of accretion and scour during the study period and for the 5-year period since the breach was opened are reported in Table 4. The average accretion rate during the study period was the same as the longer-term rate.

Spatial changes in splay complex cross-sectional area vary with distance from the breach (Fig. 13b). At the Accidental Forest floodplain, the maximum depo-

Table 3
Corps Breach splay-channel slopes and channel-mouth bar heights

Channel segment	Slope[a] (m/m)	Channel mouth bar height 1999/2000 (m)	Maximum deposition rate[b] (m/year)
Main channel	0.0001	none/0.01	0.11
Secondary channel A	0.0018	0.51/1.48[c]	0.17
Secondary channel B	− 0.0022	0.21/0.16	0.15
Secondary channel C	− 0.0014	0.26/0.13	0.19
Connector channel	0.0026	0.17/0.19	0.21

[a] Negative values indicate reverse slopes.
[b] Rates measured from thalweg profiles.
[c] 2000 height is relatively large due to progradation of secondary channel A into the excavated pond.

sition rate (fill per cross-sectional area between 1999 and 2000 divided by cross-sectional width) ranges from 0.11 m/year at the proximal end of the splay to 0.003 m/year near the distal end of the splay. Fig. 13b illustrates the dominance of scour near the breach and fill beyond the scour zone. The cumulative volume of sediment sequestered on the floodplain in the splay complex increases beyond the scour zone (Fig. 13c). Estimates of cumulative volume of sediment deposition and scour between 1999 and 2000 are 2140 and 610 m^3, respectively. During the 5 years since the Accidental Forest breach, these values are estimated as 10 980 and 1525 m^3, respectively.

At the Corps Breach floodplain, maximum splay thickness is ~0.80 m on the high splay. The maximum deposition rate between 1999 and 2000 occurred down-floodplain of the breach scour zone on the intermediate lobe and proximal portions of the low lobe (Table 4). The accretion rate during the study period is somewhat higher than that estimated for the 3-year period since the breach was opened, consistent with our observation that less sand was deposited on the Corps Breach floodplain during the first year the breach was opened than during subsequent years.

Sediment accretion and scour on the floodplain-splay complex varies with distance from the Corps Breach. The maximum deposition rate ranges from 0.14 m/year at the proximal end of the splay to 0.05 m/year at the distal end of the splay. Changes in area at each cross-section resulting from deposition and scour vary with distance from the breach (Fig. 14b). The total volume of sediment sequestered on the floodplain between 1999 and 2000 was ~5270 m^3, and the total volume scoured during the same period was ~985 m^3. Total fill and scour volumes during the 3 years the breach opened are estimated as 8732 and

Table 4
Rates of accretion and scour on splay complexes

	Maximum accretion rate (m/year)	Average[a] accretion rate (m/year)		Average[b] scour rate (m/year)
	1999–2000	1999–2000	Total period	Total period
Accidental Forest		0.04	0.04[c]	0.05[d]
Lateral levee[e]	0.26			
Corps Breach		0.1	0.08[f]	0.03[g]
Lateral levee	0.30			
Rice field fan	0.19			
High lobe	0.36			
Intermediate lobe	0.39			
Low lobe	0.39			

[a] Fill per cross-section area divided by cross-section width and then averaged over all cross-sections.
[b] Scour per cross-section area divided by cross-section width and then averaged over all cross-sections.
[c] Estimate for 5-year period 1995–2000.
[d] Estimate for 5-year period 1995–2000.
[e] Lateral levee on south side of breach.
[f] Estimate for 3-year period 1998–2000.
[g] Estimate for 3-year period 1998–2000.

