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From deposition to erosion: Spatial and temporal variability of sediment sources, storage, and transport in a small agricultural watershed

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ABSTRACT

The spatial and temporal variability of sediment sources, storage, and transport were investigated in a small agricultural watershed draining the Coast Ranges and Sacramento Valley in central California. Results of field, laboratory, and historical data analysis in the Willow Slough fluvial system document changes that transformed a transport-limited depositional system to an effective erosion and transport system, despite a large sediment supply. These changes were caused by a combination of factors: (i) an increase in transport capacity, and (ii) hydrologic alteration. Alteration of the riparian zone and drainage network pattern during the past ~150 years included a twofold increase in straightened channel segments along with a baselevel change from excavation that increased slope, and increased sediment transport capacity by ~7%. Hydrologic alteration from irrigation water contributions also increased transport capacity, by extending the period with potential for sediment transport and erosion by ~6 months/year. Field measurements document Quaternary Alluvium as a modern source of fine sediment with grain size distributions characterized by 5 to 40% fine material. About 60% of an upland and 30% of a lowland study reach incised into this deposit exhibit bank erosion. During this study, the wet 2006 and relatively dry 2007 water years exhibited a range of total annual suspended sediment load spanning two orders of magnitude: ~108,500 kg/km^2/year during 2006 and 5,950 kg/km^2/year during 2007, only 5% of that during the previous year. Regional implications of this work are illustrated by the potential for a small tributary such as Willow Slough to contribute sediment – whereas large dams limit sediment supply from larger tributaries – to the Sacramento River and San Francisco Bay Delta and Estuary. This work is relevant to lowland agricultural river–floodplain systems globally in efforts to restore aquatic and riparian functions and where water quality management includes reducing fine sediment contributions that can couple with other pollutants.

1. Introduction

Converting lands from natural systems to agricultural activities such as grazing or cultivation transforms fluvial processes and sediment dynamics. For example, reduced soil infiltration capacity and increased runoff resulting from such activities in turn increase sediment erosion and water and sediment contributions to agricultural drainage systems (Wischmeier and Smith, 1960; Costa, 1975; Pimentel et al., 1995; Trimble, 1999; Trimble and Crosson, 2000; Knox, 2001; Montgomery 2007a,b). Conventional agricultural practices cause erosion rates to greatly exceed preagricultural erosion rates (Bennett, 1928; Wolman, 1967, Jacobson and Colman, 1986) and to exceed soil production rates over longer geologically relevant timescales (Montgomery, 2007a,b). Although sediment sources, sinks, and fluxes in fluvial systems are highly variable in time and space (Trimble, 1999), increases in suspended sediment loads of rivers are apparent globally as a result of human activities that accelerate erosion (Walling, 2006).

This paper reports results of field investigations to address changes in basin-scale, temporal and spatial variability of sediment sources, storage, and transport to understand effects of agricultural land use activities on geomorphic processes and sediment dynamics over the past century and a half. Our field area is a small agricultural watershed in central California that drains areas of the California Coast Ranges and the Sacramento Valley called Willow Slough (Fig. 1A). In this watershed, interactions between human activities and the spatial distribution of a longitudinal array of Quaternary sediment deposits govern modern sediment sources. The purpose of this work is to understand how variability in sediment sources and erosion processes affect timing and magnitude of suspended sediment load and its effects on water quality. First, we assess historical alteration of the drainage system configuration

