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Changes in lowland floodplain sedimentation processes: pre-disturbance to post-rehabilitation, Cosumnes River, CA

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Abstract

During the late Holocene, sediment deposition on the lowland Cosumnes River floodplain, CA has depended on factors that varied temporally and spatially, such as basin subsidence, sea level rise, flow, and sediment supply from both the Sacramento River system and from the Cosumnes River system itself, and anthropogenic changes. Through field investigations and analyses of historical maps, bridge core logs, and sediment size distributions, we link hydrogeomorphic processes to three stages of floodplain sedimentation on the lowland Cosumnes River. Stage I (1000–200 YBP) combined late Holocene pre-disturbance flood basin overflow and anastomosing river processes deposited spatially variable sediment consisting of gray–blue clay (87% clay) interlayered with relatively thin coarser sediment. Pre-disturbance Holocene deposition rates of up to ~ 3.0 mm/year kept pace with sea level rise and tectonic basin subsidence. Stage II (200 to ~ 10 YBP) anthropogenic disturbances caused a rapid increase in floodplain sedimentation rates up to 25 mm/year between 1849 and ~ 1920, and deposited a relatively coarser reddish-brown sandy clay (~ 40% clay) layer that overlies the basin deposits. Between ~ 1920 and 1990 AD, sedimentation was greatly limited on the lower Cosumnes floodplain because levees inhibited connectivity between both the Sacramento and Cosumnes River systems and the Cosumnes floodplain. During this stage, the density of channel segments in the anastomosing river floodplain decreased by 30% as agricultural activities filled secondary channels and leveled floodplain topography. During Stage III (~ 10 YBP to the present), post-rehabilitation floodplain sand splay complex sediment deposited after 1998 AD resulted from intentionally breaching levees to promote habitat at the Cosumnes River Preserve. The splay complex is dominated by medium to very coarse sand with finer intervening layers. The post-rehabilitation splay complex overlies the older basin deposits in a generally upward coarsening sequence that reflects depositional processes and land use changes that continue to affect the lowland Cosumnes River floodplain.

Keywords: Floodplain sedimentation; Anastomosing river; Sacramento Flood Basin; Sand splay complex; Rehabilitation; Restoration

1. Introduction

In lowland anastomosing river systems, the interactions between channel and floodplain processes create distinctive sediment assemblages reflecting the hydrogeomorphic environment in which they were

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deposited, and these environments vary temporally and spatially. Interconnected networks of active and abandoned channels and associated wetlands separated by islands characterize such systems (Smith et al., 1989). Deposition of sediment from overbank flow is a critical component of lateral connectivity between river channels and their floodplains that sustains riparian ecology and biodiversity (Ward and Trockner, 2001) and that may significantly reduce a river's total suspended sediment load (Walling et al., 1996). Understanding the relation between floodplain sediment assemblages, geomorphic processes, and land uses is significant for predicting changes in depositional processes that result from anthropogenic disturbances as well as from recent attempts to rehabilitate habitat in lowland river systems. In the lowland Central Valley, CA (Fig. 1), sequestration of fine sediment in floodplains benefits water quality and channel habitat for sensitive native species such as Chinook salmon (*Oncorhynchus tshawytscha*). Additionally, vertical accretion of sediment on the Cosumnes River floodplain at intentional levee breaches leads to changes in floodplain topography, the physical structure of floodplain habitat necessary for establishment and sustainability of diverse riparian species (Florsheim and Mount, 2002; Mount et al., 2002).

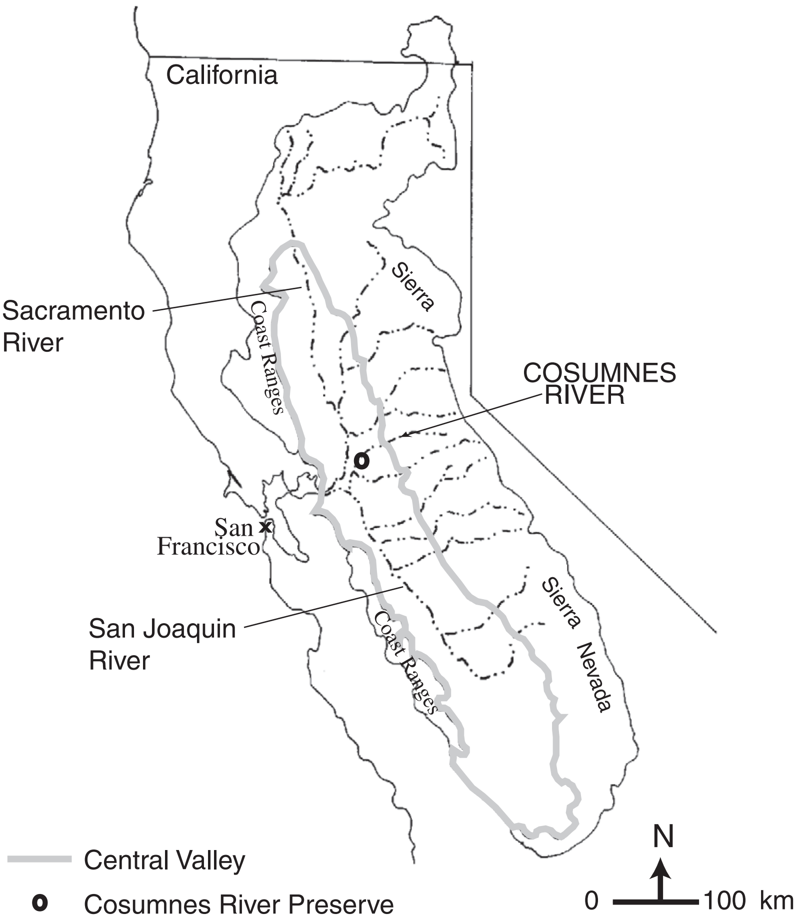

Fig. 1. Map of the Central Valley drainage basin. The Sacramento-San Joaquin Rivers drain the largest watershed in California. Study area is lower 15 km of Cosumnes River. Cosumnes River Preserve is area upstream of the confluence with the Mokelumne River.

Prior research shows that vertical profiles of floodplain sediment strata reflect land use changes that occurred with the onset of basin-scale anthropogenic activities such as agriculture, timber harvest, mining, or, alternatively, land conservation (Costa, 1975; Magilligan, 1985; Jacobson and Coleman, 1986; Brakenridge, 1984; Gilbert, 1917; Knox, 1987). Other anthropogenic activities such as artificial levee construction obstruct channel–floodplain connectivity and greatly limit the supply of water and sediment to the floodplain. Investigating the stratigraphic record of floodplain sedimentation to predict potential future changes is useful because it provides insight to the dominant floodplain sedimentation processes inherent in the fluvial system prior to the anthropogenic changes. However, in the lowland Central Valley, studies documenting the character of combined anastomosing river and flood basin sediment deposition and their associated hydrogeomorphic processes prior to anthropogenic alteration, are lacking. Moreover, detailed documentation of historical changes to floodplain processes in the Sacramento Valley flood basins are only recently considered outside the context of flood control or hazard reduction for adjacent development.

The purpose of this study is to correlate predisturbance Holocene, historical, and current floodplain processes with the sediment record, and quantify changes caused by past and present anthropogenic disturbances. This study builds on our prior work at the Cosumnes River Preserve, CA (Florsheim and Mount, 2002), and documents three stages of floodplain sedimentation through field investigation of a coarsening upward vertical sediment profile that reflects distinct temporal and spatial changes in regional, watershed, and local conditions during three stages. In this paper, we link sedimentation processes with historical analysis of maps and data, field interpretation of key Holocene deposits, and laboratory textural analysis of sediment samples. Results documenting the pre-disturbance anastomosing character of the lower Cosumnes River have significance for river management and restoration activities in the entire lowland portion of the Central Valley, a watershed receiving critical attention from numerous Federal, State, and local agencies in an attempt to restore the largest fluvial and estuarine system in California.