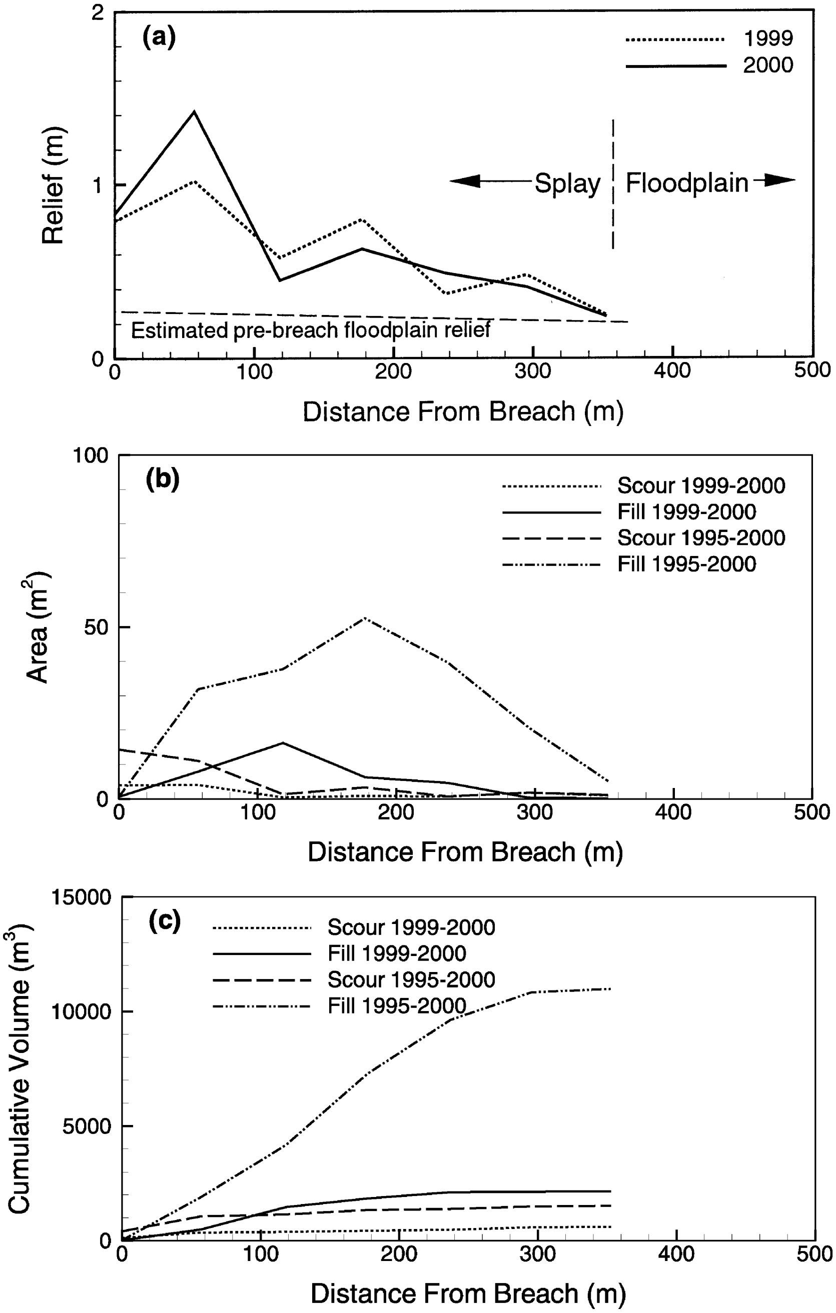


Fig. 13. (a) Change in topographic relief with distance from the Accidental Forest breach measured at cross-sections surveyed in 1999 and 2000 is greatest near the breach and decreases down-floodplain. (b) Change in cross-sectional area with distance from the Accidental Forest Breach illustrates that maximum splay complex scour near the breach, is followed by maximum deposition occurring hundreds of meters from the breach. Comparison of repetitive cross-sections surveyed in 1999 and 2000 suggests that recent maximum deposition occurs closer to the breach than in prior years. (c) Change in cumulative volume with distance from the breach illustrates a rapid volumetric increase where sediment is sequestered on the floodplain-splay complex downstream of the breach.