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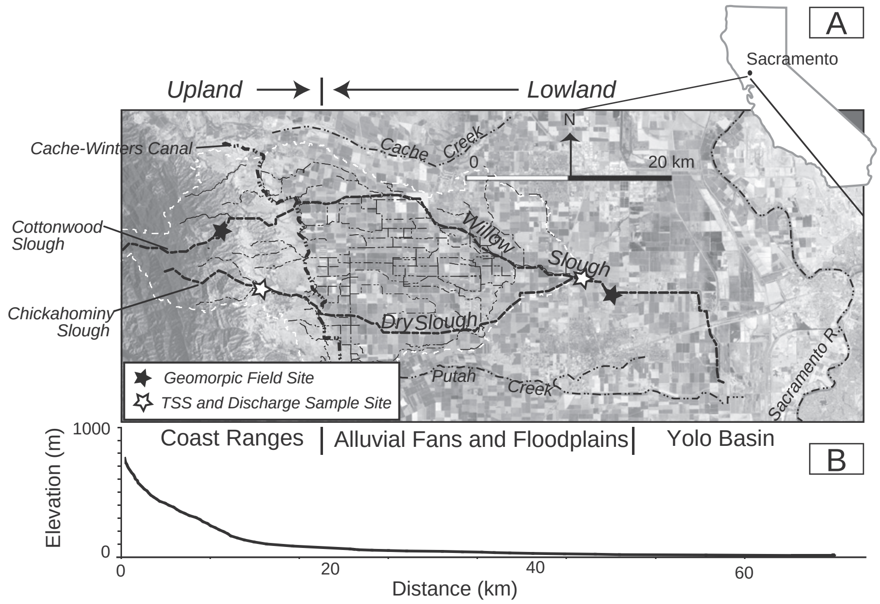

Fig. 1. (A) Location of tributaries to Willow Slough draining the northern California Coast Ranges and Sacramento Valley. Upland and lowland geomorphology field sites indicated with black star; discharge and TSS field sites indicated with white star. (B) Elevation profile highlighting the lowlands between the Coast Ranges and the natural alluvial levees west of the Sacramento River. Dashed line indicating watershed boundary upstream of confluence of Dry Slough and Willow Slough for reference is the same in Figs. 2 and 4.

and modified sediment routing pathways. Second, we characterize differences in sediment sources and contributions between upland and lowland areas with respect to morphology and grain size distributions within these environments. Third, we examine temporal alteration of suspended sediment transport dynamics attributable to modified hydrology resulting from irrigation practices. Finally, drawing on the results of our field and laboratory characterizations, we construct a conceptual model illustrating how changes in sediment pathways and erosion of Quaternary sediment deposits have transformed Willow Slough from a depositional to an erosional and transfer system over the past ~150 years.

This work adds to our fundamental knowledge of spatial and temporal variability in a basin-scale system subject to geomorphic alterations that result from conversion to agricultural use. Previous studies addressed the influence of water withdrawals from river basins and the effect of reduced flows on ecosystem services (Falkenmark and Lannerstad, 2005), particularly in large river systems globally (Scanlon et al., 2007). However, little work has been done to assess the geomorphic effect of increased flows from irrigation water contributions in small agricultural drainage systems. Thus, this study is significant in providing insight as to the effects of altered hydrology in an agricultural system where flows increase. Results are significant with respect to ecosystem-based management in agricultural regions where bank erosion and channel incision are considerable and where loss of floodplain connectivity is common. Because agricultural practices that mobilize sediment are likely to have a direct and significant impact on dissolved organic carbon (DOC) composition (Hernes et al., 2008), our results also have application in addressing sediment-derived water quality problems, such as with respect to pesticides and other contaminants that couple with sediment in agricultural runoff (Bergamaschi et al., 1999; Weston et al., 2004; Schoellhamer et al., 2007; Smalling et al., 2007).

2. Regional setting

The Willow Slough fluvial system originates within the northern California Coast Ranges and flows eastward to the Sacramento Valley between Cache Creek and Putah Creek (Fig. 1A). The two main tributaries to Willow Slough include Cottonwood Slough and Chickahominy Slough–Dry Slough. The expression 'slough' originated locally to describe sluggish or swampy channel segments as well as dry channels (Bryan, 1923); the Willow Slough drainage system is fluvial, not tidal.

The semiarid Mediterranean climate of the Sacramento Valley east of the Coast Ranges includes episodic winter storms and hot, dry summers. Average annual precipitation was 490 mm between water years 1983 and 2009, at the nearby Davis, Yolo County station (CIMIS, 2010). However, rainfall is strongly seasonal with the majority falling between November and March, and with large variations such that only a small number of wet days accumulate the majority of the annual precipitation (Dettinger et al., 2011). Because of the rain shadow effect of the Coast Ranges, tributaries draining the Coast Ranges were generally intermittent or ephemeral (Bryan, 1923) prior to the onset of irrigation practices that modified the hydrology of the system. During most years, the eastern side of the Coast Range and Central Valley dry season is characterized by virtual drought from June to August or longer; today upland channels are mostly dry during this period.