2. Study area

2.1. Sacramento Flood Basin

The Cosumnes River (basin area is $\sim$ 3000 km^2) drains the west side of the Sierra Nevada and joins Mokelumne River in the Central Valley near the margin of the Sacramento–San Joaquin River Delta (Fig. 1). The downstream 15 km of the lowland river is below an elevation of $\sim$ 9 m (NGVD) and has a gradient of $\sim$ 0.0005. Winter rainfall and runoff generated from smaller spring storms and snowmelt influence the mostly unregulated flow of the Cosumnes River. At the Cosumnes River Preserve study area (Fig. 2a; elevation range from below sea level to $\sim$ 4.0 m NGVD), the floodplain would be seasonally inundated in the absence of constructed levees. Abandoned channels remaining as "sloughs" are tidally influenced but were formed by the anastomosing Cosumnes River system, rather than by tidal processes.

The downstream 15 km of the Cosumnes River system is situated in the Sacramento Flood Basin (Fig. 2a), the southern-most flood basin along the Sacramento River identified by Gilbert (1917). The Sacramento Flood Basin extends from the City of Sacramento to the Delta margin. It is bordered on the west by the natural levees, now augmented by engineering practices, along the east side of the Sacramento River (Bryan, 1923; Wagner et al., 1981) and on the east and northwest by late Pleistocene fans of the Riverbank Formation (Fig. 2b; Atwater and Marchand, 1980). The flood basins were dry for the majority of each year, as well as during drought years. In contrast, during wet years, the basins were inundated "inland seas," with only levee tops emergent (Bryan, 1923). During floods, stage in the flood basins equalized with stage in the Sacramento River channel as flow overtopped or seeped through sandy layers, flowed through low areas or breaches in the natural levees, or flowed through connections present at the downstream ends of most of the basins. Bryan (1923) noted that overbank flows from the perennial Cosumnes, and adjacent Mokelumne and American Rivers, created floodplain lakes and seasonal marshes that slowly drained through multiple channels within the flood basins. Relatively coarser sand transported in the anastomosing channel network was suspended in flow and deposited in the levees or crevasse splays adjacent to channels, while finer clay and silt was carried in suspension farther into the flood basins. Flood basin deposits are clay-rich sediment derived from overbank flood flows trapped between the natural levees formed by the Sacramento River and its tributaries and the edge of the fans (Gilbert, 1917; Bryan, 1923; Olmsted and Davis, 1961).

Central Valley Rivers and the Cosumnes floodplain experienced significant changes in the past two centuries as a result of land use practices initiated in the 1800s. Hydraulic gold mining practices caused excessive sedimentation in the Sacramento River, raising the bed elevation at the City of Sacramento by over 3.0 m between 1890 and

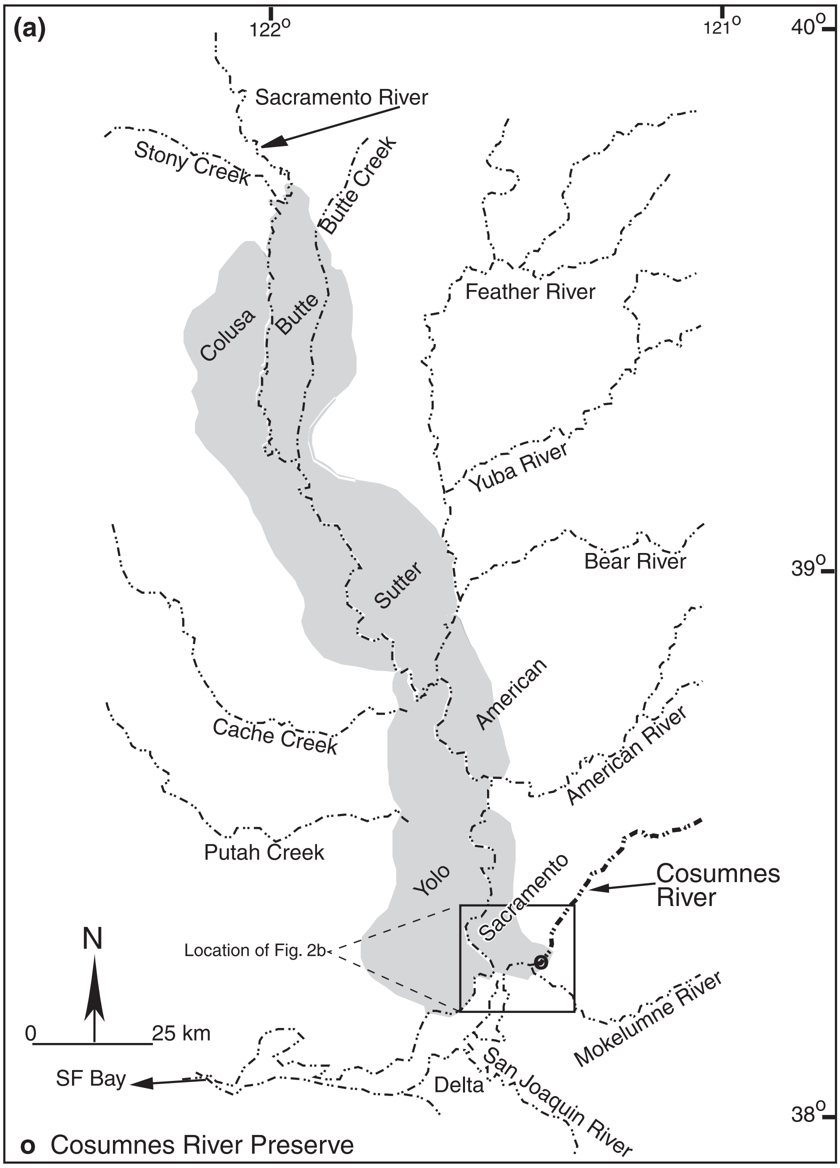

Fig. 2. (a) Sacramento River valley flood basins (Gilbert, 1917) showing location of Cosumnes River Preserve study area. (b) Geologic map of the lower Cosumnes River floodplain showing Sacramento Flood Basin deposit.

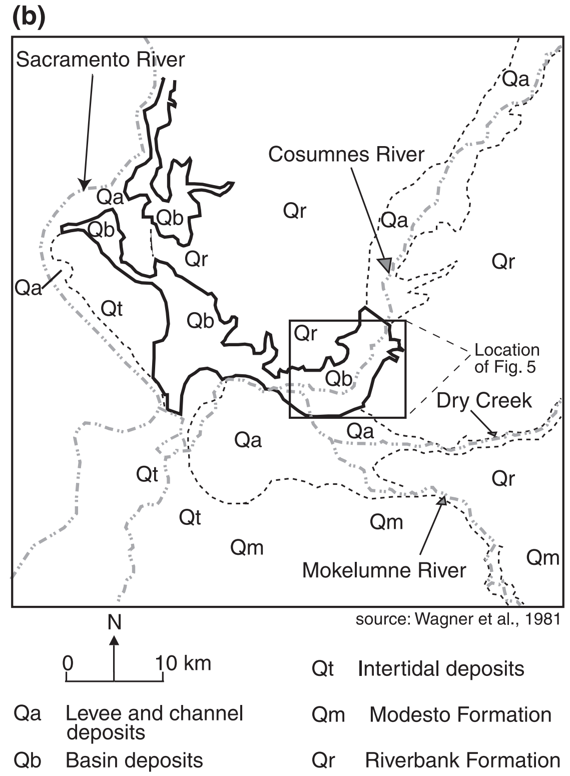

Fig. 2 (*continued*).