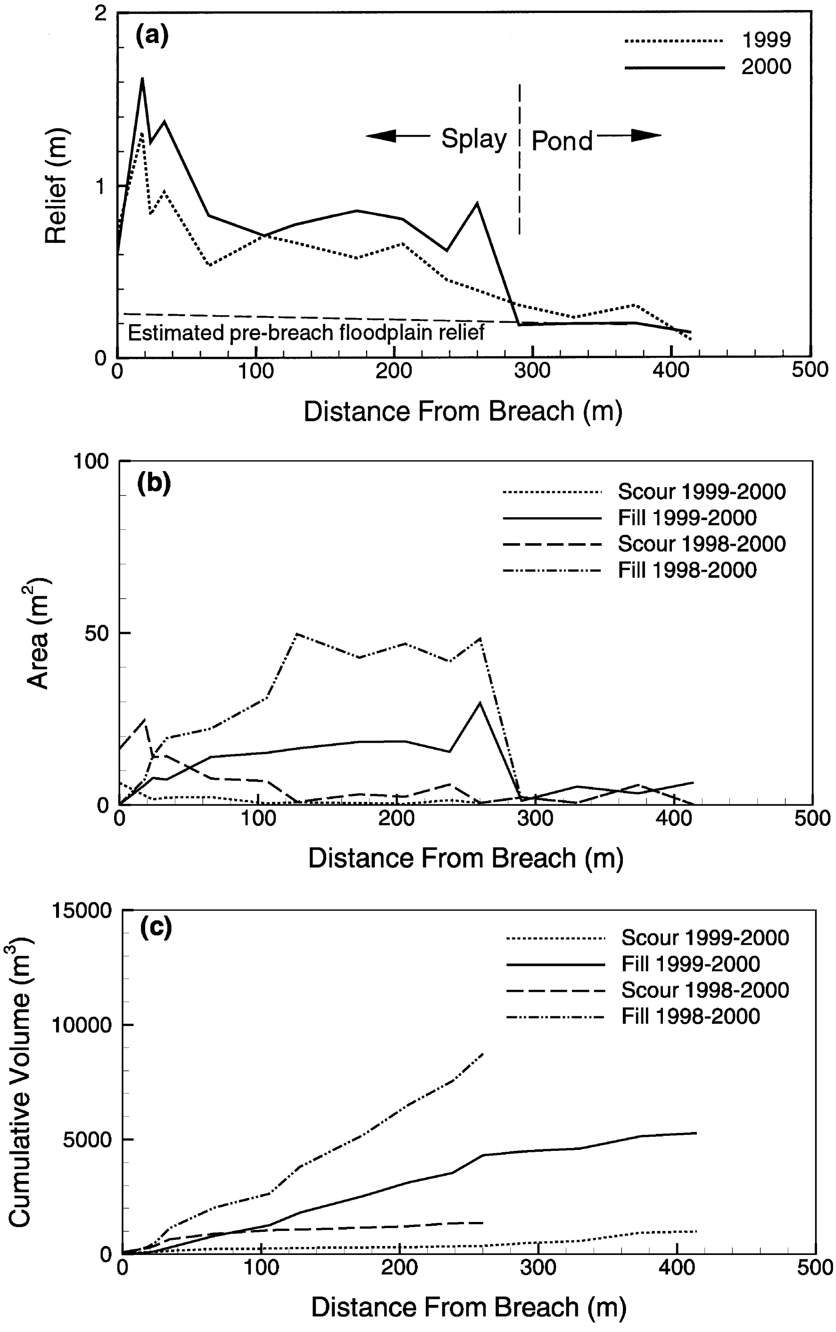


Fig. 14. (a) Change in topographic relief with distance from the Corps Breach measured from repetitive cross-sections surveyed in 1999 and 2000 generally decreases down-floodplain, except at the distal margin where secondary channel A progrades into the excavated pond. Floodplain relief past the distal margin of the splay is similar to the relatively level topography present prior to the breach. (b) Change in cross-sectional area with distance illustrates that maximum scour occurs near the breach, and maximum deposition occurs in the mid portion of the splay complex. Recent deposition is prominent at the distal end of the splay. (c) Change in cumulative volume with distance from the breach illustrates a volumetric increase where sediment is sequestered on the floodplain-splay complex and a flattening of the curve beyond the splay. Volume not calculated using prebreach estimates of floodplain elevations due to disturbance such as tire tracks in some areas downstream of the splay.

1363 m^3, respectively. Cumulative volume of sediment sequestered on the floodplain also varies with distance from the breach (Fig. 14c).

6.6. Sediment texture

The size range of particles deposited in the Accidental Forest sand splay during the winter of 1998–1999 is relatively homogeneous with ~75% to 95% of the sediment deposited consisting of medium and coarse sand. The median particle size (ranging from 0.51 to 0.56 mm) and percent silt within the sand layers (ranging from 0.5% to 1.6%) show little variation relative to distance from the breach. A veneer composed mainly of silt and clay (ranging from a few millimeters to 0.025 m in thickness) was deposited over the coarser sand in some portions of the main channel and on the lateral levees.