The headwaters of Willow Slough originate in the Mesozoic Great Valley complex and Pliocene rocks from the Vacaville assemblage of the Tertiary Tehama Formation (Marchand and Allwart, 1981; Graymer et al., 2002). The Tehama Formation flanks the Coast Ranges and formed as alluvial fans associated with the early rising of the Coast Ranges. These deposits now exist as a series of isolated rounded hills and ridges that slope eastward toward the Sacramento Valley. This reddish unit contains sands, silts, and volcaniclastic rocks; and in its basal layers is characterized by large boulders derived from the underlying Great Valley complex. The Tehama Formation hills are separated by valleys filled with Quaternary Alluvium (Fig. 2). In lowland areas, tributaries to Willow Slough flow through a longitudinal array of Quaternary deposits including terraces, alluvial fans, and floodplains; and further eastward, Willow Slough flows through flood basin deposits and associated floodplains and alluvial levees (Marchand and Allwart, 1981; Graymer et al., 2002). The downstream portion of the modern system is a flood-bypass channel that merges with flow from adjacent watersheds in the Yolo bypass en route to the San Francisco Bay-Delta Estuary.

The watershed is situated in an area that is tectonically active and regionally deformed. The Great Valley sequence is tilted to the east along the western margin of the Sacramento Valley; tilting probably began within the past 1–3 million years. Fluvial erosion of the tilted Great

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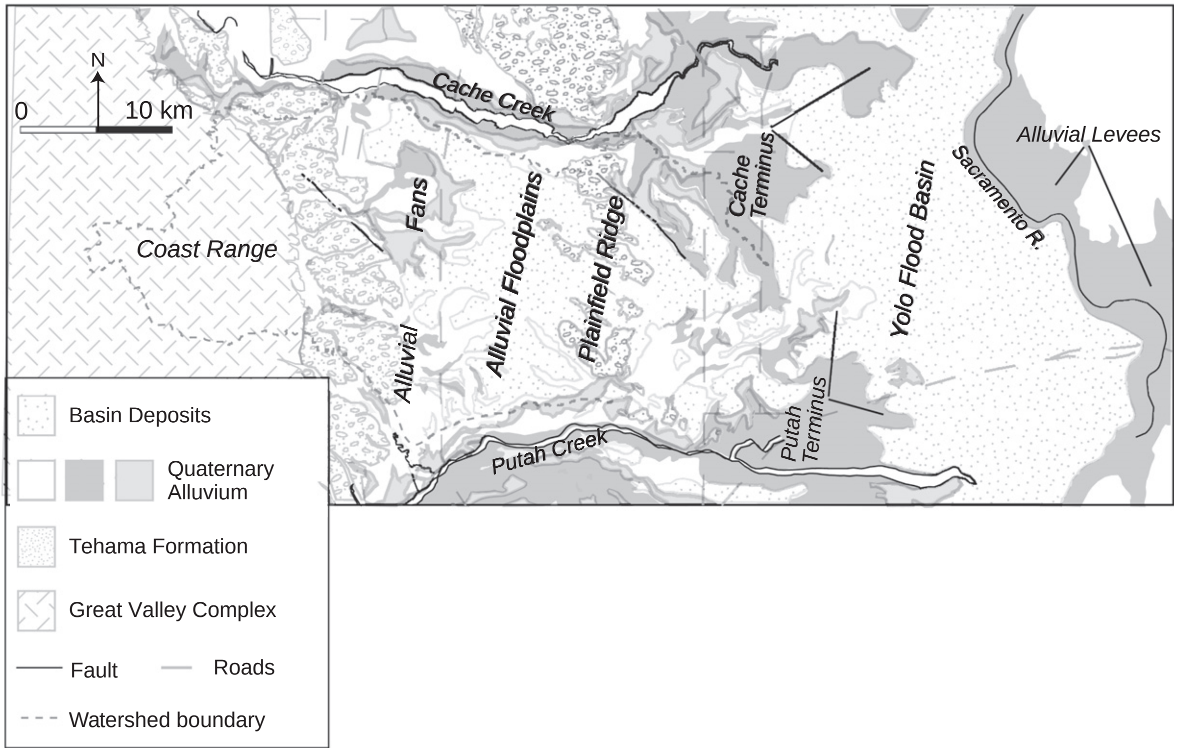