1900 (Gilbert, 1917). This in turn raised the low water stage by 2.1–2.4 m, causing a portion of the seasonal marsh in the American flood basin, that was originally drained by deep channels or sloughs, to remain wet year-round (Bryan, 1923). Similar influences are likely to have altered the hydrosystem of the adjacent Sacramento Flood Basin, by creating a backwater effect that increased flood stage and duration on the Cosumnes floodplain. In the Cosumnes watershed upstream of the study area, hydraulic mining of Tertiary auriferous gravel, tunneling, where volcanic rock capped the gravel, and terrace and floodplain dredging followed channel placer mining. The largest mines affecting the Cosumnes floodplain included Mendon and Indian Diggins on the South Fork and Henry Diggins on the Middle Fork of the Cosumnes River, and several others in Dry Creek, Deer Creek, and the Mokelumne River watersheds (Lindgren and Turner, 1892; Turner, 1892). Gold "diggins," disturbed the reddish colored sediment of the Eocene Ione Formation in the Dry Creek watershed and produced tailings that became a local source for fine sediment to the downstream Cosumnes floodplain near the confluence of these systems. Gilbert (1917) suggested that hydraulic mining sediment supply to the Cosumnes River was limited and that sedimentation damage to downstream floodplain farms occurred but was less severe than in other mining areas of the Sacramento watershed. Nonetheless, mining activities in the Cosumnes watershed are likely to have increased sediment supplied to the downstream channel and floodplain. Moreover, other land uses such as grazing, vegetation removal, and establishment of vineyards on higher elevation Plio-Pleistocene alluvial fans, sometimes called the "red lands" because of their red color (Bryan, 1923), also significantly accelerated erosion and provided a source of sediment to the downstream channel and floodplain. Although the channel upstream of the Cosumnes River Preserve is currently incised (Vick et al. 1997; Andrews, 1999; Constantine et al., 2003), the initial response of the Cosumnes River to historic mining and land conversion was probably aggradation. In contrast, in the downstream study reach, the main Cosumnes River channel is not significantly incised at present. At the Cosumnes River Preserve, habitat degradation resulted from direct disturbances such as leveling floodplain topography, filling in channels, draining wetlands, clearing riparian forests, land conversion to agriculture, and construction of levees that isolated the floodplain from the anastomosing channel network. The loss of habitat and the dynamic processes that transported water and sediment to various portions of this lowland floodplain led to an effort in the past decade to rehabilitate riparian habitat by intentionally breaching levees at the Cosumnes River Preserve (The Nature Conservancy (TNC), 1992). Florsheim and Mount (2002) describe the geomorphic processes in the post-rehabilitation sand splay complexes formed at the levee breaches.

2.2. Quaternary geomorphology

The Quaternary geomorphology of the lower Cosumnes basin is affected by Plio-Pleistocene tectonic uplift in the Sierra Nevada and relative subsidence in the Central Valley (Bovis, 1987; Wakabayashi and Sawyer, 2001) and by both glacial processes and sea level fluctuation associated with Quaternary climate change (Bateman and Wahrhaftig, 1966; Wahrhaftig and Birman, 1965; Shlemon, 1995; Wagner et al., 1981; Atwater and Marchand, 1980). Estimated rates for sea level rise and for tectonic subsidence (Table 1) are used in this paper to infer floodplain sedimentation rates in the absence of direct dates from subsurface strata at the Cosumnes River Preserve. In San Francisco Bay, sea level rose at a rate of ~ 1.0–2.5 mm/year from ~ 6000 YBP to the present (Atwater et al., 1977; Peterson et al., 1995). Thus, an estimate of the pre-disturbance Holocene floodplain sedimentation rate corresponding to sea level rise alone would be 1.0–2.5 mm/year. However, Holocene floodplain sedimentation rates kept pace with both sea level rise and tectonic basin subsidence. Band (1998) suggested that the Midland Fault, located parallel to the Delta margin immediately west of the Cosumnes–Mokelumne River confluence, is an active west dipping reverse fault with a relative slip rate of 0.2–0.5 mm/year (with the Montezuma Block rising relative to the Central Valley Block). Estimates for tectonic subsidence in the Central Valley during that period are uncertain, but probably ranged from 0.15 to 0.5 mm/year (Wakabayashi, personal communication, 2002), similar to the recent slip rate on the Midland Fault. Assuming that the Cosumnes River Preserve is situated west of the Sierran uplift hinge line, estimates of average late Holocene floodplain sedimentation rates may have ranged from ~ 1.15 to 3.0 mm/year. While local rates are highly variable, an average estimate for the total pre-disturbance Holocene Cosumnes River floodplain sedimentation over the past 1000 years is ~ 1.15–3.0 m.

Table 1
Pre-disturbance Holocene (1000 YBP to present) floodplain sedimentation rates

	Low estimate (mm/year)	High estimate (mm/year)
Rate of sea level rise	1.0[a]	2.5[b]
Rate of tectonic subsidence	0.15[c]	0.5[c]

[a] Atwater et al. (1977) reported range as 1–2 mm/year.
[b] Peterson et al. (1995) reported as up to 2.5 mm/year.
[c] Wakabayashi, personal communication, 2002.

3. Methods

A combination of methods employed to investigate the three stages of floodplain sedimentation included: (1) analysis of historical records such as bridge core logs, maps, and photographs; (2) field reconnaissance and mapping; (3) field sediment textural analysis and sampling; and (4) laboratory sediment analysis. The geomorphic response of the lower Cosumnes River to anthropogenic change was inferred through review of historic planimetric and topographic maps, historical accounts of early explorers to the region and to the lower Cosumnes, and published geologic and geomorphic data. As in similar studies, problems in historic map comparison include varying scale (Leys and Werrity, 1999) and are limited by changes in mapping accuracy and selection of features mapped (Hooke and Redmond, 1989). For example, early maps depicting the Cosumnes River (U.S. Surveyor General, 1863, 1867; U.S. Geological Survey, 1894) offer little detail with respect to topography or geomorphic features such as secondary channels and marshes, compared to more detailed later maps (U.S. Geological Survey, 1910, 1980).

We quantified changes resulting from anthropogenic activities to the low sinuosity anastomosing river channel–floodplain character by selecting morphometric parameters that characterize the anastomosing system attributes: (1) the number of channel segments, n; (2) the length of channel segments, L; and (3) floodplain drainage density (D_{fp}):

$$D_{fp} = \sum L/A \quad (1)$$

where ΣL is the sum of the lengths of all channel segments within a measured floodplain area, A. Floodplain drainage density is a particularly useful parameter used in this context to quantify changes in channel–floodplain interactions in the anastomosing system between 1910 and 1980.

Grain-size analyses using a Coulter laser granulometer differentiated the percent silt from clay from sand in samples collected from the Corps Breach restoration area (Fig. 3a). Post-rehabilitation sand splay complex bulk sediment samples were collected from 31 locations in 2000 using a 10-cm diameter metal container. The fine veneer capping the sand spay deposit, present at nine of these locations, was sampled by separating