Particle sizes in the Corps Breach sand splay range from silt to small gravel with sand layers separated by thinner layers of silt or leaf litter. Three depositional cycles of sand with a silt veneer exist in a small portion of the Corps Breach sand splay complex, indicating that sediment was available to construct the splay complex in each year since the breach opened. However, deposition during the first year was limited in extent to the middle portion of the main splay deposit. The remainder of the splay complex shows two depositional cycles corresponding to deposition in the second and third year the breach was opened. The sand layers are relatively homogeneous and are composed of ~70% to 95% medium and coarse sand. Longitudinal variation of median particle size and percent silt within the sand layers shows little correlation with distance from the breach. Some of the gravel-sized grains were rounded agglomerations of clay and may have been derived from erosion of the cohesive floodplain sediment at the breach.

6.7. Effect of initial engineering grading on floodplain deposition and erosion patterns

Initial engineering grading at both the Accidental Forest Breach and the Corps Breach floodplain restoration areas prior to breaching the levees affected the pattern of sand deposition and erosion on the splay complexes and affects their evolution. At both study areas, the maximum scour occurred inside the breach and not in the zone that was formerly under levee. Compaction of sediment under the levees may retard breach scour and new floodplain channel formation in the short term at both sites. Rip-rap and a grouted culvert outfall placed in the Corps Breach further impedes scour, while a ditch on the floodplain inside the main Corps Breach levee prior to the intentional breach coincides with a pitted area in the scour zone.

An initial constraint at the Accidental Forest was the narrow breach width (15 m), however, the width more than doubled to 39 m within the first 3 years the breach was opened to flow (M. Eaton, TNC, personal communication, 1999). An attempt made to direct initial floodplain flow in a pilot channel was filled by splay complex deposition but still may influence small flows beyond the splay complex and, to some extent, reduce the duration of ponding by draining the local floodplain area.

Engineering grading of the low setback berm and the mitigation pond at the Corps Breach has a profound effect on the morphology of the sand-splay deposit and may affect the development of floodplain topography as long as these features are maintained. The low setback berm is intended to minimize erosion and sedimentation in the path of the main flow coming in through the breach in order to accommodate rice farming on the far side of the setback berm. During small floods (recurrence interval 3 to 5 years), water overtops and erodes the setback berm and deposits sediment in the rice field. The Corps Breach splay morphology (with the main splay channel following the inside of the setback berm) sand lobes separated by secondary channels, and the rice field fan persisted over the period of observation, suggesting that the pattern is forced by the setback berm that directs lower magnitude floods away from the rice field.

Future routing of the sand down-floodplain toward an excavated mitigation pond will trap sand and inhibit splay complex progradation to the distal part of the floodplain (Florsheim and Mount, 2000). Although seasonal marshes and lagunitas were once a common feature on the expansive Cosumnes River floodplain, artificial excavation of ponds in the relatively small restoration area traps sediment and fish and affects the future evolution of floodplain topography that would have resulted from uninhibited progradation of the splay complex. Initial site grading that includes setback berms, mitigation ponds, and training channels influences floodplain flow direction, splay complex morphology, sediment transport, deposition and erosion patterns, and the evolution of floodplain topography. Accommodation of erosion and deposition processes that form splay complexes without constructing inhibiting structures, such as the setback berm or excavation of the pond, would help minimize future maintenance.

Finally, prebreach agricultural activity that lowered the Corps Breach floodplain restoration area by ~ 0.15 to 0.60 m affects sand supply to the floodplain from the main river channel, and sediment transport, scour, and deposition on the splay complex. In particular, the lowered elevation increases the frequency and duration of floodplain inundation relative to adjacent nonleveed floodplain areas and thus may increase deposition of silt and clay carried in suspension to low portions of the splay complex and to inundated areas beyond the splay in the floodplain restoration area.

7. Discussion

7.1. Conceptual model: generation of floodplain topography at intentional levee breaches

The development of floodplain topography at intentional levee breaches is dependent on a number of factors related to breach hydraulics and new input of sand, including (i) the ability of sediment to be transported from the main river through the breach onto the floodplain; (ii) the sediment supply in the system available to form a splay complex; and (iii) the frequency, magnitude, and duration of the flood pulse that inundates the floodplain. Once these conditions are satisfied, splay complex erosion and deposition inside intentional levee breaches initiate development of floodplain topography. Hydrologic data (Fig. 3) and field observation during floods of water years 1999 and 2000 suggest that splay complex formation and modification occur during a small number of relatively short duration events. We present here a conceptual model that describes initiation of a sand splay and modification of floodplain topography at an intentional breach during an idealized flood event (Fig. 15a,b).