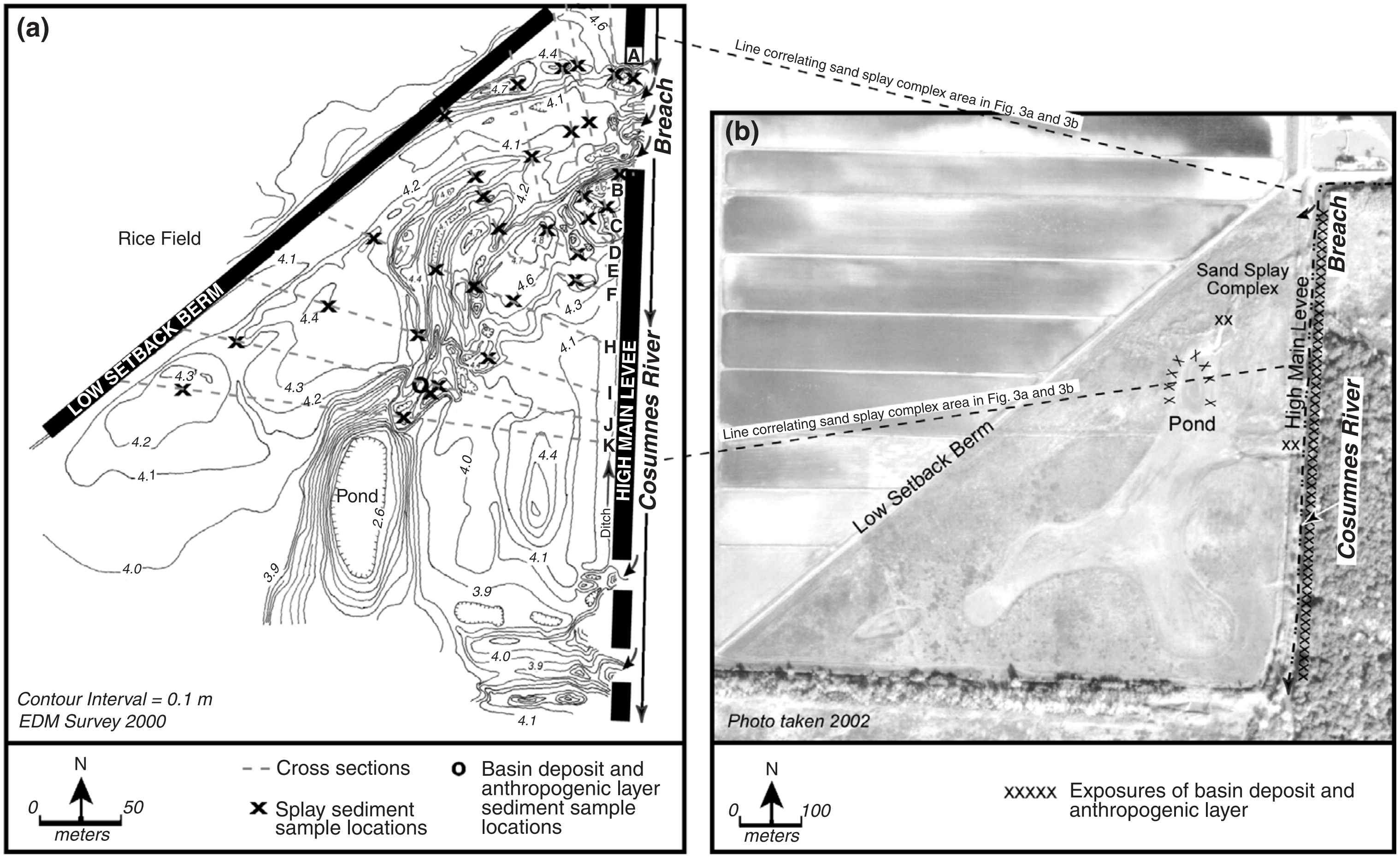

Fig. 3. (a) Sediment sample locations along cross-sections surveyed at Corps Breach floodplain sand splay complex. Source of topographic map is Florsheim and Mount (2002). (b) Locations of basin deposit and anthropogenic layers visible in study area.

the desiccated fine veneer from the coarser sand beneath. Some error inherent in this sampling method resulted from coarser sand from the layer below sticking to the veneer. The basin deposit and the anthropogenic layer were identified on the basis of color and field textural analyses during field reconnaissance of the Cosumnes River Preserve (Fig. 3b). Samples from both deposits collected from a location at the base of an incised floodplain channel within the splay complex were analyzed using the granulometer (Fig. 3a).

4. Results

4.1. Pre-disturbance Holocene Cosumnes River floodplain 1000–200 YBP

Geomorphic processes in the pre-disturbance Cosumnes River floodplain are inferred from historic documents, from sediment composition observed during field reconnaissance, and analyses of bridge core logs. Geologic maps document flood basin, levee, splay, and channel deposits underlying the Cosumnes River floodplain (Fig. 2b; Atwater and Marchand, 1980; Wagner et al., 1981). In the study area, the high clay content of the basin deposit was apparent from field examination of the unit visible in the banks of the main Cosumnes River channel, at the base of a new floodplain channel incised in the sand splay complex, and at the margin of the excavated pond (Fig. 3b). Laser granulometer analysis of a sample collected from the base of a newly incised floodplain channel in the restoration area indicates that the basin deposit composition is ~ 87% clay (Table 2). The color of the basin deposit reflects gleying under the influence of excessive moisture. Field reconnaissance suggested that the basin deposit is fairly uniform within the study area, however, other evidence illustrates spatial variability within the unit. For example, (Atwater and Marchand, 1980) describe the basin deposit further downstream near the confluence with the Mokelumne River as silty clay and clayey silt containing $CaCo_3$ (nodular or disseminated), black sand-sized spherules (probably Mn-oxide), and gastropods.

Bridge core logs also illustrate the variability of sediment strata that comprise the floodplain of the lower Cosumnes River in the vertical dimension (Fig. 4). Most strata logged consist of gray blue to brown clay and silt. However, a few layers contain peat or organic material, while others contain sand and gravel. Strata composed primarily of sand likely represent paleochannels, levees, or splays common in anastomosing fluvial systems. Peat traces logged at depths of 6–12 m below the surface in one core at Twin Cities Road (Sacramento County, 1979) and organic material near the surface in several cores at Lost Slough Bridge (California Department of Transportation, 1977) may be: (1) remnants of perennial wetlands in inter-levee ponds or in abandoned channels commonly associated with anastomosing river processes, or (2) former wetlands formed by prolonged periods of inundation in the flood basin. However, the cores do not contain the peat soils such as are pervasive in the freshwater tidal wetlands in the adjacent Delta (Wagner et al., 1981; California Department of Water Resources, DWR, 1995) suggesting that, at the Cosumnes River Preserve, the floodplain marsh was seasonal. Gravelly, layers present in the cores represent periods of higher stream energy such as floods with sufficient energy to transport coarser sediment in the low gradient paleochannels, that were subsequently buried by finer flood basin sediment.

Table 2
Average particle size distributions: Corps Breach floodplain sample sites

	Clay (%)	Silt (%)	Very fine sand (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)	Very coarse sand (%)	Gravel (%)
Sand splay complex								
Sand layers	3.9	0.6	2.0	5.7	23.6	44.4	15.9	0.8
Intervening finer layers	36.3	10.3	16.4	10.0	8.8	13.7	4.5	0.0
Basin deposit	87.3	5.4	5.6	0.9	0.0	0.0	0.0	0.0
Anthropogenic layer								
	38.9	13.8	26.3	20.2	0.8	0.0	0.0	0.0

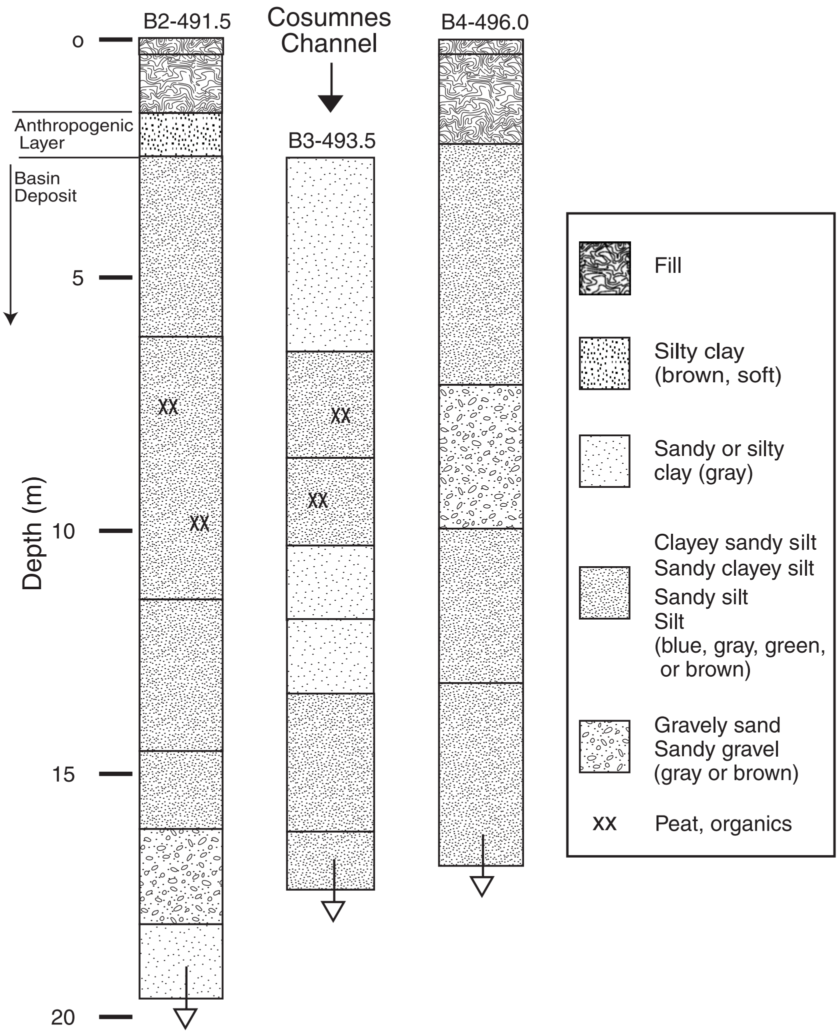

Fig. 4. Example of bridge core logs from Twin Cities Road Bridge (modified from Sacramento County, 1979).