7.1.1. Stage 1R: rising hydrograph interval between base flow and floodplain connectivity

As stages rise in the main Cosumnes River channel, the adjacent floodplain ground water table also begins to rise and seep into depressions—adding to direct precipitation that wets the floodplain prior to connectivity.

7.1.2. Stage 2R: rising hydrograph interval between floodplain connectivity and threshold of sediment transport onto floodplain

As river stage rises above bankfull, flow through the breach hydrologically reconnects the floodplain restoration area to the river. Water is routed into splay complex secondary channels and then spreads along the path of steepest floodplain gradient. No new sand is supplied from the river to the floodplain during this interval of the rising flood stage, but the low-magnitude floodplain flow is capable of mobilizing and reworking sand present in main and secondary splay channels.

7.1.3. Stage 3R: rising hydrograph interval between threshold of sediment transport onto floodplain and peak flow

As river stage continues to rise, water surface slope from the main river channel to the floodplain increases progressively. This stage is characterized by formation, accretion, and modification of the splay complex, by breach scour, and by recruitment of large woody debris. Once the threshold for main river sediment transport onto the floodplain is exceeded, available sediment is transported onto the floodplain as bed load or suspended load. Both the volume of sediment supplied to the floodplain through the levee breaches and the transport mechanisms are influenced by the relative height of the floodplain above the main channel bed (l). Where the elevation change from the channel onto the floodplain is relatively low and gradual, sediment is probably transported through the breach as bed load when the boundary shear stress, τ_o, is greater than the critical shear stress, τ_c. Where the elevation change from the bed of the channel onto the floodplain is relatively large and abrupt, sediment entering a breach must be suspended by the turbulent motion of flow—that may be enhanced by secondary circulation and turbulence around channel bends.

At high stages, flow confined through the breach has relatively high hydraulic head, a steep gradient, and high velocity; thus, scour in the zone near the breach is common. Beyond the breach scour zone, floodplain flow loses its confinement, and flow velocity, depth, the level of turbulence, and shear stress decrease. These decreases, in combination with secondary circulation patterns, result in the deposition of