Historic documents from Spanish Explorers in the 1770s (Farquhar, 1966) suggest that prior to anthropogenic disturbance, the downstream 15 km of the Cosumnes River and floodplain system supported a seasonal freshwater wetland mapped as "Tulares," or tules (*Scirpus lacustris*). Based on the geologic evidence documented in field reconnaissance and analysis of the bridge log cores, we infer that this condition was similar to that of the late Holocene when the wetland was the physical setting for deposition of the clay-rich basin deposits. In this pre-disturbance system, overbank floods left a vertical profile of clayey sediment interspersed with coarser layers containing silt, sand, and sometimes gravel, reflecting the integration of settling of sediment from suspension during overbank flow and dynamic anastomosing channel, splay, and levee formation.

4.2. Cosumnes River floodplain changes 1849–1995

Changes in sedimentation processes on the Cosumnes River floodplain that began with the 1849 Gold Rush are inferred from historic map analysis, field reconnaissance, and sediment grain size analyses. Fig.

5a–c shows changes in river channel pattern documented on maps in 1884, 1910, and 1980, and illustrates the reduction of hydrologic complexity in the Cosumnes channel–floodplain system due to anthropogenic activities. Quantification of changes in anastomosing river morphometry in the lower 15 km of the Cosumnes River between 1910 and 1980 are reported in Table 3. Fig. 5b shows a seasonal floodplain marsh that was the remnant of the large marsh mapped as "swamp and overflowed" land in the mid-1800s, but the marsh was still hydrologically connected to the channels and to the lagunitas on the east side of the floodplain. Floodplain drainage density, a measure of the density of channel segments, decreased by ~30% between 1910 and 1980 in response to the land use changes summarized in Table 4. This reduction in floodplain channel density has significant hydraulic and ecological implications. Analysis of earlier boundary survey maps also suggests that numerous small channels were present at the Cosumnes River Preserve. For example, ~20 small channels were mapped as "slough" crossings along the eastern edge of the flood basin (U.S. Surveyor General, 1863). Timbered or dense forest vegetation noted alongside suggests that these "sloughs" were abandoned or inactive channels of the anastomosing system, with riparian trees established on adjacent natural levees. A modern analog is the remnant climax oak forest along Wood Duck Slough at the Cosumnes River Preserve (Fig. 5c), one segment of the anastomosing Cosumnes River mapped in 1884.

Field reconnaissance documents the presence of a reddish-brown sediment layer overlying the basin deposit (Fig. 3b). This sediment was easily distinguished in the field from the basin deposit by its red-brown color and higher silt content and is consistent with the "anthropogenic layer" overlying the basin deposit documented in a preliminary geologic map of the area prepared by Atwater and Marchand (1980). Analysis of a sample of this red–brown colored sediment collected from a layer stratigraphically above the basin deposit in a newly incised floodplain channel in the restoration area (Fig. 3a) quantifies the grain size distribution as a sandy clay with ~40% clay and 14% silt (Table 2). The contact between the basin deposit and the anthropogenic layer observed in Cosumnes River channel banks is irregular, reflecting the predisturbance topography of the floodplain prior to deposition of the anthropogenic layer. Consequently, the thickness of the anthropogenic layer is spatially variable and is not present in all of the bridge cores (Fig. 4; Table 5). The anthropogenic layer is identified in the bridge core logs as the coarser surface layer composed of very loose, brownish, very fine sandy silt, or as soft brown silty clay (Fig. 4).

The thickness of the anthropogenic layer is measured as 0.98 m in the channel bank near the downstream end of the Corps Breach splay complex. This measurement reflects a minimum value, since surface erosion of the floodplain occurs in that area. An estimate of the average thickness of the anthropogenic layer at the Cosumnes River Preserve is interpolated between Lost Slough Bridge and Twin Cities Road Bridge core logs. Where present, the thickness ranges from 0.6 to 2.4 m at Lost Slough and from 0.9 to 2.1 m at Twin Cities Road and an average thickness at the Cosumnes River Preserve estimated from the logs of bridge test cores is ~1.5 m. Thus, a rapid rate of sedimentation as high as 25 mm/year created the anthropogenic layer during the decades following the gold rush, while the lowland Cosumnes floodplain in the flood basin remained "swampy and overflowed" (U.S. Surveyor General, 1863, 1867). During this period, while the anthropogenic layer was deposited, the flood basin received water and sediment from the severely disturbed Sacramento system as well as from the Cosumnes River–Dry Creek–Mokelumne River system. After ~1920, constructed levees significantly limited flow and sediment from the Sacramento and Cosumnes systems to the area of the Cosumnes River Preserve and floodplain sedimentation during this second phase of Stage II is assumed to be negligible.

4.3. Cosumnes River floodplain rehabilitation 1995 to the present

In an effort to reverse the direction of change from floodplain habitat degradation toward restoration, breaches in the levee separating the Cosumnes River from its leveled floodplain were constructed during the 1990s at the Cosumnes River Preserve. Rapid vertical accretion and floodplain scour created sand splay complexes where deposition of vertically organized strata are associated with stages of the hydrograph: with thicker sand layers deposited by high stage separated by a silty veneer deposited during receding

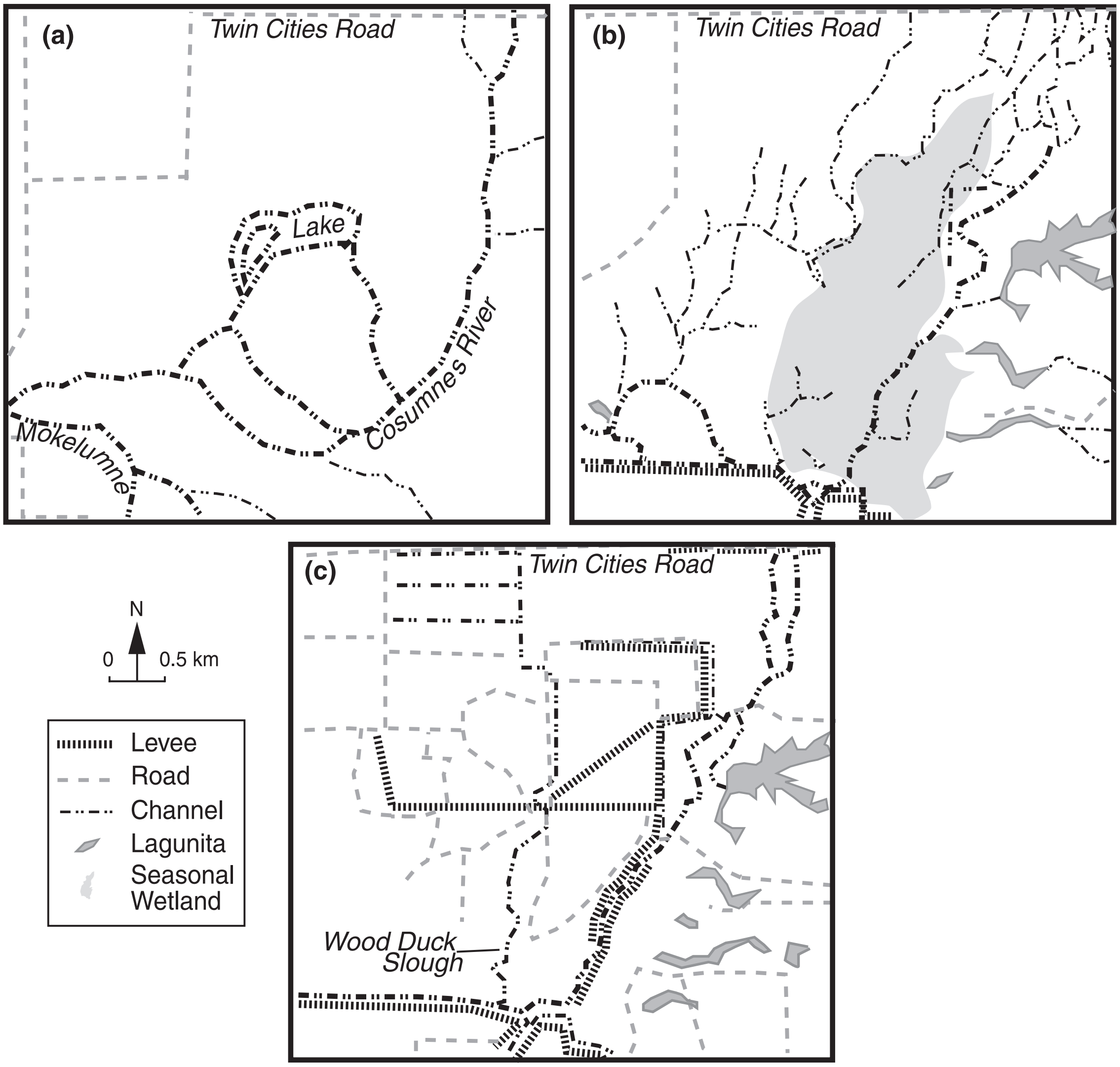

Fig. 5. Historic changes in anastomosing river channel floodplain interactions resulting from anthropogenic disturbances. (a) 1884/8 (USGS map 1:125,000), a main and secondary channel of the Cosumnes River were farther west than in 1980. Immediately upstream of the confluence with the Mokelumne River, three channel branches form a loop-like pattern; the northern-most segment widens as a lake; (b) 1910 through 1947 (USGS map 1:62,000) the Cosumnes River floodplain contained at least six discrete channel segments separated by islands across a floodplain width of $\sim$ 2.5 km. Anthropogenic changes included a drainage ditch with a 90° bend (immediately east of the Cosumnes River Preserve study area) and a constructed levee that straightened the main channel upstream of the confluence with the Mokelumne (completed in 1907). Concurrently, levees along the Sacramento River already limited overbank flow to the flood basin. The main Cosumnes channel avulsed into the levee borrow ditch with the 90° bend sometime between 1968 and 1975. (c) 1980 (USGS map 1:24,000) the multiple channel system mostly concentrated into a main channel, the seasonal marsh is replaced with agricultural fields, and levees divide and isolate the floodplain from other components of the fluvial system.

flood stage (Florsheim and Mount, 2002). Additional data presented here include laser granulometer particle size analyses of sand and intervening finer layers that were collected from the Corps Breach sand splay following the floods that occurred during water year 2000 (Table 2; see Fig. 3a). These detailed sediment analyses quantify clay and silt components and facilitate comparison to sediment samples from the gray

Table 3
Changes in anastomosing Cosumnes River morphometry between 1910 and 1980[a]

Σ lengths (km)			Channel segments (#)			Drainage density (m/m^2)		
1910	1980	Difference	1910	1980	Difference	1910	1980	Difference
116	36	− 80	68	14	− 54	2.6	0.8	− 1.8

[a] Floodplain area $A = wl$ where w is ~ 2.5 km and l is ~ 17.7 km.

blue basin deposit and from the reddish brown anthropogenic layer (Table 2). The majority of sand layers in the post-rehabilitation Corps Breach splay complex are composed of medium to very coarse sand with minor amounts of clay and silt (Table 2). Gravel comprises less than 1.0% of this deposit and is segregated in patches present on the higher elevation portions of the splay lobes, or in the new floodplain channel close to the breach.

Intervening finer layers within the sand splay complex, deposited as a veneer as floodplain stage recedes, are composed of sand, clay, and silt (36% clay and 10% silt), and are generally only found in channels or on lower elevation areas of the splay complex (Table 2). These layers have similar clay and silt content but coarser sand component than exists in the anthropogenic layer. The coarser sand size distribution appears to be an artifact of the sampling method, where coarser sand adheres to the overlying finer veneer. However, such a difference in sand size distribution could occur if: (1) the splay complex represents a locally higher energy environment than existed in the flood basin during deposition of the anthropogenic layer; or (2) current upstream land use disturbances in the Cosumnes basin supply coarser material to the flood basin than it did in the past.

The intervening finer layers of the splay complex are likely to have a similar size distribution to sediment deposited on the floodplain beyond the splay complex in the restoration area at the Cosumnes River Preserve.

Table 4
Time line of land use changes affecting Cosumnes system floodplain sedimentation

Date	Land use change	Effect on floodplain sedimentation	Reference
1861	Initiation of land conversion from floodplain marshes and riparian forests to agricultural fields	Draining wetlands, filling secondary and abandoned channels and sloughs, and leveling floodplain topography	Commissioner of Public Works, Sacramento, CA, 1861
1890–1900	Hydraulic mining for gold	Excessive sedimentation in Sacramento River raised the bed elevation by over 3 m at Sacramento City Caused backwater in American flood basin and increased duration of flooding in flood basins	Gilbert, 1917 Bryan, 1923
1907	Initiation of levee construction and channelization along the Cosumnes system	Concentration of flow from multiple channels into fewer channels, limitation of river-floodplain connectivity reduced floodplain sedimentation	R Bauer, Reclamation District 100, personal communication, 1999; U.S. Geological Survey, 1910
1908	Levee construction along the Sacramento system	Limitation of Sacramento River-flood basin connectivity reduced floodplain sedimentation	U.S. Geological Survey, 1908
1908–1995	Continued levee construction and land conversion to agriculture	Progressive limitation of river-floodplain connectivity reduced floodplain sedimentation, except during accidental levee breaches	U.S. Geological Survey, 1910, 1980
1995–present	Intentional levee breaches for floodplain habitat restoration at the Cosumnes River Preserve	Re-created channel and floodplain connectivity	Florsheim and Mount, 2002

Table 5
Logs of bridge test cores with anthropogenic layer present[a]

	Number of cores (#)	Average thickness (m)	Data source
Lost Slough Br.	4[b]	1.6	California Department of Transportation, 1977
Twin Cities Rd.	3[c]	1.4	Sacramento County, 1979

[a] Cores in modern channels excluded; road fill that overlies anthropogenic layer is not included in analysis.
[b] B2 at 578.25, 485.18, 491.25: very loose brown very fine sandy silt or soft brown silty clay.
[c] B18, B12, B6, B11: brown clayey silt to gray–brown clayey silt with organic material.

Over time, splay complex progradation over this finer sediment may occur. Nonetheless, even the finest component of the sediment sampled from the sand splay complex is substantially coarser than the pre-disturbance late Holocene basin deposits. Results of these analyses of sediment samples collected at the Cosumnes River Preserve show an upward coarsening sequence of sediment deposits that is significant because it documents the effect of upstream land use changes on floodplain sediment character.

5. Discussion

Three distinct stages of floodplain sedimentation are documented in the vertical profile exposed in portions of the Cosumnes River Preserve, including: Stage I pre-disturbance Holocene, Stage II anthropogenic disturbances, and Stage III post-rehabilitation floodplain sedimentation. The change in dominant depositional processes and sediment sources are reflected in the upward coarsening vertical profile illustrated in Fig. 6. This conceptual vertical accretion model suggests that sedimentation varied temporally and spatially depending on the balance between flow regime and sediment supply from the both the Sacramento River to the west and the Cosumnes–Mokelumne River systems to the east. Basin subsidence, sea level rise, and anthropogenic changes have governed this balance to varying degrees in the past millennia. Over time, locally variable floodplain erosion adds to the complexity of the floodplain sediment assemblage.

5.1. Stage I: pre-disturbance Holocene floodplain sedimentation

During Stage I pre-disturbance Holocene floodplain sedimentation, the Sacramento River flood basin received sediment from both the Sacramento River and the Cosumnes River–Dry Creek–Mokelumne River systems and deposition roughly kept pace with sea level rise and basin subsidence. An average estimate for the total pre-disturbance Holocene Cosumnes River Floodplain sedimentation over the past 1000 years based on estimates of sea level rise and basin subsidence is ~ 1.15–3 m. Analysis of bridge core logs within the Sacramento Flood Basin suggests that the clay-rich flood basin sediment assemblage is composed of sediment derived from overbank flow from both the Sacramento and Cosumnes Rivers, interspersed with thinner layers of coarser sediment deposited in channels, levees, and sand splays associated with the anastomosing Cosumnes River system. The gray-blue color of the silty clay at the Cosumnes River preserve distinguishes this pre-disturbance deposit that formed over a period when natural processes dominated the complex Central Valley hydrosystem. Prior to anthropogenic disturbances, contribution of floods from the upstream Sacramento River watershed combined with floods from the Cosumnes River system, and is likely to have increased the flood stage and duration on the Cosumnes River floodplain by creating a backwater.