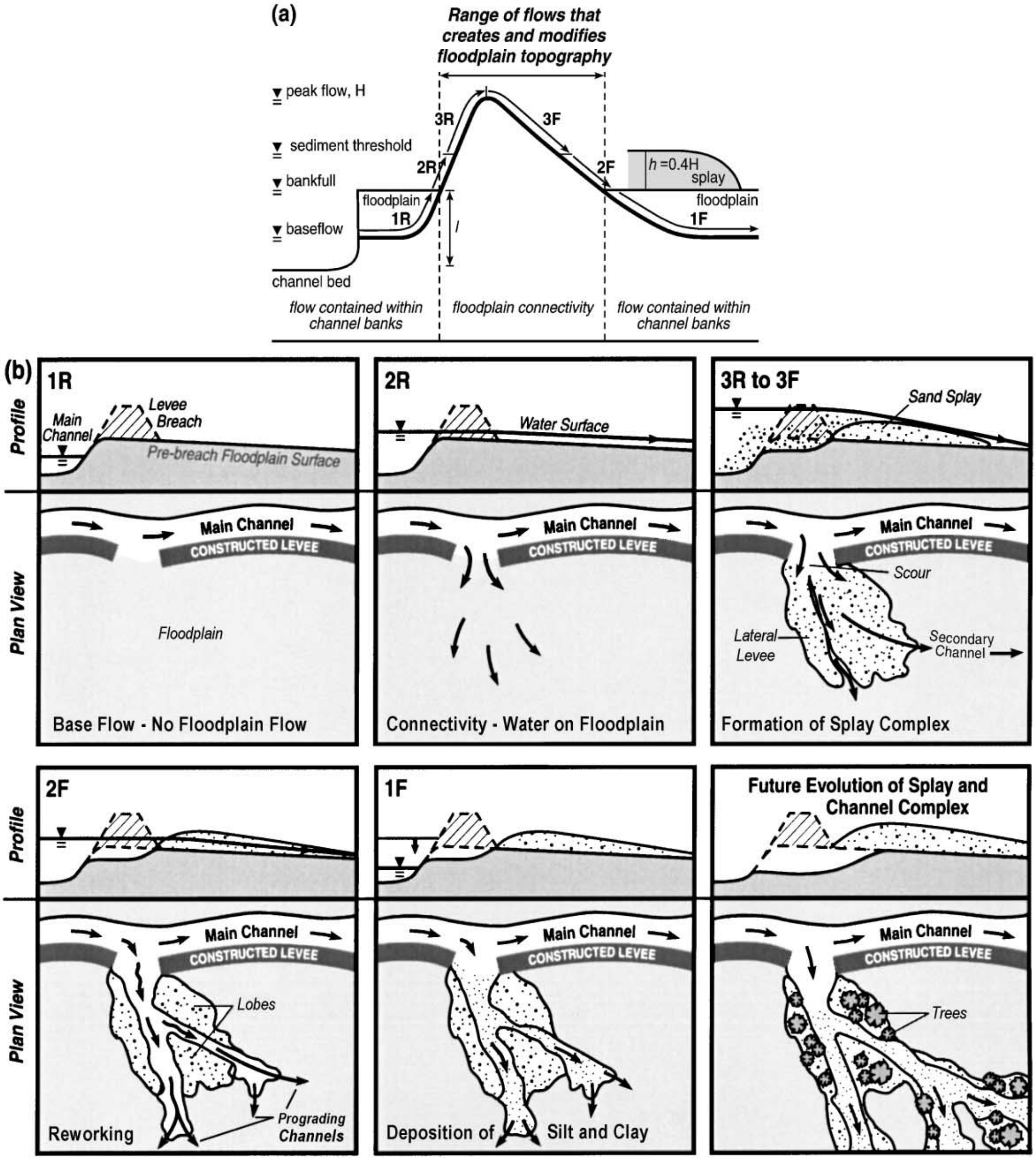


Fig. 15. Conceptual model describing sand-splay complex formation and development of floodplain topography. (a) Development of floodplain topography is related to three rising (1 to 3R) and falling (3 to 1F) stages of the hydrograph. (b) Schematic profiles and maps describing stages of evolution of floodplain topography are correlated with six stages of the conceptual hydrograph.

lateral levees at the margins of the main force of the floodplain flow. Splay height and thickness decrease with distance from the breach, as flow depth decreases down-floodplain. Scour into the former prebreach floodplain surface and deposition of sand in lateral levees during high flow stages create an incipient floodplain channel. This new floodplain channel may attain a convex bed profile due to scour at the channel head followed by deposition down-floodplain. Large wood recruited through the breach adds complexity and locally alters splay complex sediment scour and deposition patterns and floodplain topography.

7.1.4. Stage 3F: falling hydrograph interval between peak flow and threshold of sediment transport onto floodplain

After the flood peak, the main river stage falls; and water surface slope decreases from the river channel to the floodplain. However, breach scour and splay accretion continue until the sediment transport threshold is crossed, no sediment is added to the floodplain, and available shear stress falls below the critical value needed for breach scour. Falling stage affects the hydraulics of flow entering the floodplain through the breach because of the decrease in water surface slope and the corresponding decrease in energy available to transport sediment. Depending on the rate of decline in the stage, a rapid decrease in floodplain transport capacity may lead to rapid sediment deposition over a large portion of the splay complex. Additionally, as sediment concentration decreases during flood recession, splay channel scour may increase.

7.1.5. Stage 2F: falling hydrograph interval between threshold of sediment transport onto floodplain and floodplain connectivity

As the stage falls below the elevation of the splay surface, the lateral levees are progressively exposed, and flow is confined to new floodplain main and secondary channels and low areas on the floodplain. Extensive reworking of sand and associated channel progradation occur during this stage. Because even small floods in new floodplain-splay channels easily mobilize and rework sand, the progradation distance is controlled by flow duration. Incision of secondary channels may divide the down-floodplain lateral levee into distinct lobes.

7.1.6. Stage 1F: falling hydrograph interval between floodplain connectivity and base flow

The last depositional mechanism to operate during each flood cycle is deposition of silt and clay suspended by slow-moving or ponded water as the floodplain drains. Deposition of the fine silt and clay occurs in low elevation areas and depressions on the splay where turbulence is absent. Slackwater deposition of a silt and clay veneer results in alternating sand and silt layers in portions of the splay complex and rhythmic layers of silt on the floodplain beyond the splay. The concentration of silt and clay at the splay surface in contrast to the low percentage of fine material within the sand deposited each year provides a diversity of substrate size and texture and has implications for aquatic organisms and vegetation taking advantage of new floodplain habitat.