5.2. Stage II: anthropogenic disturbances

The century following the 1849 gold rush in California led to rapid alteration of the Sacramento Flood Basin hydrosystem. In a first phase of Stage II from 1849 to ~ 1920, anthropogenic disturbances overwhelmed the dominant anastomosing river and flood basin processes and accelerated the floodplain sedimentation rate. This first phase of disturbance included hydraulic and other types of mining for gold, progressive denudation of riparian forests, and the initiation of agriculture within the upstream Sacramento River watershed. These land uses tended to increase upstream erosion and sediment supply, and, in response, the Sacramento River and its tributaries aggraded (Gilbert, 1917; James, 1991, 1993). Similar changes taking place in the Cosumnes basin at the same time added

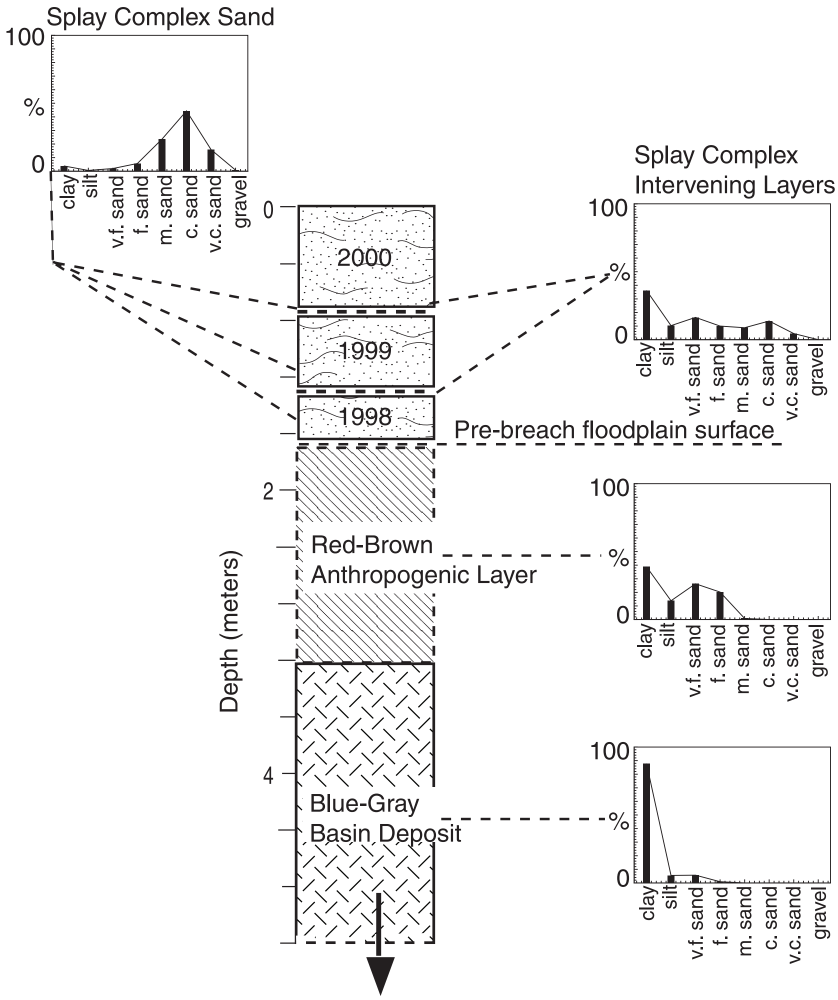

Fig. 6. Changes in particle size distributions illustrate an upward coarsening profile of floodplain sediment assemblage. Histograms from the post-rehabilitation sand splay complex are composites of samples collected at the levee breach sand splay complex, Cosumnes River Preserve. Basin subsidence, sea level rise, and anthropogenic changes governed floodplain sediment deposition rates and size distribution during the past millennia.

to the sediment load, and likely caused local aggradation in the anastomosing system leading to an observation by Piper et al. (1939) that the multiple channels of the Cosumnes system were hydraulically inefficient. Reduced channel capacity in both the Sacramento and Cosumnes Rivers, led to more frequent and higher flood stages that breached or overtopped natural levees providing a conduit for coarser silt and sand to leave the channels via overbank flow. This scenario accounts for a coarser anthropogenic layer deposited over the pre-disturbance basin deposit at a rapid rate up to 25 mm/year. The reddish brown color of the sandy, silty, clay in the anthropogenic layer reflects accelerated erosion of reddish soil throughout the watershed and of the reddish colored slickens that coated the hydraulically mined Eocene gravel.

During the second phase of Stage II, from ~ 1920 to 1990, riparian forest denudation continued and floodplain topography was leveled for agriculture. Progressive construction of levees along both the Sacramento and the Cosumnes systems led to a significant reduction of floodplain sedimentation, and the rate of floodplain sedimentation in the Sacramento Flood Basin was ∼ 0.0 m/year from the 1920s to the 1990s, except during accidental levee breaches. Accidental breaches in constructed levees promote sedimentation similar to that which occurred along the Mississippi and Missouri Rivers in 1993 (Gomez et al., 1997; Jacobson and Oberg, 1997; Schalk and Jacobson, 1997) or to that which occurred on the lower Cosumnes River in 1985 (Florsheim and Mount, 2002).

Levees that blocked floods from the Sacramento River changed the hydrogeomorphology of the lowland flood basin, and the Cosumnes River is currently the dominant source of water and sediment to the adjacent floodplain. Since completion of the levee systems on the Sacramento and Cosumnes Rivers, floodplain flows that exist are likely to have significantly lower stages and shorter duration than during the pre-disturbance Holocene. Levee construction concentrated flow from multiple secondary channels and likely increased velocity and shear stress in the main channel leading to the incision upstream of the study area. Further, levees limit transport of sediment, water, and nutrients from the channel onto the adjacent floodplain, except during accidental breaches such as occurred at the Accidental Forest at the Cosumnes River Preserve (Florsheim and Mount, 2002). The loss of connectivity and reduction in the number of shallow water anastomosing channel segments reduced edge habitat and affected ecosystem diversity in the floodplain ecotone. Finally, these floodplain and channel changes were compounded by riparian vegetation denudation and agricultural leveling that subsequently dominated floodplain morphology.

5.3. Stage III: post-rehabilitation

During Stage III post-rehabilitation floodplain sedimentation, intentional levee breaches at the Cosumnes River Preserve re-established channel floodplain connectivity in several locations. Floodplain monitoring following the opening of the Corps Breach documents development of a sand splay and channel complex with annual deposition of medium to very coarse sand layers capped by silty clayey sand. Sediment sampling on the Corps Breach sand splay illustrates the vertical variation of sediment sizes. A relatively rapid short-term depositional rate of medium to very coarse sand in lobes, levees, and channels of the splay complex was measured as ∼ 80 mm/year (Florsheim and Mount, 2002).

Rates of sedimentation on the Cosumnes floodplain Corps Breach sand splay complex are highly variable and are substantially lower on the relatively level floodplain beyond the splay deposit. Thus, although averaged over the entire splay complex, including channels and some areas with no deposition, the rate of 80 mm/year represents the near-breach depositional rate, rather than the rate in the distal floodplain area. Moreover, size distribution of the majority of the sediment deposited in the sandy splay complex is likely to be coarser than sediment deposited on the floodplain beyond the splay. Although, during the falling hydrograph stage, deposition of the intervening finer layers on the splay is probably similar to sediment transported past the splay onto the distal portion of the floodplain. This relatively fine splay-complex sediment component has a similar proportion of clay and silt as the anthropogenic layer suggesting that the watershed scale disturbances that altered the flood basin sediment character continue today.

Numerous dams and pervasive levees along the modern Sacramento River and its tributaries preclude contribution of water and sediment from the Sacramento system to the lower Cosumnes floodplain. Widespread flooding in the lower Cosumnes floodplain resulting from accidental levee breaches is limited to the largest magnitude floods such as occurred in January 1997. Thus, there is a substantially reduced source for the finest clay-rich sediment that once dominated the flood basin. However, in the past decade, contribution of Stage III post-rehabilitation sediment derived from the Cosumnes watershed was supplied to the floodplain at the levee breaches. This Stage III sediment reflects upstream watershed conditions including an incised channel with levees that efficiently transport sediment downstream to the Preserve. Monitoring of the sand splay complexes suggests that post-rehabilitation floodplain sedimentation is sufficient to initiate floodplain topography necessary for establishment of cottonwood and willow riparian forest patches (Mount et al., 2002).