7.2. Long-term evolution of floodplain topography

Dynamic erosion and deposition processes that operate on floodplains at intentional levee breaches will modify the physical structure of incipient splay complexes and influence the evolution of floodplain topography. If the geomorphic processes documented during this short-term study continue, our results suggest that floodplain topography will be affected by (i) vertical accretion on the splay complex that requires progressively higher magnitude flows to inundate and carry sand to the surface; (ii) splay channel incision and planform adjustment; (iii) progradation of the splay and channel complex; (iv) recruitment of large wood through the breach that promotes local scour and deposition; and (v) establishment of riparian vegetation patches on the splay.

The lower Cosumnes River was an anastomosing system prior to concentration of flow into a single channel constrained by levees (Florsheim and Mount, 1999). The geomorphic processes and splay morphology observed in the first few years following the levee breaches at the Accidental Forest and the Corps Breach mimic the early stages of avulsion and associated development of floodplain sand splays—similar to what might have occurred in the predisturbance anastomosing Cosumnes River system, or what might occur over the long term if the entire constructed main levee is eroded or is removed (assuming the format–ion of a natural levee alongside the Cosumnes River channel and subsequent natural breaches typical in anastomosing systems). Evolution of the incipient splay complexes at the intentional breaches may progress according to an anastomosing river model such as that proposed by Perez-Arlucea and Smith (1999), where distributary channels become abandoned or merge to form an anastomosing channel network in the splay complex. As new sand levees alongside the prograding splay-channel breach, they initiate floodplain splay and channel formation in low areas further down-floodplain. Thus, as the splay complex progrades across the floodplain, it constructs topography by transporting sand over layered fine sediment deposited beyond the initial splay margin.

Within the Cosumnes River splay complexes, channel profiles may become progressively more convex due to continued incision at their head and distal end and deposition in their mid portion. At some range of low-to-moderate magnitude floods, normal bed slopes in secondary channels probably favor persistence and progradation, while reverse bed slopes favor fillings and abandonment. However, during high-magnitude floods, down-floodplain water surface slope is probably adequate to overcome the effect of local bed gradient.

Avulsion of the main Cosumnes River into new floodplain channels at the intentional breach study sites may be inhibited by (i) floodplain width, which is constrained near the Corps Breach; or (ii) the lack of a long-term avulsion driving mechanism. For example, erosion of the levees and breach widening may eventually lead to a reduction of the velocity and head that artificially creates a mechanism to entrain sediment from the main Cosumnes River channel and to route it onto the floodplain. However, the incipient trend of scour upstream and sediment deposition downstream of both breaches documented in Cosumnes River channel cross-sections (unpublished data, 2000) suggests one possible mechanism to cause avulsion at the intentional breaches, especially if the channel downstream of the breaches continues to aggrade. In natural systems, avulsion occurs when there is an adequate gradient from the main river channel to the new floodplain channel (Smith et al., 1989). Further, Singerland and Smith (1998) suggest that avulsion into a new floodplain channel at natural levee breaches is dependent on the ratio of floodplain-channel slope to main channel bed slope and the ratio of the height of the floodplain lip above the main channel bed to flow stage. Thus, evolution of the splay complexes at the two study sites may differ because of differences in the ratio of the height of the floodplain lip above the main channel bed, with avulsion less likely at the Corps Breach ($l = 3.0$ to 5.0 m) than it is at the Accidental Forest Breach ($l = 1.5$ m). As the heads of the new floodplain-splay channels scour closer to the thalweg of the main channel, the sediment concentration of flow entering the breaches may increase. Future monitoring will document the effect of these variables on avulsion and splay complex evolution.

The new floodplain topography created by the splay complexes at intentional levee breaches at the Cosumnes River Preserve provides variability in the physical structure of habitat, a range of elevations above surface flow and saturated ground, and a range of sediment textures needed for establishment of vegetation patches adjacent to the new floodplain channels. Moreover, variation in elevations created by new topography may contribute to complex habitat on the floodplain related to upwelling of baseflow and downwelling of the river water into texturally variable bed sediment, processes identified as essential components of floodplain restoration (Stanford et al., 1996; Tockner et al., 1999). Floodplain erosion and sedimentation that occur as splay complexes evolve are the natural disturbances critical for ecological success— ion and in restoring dynamic ecosystem biodiversity (Bravard et al., 1985; Amoros et al., 1987; Petts, 1990; Pinay et al., 1990; Sparks et al., 1990; Wissmar and Swanson, 1990; Bayley, 1991; Stanford et al., 1996). Dynamic changes in floodplain channels during subsequent floods resulting from bank erosion, incision, deposition, and progradation provide disturbances necessary to promote riparian vegetation succession and eventually a mosaic of riparian patches of various ages.

Local floodplain topography, large wood, and new vegetation all contribute to floodplain roughness and influence the velocity field in rivers; thus, these elements also affect flow resistance and the velocity and shear stress distribution that influence fish use of the floodplain. For example, at the scale of the new floodplain-splay complex channels, fish use is currently limited to refugia where exposed roots of newly established vegetation or woody debris slow velocity and provide cover (P. Moyle and K. Whitener, University of California, Davis, personal communication, 2000). Thus, the diversity of new floodplain habitat is likely to promote utilization by fish and other aquatic or terrestrial organisms.

8. Conclusions

Intentional levee breaches on the lower Cosumnes River initiate restoration of floodplain topography on formerly level agricultural fields previously disconnected from the river by levees. Results of this study that document the morphology and relief associated with deposition of sand-splay complexes at intentional levee breaches at the Cosumnes River Preserve suggest that (i) rapid vertical accretion of sediment on splay complexes is organized into landforms that include lateral levees, lobes, and new floodplain channels; (ii) the juxtaposition of breach scour and adjacent sediment deposition creates relatively high floodplain relief that decreases with distance from a breach; (iii) relief will become more pronounced over time as higher magnitude floods scour the old floodplain sediment and add new sand and silt onto the surface of the splay deposit; (iv) sediment is transported in main and secondary channels that prograde down-floodplain and extend topographic variability down-floodplain; (v) large wood recruited onto the floodplain through breaches promotes local scour and deposition, and enhances relief that can be as much as six times larger than the average relief; and (vi) initial site construction and grading force change in floodplain flow direction and create potential sediment traps, thereby inhibiting erosion, deposition, and progradation and altering splay complex morphology.

Floodplain topography resulting from intentional levee breaches is a first step toward creation of the variability in physical structure needed for habitat restoration. The development of sand-splay complexes sequesters and increases the residence time of sediment and nutrients in off-channel storage areas, and provides a diverse range of elevation and morphology that creates variability in flow strength, depth, velocity, and inundation duration and frequency. As such, intentional levee breaches are an impressive example of the potential to restore geomorphic processes on floodplain areas previously leveled for agriculture where lateral connectivity between the channel and floodplain was lacking. Restoration of geomorphic processes that create floodplain topography—by development of dynamic sand-splay complexes at intentional breaches—is one method to promote the variability in physical structure needed for biodiversity of species. The short-term monitoring results presented in this study are intended to document physical processes where moderate to large floods build floodplain topography and initiate physical complexity and smaller floods rework the splay and channel complex and create habitat during each flood pulse. Integration of these results with fisheries and vegetation monitoring data will provide insight into use of levee breaches as a method to restore ecological floodplain functions in channelized rivers. Further monitoring at the intentional levee breaches will decrease uncertainty associated with sustainability and long-term ecological benefits resulting from the intentional levee breaches. These results have application toward floodplain restoration initiatives and management in lowland rivers in California's Central Valley and in other alluvial floodplain river systems where agriculture and other land uses have leveled floodplain topography.

Acknowledgements

We thank the Cosumnes River Preserve Partners for their help in facilitating this monitoring project. R. Reiner and R. Swenson, Project Ecologists for The Nature Conservancy provided insight, guidance, and support. We appreciate field and logistical assistance from M. Strudley for two seasons; and from W. Trowbridge, N. Harrison, C. Wang, L. Rutten, C. Fehr, C. Oldenburg, J. DeCarlo, S. Blake, P. Crain, and R. Clarke. The manuscript was improved from helpful reviews by A. Miller, J.P. Bravard, and R. Marston and discussions with P. Moyle, K. Whitener, G. Pasternack, and T. Dudley. This project was funded by the David and Lucile Packard Foundation Conservation Program (1998-3584) and the CALFED Bay-Delta Ecosystem Restoration Program (99N06).

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