Ongoing changes in the Cosumnes basin include extensive regional groundwater withdrawal that could, over the long-term, lead to subsidence that overshadows tectonic subsidence in the lower Cosumnes basin as it has in the Southern San Joaquin Valley (Galloway and Riley, 1999). But because groundwater pumping accelerated after construction of levees that limited exchange between the river channel and floodplain, we assume that groundwater-related subsidence did not affect Stage II sedimentation.

5.4. Implications of anthropogenic disturbance and flood basin sedimentation on current restoration efforts

Floodplain development often leads to control of river systems within levees, and many modern rivers are confined to a single channel and appear to have a meandering pattern. The geomorphic and ecological characteristics of anastomosing systems are often not recognized, but prior to disturbance, may have been prevalent in lowland rivers (Ward and Stanford, 1995; Brown, 1998; Ward et al., 2001). Moreover, engineered flood control and channel stabilization structures often prevent the combination of floodplain processes in anastomosing river flood–basin environments that included both: (1) low energy settling of sediment from suspension during overbank flow and (2) higher energy avulsion and dynamic floodplain sedimentation in natural levees and sand splays.

The dominant mechanism for floodplain construction in anastomosing systems is vertical accretion, such as at breaches in levees, where coarser sediment splays aggrade low areas of the floodplain (Smith et al., 1989; Miall, 1996). Finer sediment is deposited in inter-channel wetland basins formed between natural levees (Smith and Perez-Arlucea, 1994). Anastomosing systems are often associated with aggradation, tectonically subsiding basins, or systems with variable hydrologic regimes (Knighton and Nanson, 1993), conditions that were probably present in the Central Valley and lower Cosumnes system during the late Holocene. The average sedimentation rates estimated in this study are useful in order to compare differences in sediment supply and depositional processes during the three stages in order to quantify the effect of anthropogenic disturbances. However, actual sedimentation rates are affected by local variability present in dynamic anastomosing systems. For example, analysis of bridge core logs (Fig. 4) suggests that there is variation in strata thickness and even in the presence or absence of strata within distances on the order of meters. Similarly, ~ 4.0 km downstream of the Cosumnes River Preserve, variation in cores is attributed to the presence or absence of Sacramento River levees (K. Brown and G. Pasternack, U.C. Davis, personal communication, 2002).

Processes that formed the Stage III sand splay complex at the intentional levee breaches at the Cosumnes River Preserve appear to mimic processes inherent in undisturbed anastomosing systems. Prior to anthropogenic disturbance in the Sacramento Flood Basin, the Cosumnes River floodplain contained multiple channels incised into clay-rich flood basin sediment. In this type of low gradient, anastomosing multiple channel–floodplain system with cohesive channel banks, channel geometry is characterized by a low width to depth ratio, and low sinuosity channels tend to have low rates of channel migration (Nanson and Knighton, 1996). Flow is distributed among main and secondary channels that convey discharge at various stages (Richards et al., 1993; Harwood and Brown, 1993; Schumm et al., 1996). It follows that in the pre-disturbance Cosumnes River, the dominant process for floodplain evolution was avulsion, the dynamic switching of channel location where diversion of all or part of the discharge of a river to a lower part of the adjacent floodplain forms a new channel, or reoccupies an older channel, similar to processes described in other lowland systems (Smith and Smith, 1979; Smith et al., 1989; Richards et al., 1993). The propensity for natural levee breaching and avulsion is associated with a number of factors, such as sedimentation that causes channel elevation to approach that of the surrounding floodplain (Richards et al., 1993; Knighton and Nanson, 1993; Schumm et al., 1996; Nanson and Knighton, 1996), or channel blockage by woody debris in forested systems (Harwood and Brown, 1993). Bryan (1923) documented lateral levee formation along sand splays built into the Sacramento Valley flood basins at breaches in the natural levees along the main rivers, and the geologic record investigated in this study suggests that these processes occurred in the lowland Cosumnes system prior to anthropogenic disturbance. Monitoring post-rehabilitation geomorphic processes at the Cosumnes River Preserve will document the extent to which anastomosing rivers processes reestablish.

Geomorphic change during avulsion is episodic, causing natural erosion and deposition disturbance that is essential for riparian vegetation succession. Anthropogenic activities, such as levee construction in the Sacramento Flood Basin, isolated channels from their floodplains and prevented overbank sedimentation, avulsion, and formation of new floodplain channels. Limitation of these dynamic natural physical processes necessary to sustain a riparian ecosystem in combination with land use changes and floodplain development essentially arrested flood basin sedimentation and anastomosing river processes. The modern Cosumnes River is mostly confined to a single channel and appears to have a meandering pattern confined by levees. However, in the absence of structural control, the physical parameters that govern river channel pattern (low gradient, cohesive substrate, and a variable flow regime) could promote development of a multiple channel anastomosing system in the restoration area. While other parameters that affect channel pattern, such as sediment supply are uncertain, results from this study that document pre-disturbance geomorphic processes are an important consideration in developing sustainable restoration or rehabilitation strategies. Future hydrogeomorphic and hydraulic analyses are warranted to assess the implication of pre-disturbance processes on post-rehabilitation efforts.

6. Conclusions

The coarsening upward floodplain sediment assemblage at the Cosumnes River Preserve reflects the effects of land use changes on floodplain depositional processes. We identify three dominant stages of floodplain sedimentation: (1) Stage I pre-disturbance Holocene floodplain sedimentation (1000–200 YBP) includes Sacramento Flood Basin deposits derived from two mechanisms that include flood basin overbank flow and anastomosing river–floodplain interactions; (2) Stage II floodplain sedimentation (200 to ~ 10 YBP) is affected by anthropogenic disturbances that first accelerated, then substantially reduced sediment supply to the floodplain; and, finally, (3) Stage III post-rehabilitation sand splay and channel complex floodplain sedimentation (~ 10 YBP to the present) is accomplished at intentional levee breaches constructed to improve habitat. Analyses of sediment size distribution in samples from the Cosumnes River Preserve illustrate the change in depositional mechanisms and environment during the three stages.

During Stage I, the lower Cosumnes hydrosystem included a seasonally inundated floodplain marsh that was hydrologically connected to the multiple channels of the anastomosing river and to adjacent floodplain lakes. The pre-disturbance accretion rate that constructed the floodplain sediment assemblage was up to ~ 3.0 mm/year, through processes that included: (1) deposition of clay from suspension in overbank floods derived from both the Cosumnes–Dry–Mokelumne and Sacramento River systems; and (2) sandy, silty, or gravely layers deposited in channels or as levees and splays associated with the dynamic anastomosing river. Stage II anthropogenic disturbance related to gold mining, riparian denudation, and agricultural practices accelerated the accretion rate to ~ 25 mm/year between 1849 and ~ 1920, forming a coarser sandy clay "anthropogenic layer" of sediment over the finer basin deposit. However, progressive levee construction significantly limited channel–floodplain connectivity and further accretion. Agricultural leveling dominated floodplain morphology and a 30% loss in the density of floodplain channels reduced hydrogeomorphic complexity of the floodplain ecotone. These significant ecological implications led to restoration efforts at the Cosumnes River Preserve. During Stage III, a coarse sand splay complex rapidly formed on the floodplain inside the intentional levee breach. Finer intervening layers between sand deposited seasonally has a similar proportion of clay and silt as the anthropogenic layer suggesting that disturbance in Cosumnes Basin is still providing a source of sediment that initiated with 19th century land use activities. Although Cosumnes channel–floodplain connectivity is locally restored at the levee breach, the pre-disturbance Sacramento Flood Basin hydrosystem, influenced by both the Sacramento and Cosumnes–Dry–Mokelumne systems, was inundated over a larger area and for longer periods than at present.

Analysis of historical data suggests that the combination of anastomosing river processes and seasonal flood basin overbank floods were the dominant geomorphic processes contributing to floodplain deposition prior to anthropogenic disturbances at the Cosumnes River Preserve. These same mechanisms may have operated in many lowland Central Valley rivers and tributaries within the other Sacramento

Valley flood basins prior to disturbance and floodplain development and are an important consideration in developing ecosystem restoration and rehabilitation strategies.

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