Fig. 2. Quaternary alluvial deposits in the Willow Slough system. Alluvial fans present at base of the uplifted Coast Ranges; multiple terraces and alluvial levees adjacent to Cache and Putah Creeks prograde into Yolo flood basin forming the dynamic watershed boundary of Willow Slough; Putah Creek terminus shifted to the south; Plainfield Ridge raises Tehama Formation sediment, bisecting lowland floodplains. Modified after Marchand and Allwart, 1981; Graymer et al., 2002.

Valley complex created a strath terrace that now appears as an unconformity between these rocks and the overlying Tehama Formation. Graymer et al. (2002) suggested that slight deformation in the Pliocene Tehama Formation and uplift in early to late Pleistocene alluvial deposits indicate that deformation of older structures continued into the Quaternary. For example, folds are present along the west side of the Sacramento Valley. One such fold is Plainfield Ridge, a small tectonically active anticline that creates a low relief ridge with uplifted Tehama Formation rocks aligned approximately perpendicular to the Willow Slough flow direction. Unruh et al. (2004) suggested that this ridge may be the surface expression of a west-dipping blind thrust fault beneath the southwestern Sacramento Valley and eastern Coast Ranges mountain front activated by transpressional plate motion currently occurring in western California.

3. Study area and methods

The Willow Slough watershed has a drainage area of ~425 km^2 near the confluence of Willow Slough and Dry Slough. The basin contains relatively steep upland and relatively low gradient lowland areas (Fig. 1B). The upland grasslands portion of the watershed with an average slope of 25% includes the Coast Ranges and its foothills and accounts for ~30% of the watershed area (127.5 km^2). Rangeland currently dominates the upland areas. The remaining ~70% of the watershed area (297.5 km^2) is lowland with average slope of ~1% that includes alluvial fans and floodplains. The lowland areas are cultivated with orchards and field or row crops. The eastern margin of the Willow Slough floodplain merges with the Yolo flood basin, a former wetland currently managed for both agriculture and Sacramento River flood control. Since 1856, water exports from adjacent Cache Creek have facilitated dry season agriculture in lowland portions of the Willow Slough system. No long-term gaging station data are available for the watershed.

Several methods were used to address temporal and spatial changes to the sediment system: (i) analysis of historical maps and interpretation of historical accounts, (ii) analysis of aerial photographs, and (iii) geomorphic field mapping, surveying, and analysis of grain size distributions. Earliest historical (1907) and most recent available (1975–1993) U.S. Geological Survey maps were used to illustrate alteration of drainage network pattern. Aerial photograph assessment included examination of the 2005 NAIP images in ArcGIS. Two field sites selected to illustrate differences in geomorphic processes, morphology, and sediment characteristics between upland and lowland areas were surveyed using an automatic level; geomorphic mapping combined use of aerial imagery and tape and compass measurements with a field scale of 1 in. = 5 m. The upland site, on Cottonwood Slough, has a drainage area of ~21 km^2. The lowland site, with a drainage area of ~425 km^2 is downstream of the confluence of Dry Slough and Willow Slough. Field characterization at these two sites included analysis of grain size distributions using a standard sieve set.

Discharge measurements (at 15-min intervals; interpreted pressure transducer and ADV data) were collected during periods between 2006 and 2008. In addition, a hydrologic simulation for 2006 was generated using the coupled surface water–groundwater *Watershed Environmental Hydrologic Model* (WEHY) that includes dynamic wave river channel routing; the model is fully described in Kavvas et al. (2004, 2006) and Chen et al. (2004a,b). In this study, simulated discharge data are utilized prior to January 2006, and field measurements are utilized after that.

Sediment transport is highly dependent on flow discharge; thus to evaluate the effect of the altered hydrology on flow strength in Willow Slough, we evaluate stream power per unit bed area as a measure of sediment transport capacity at upland and lowland cross sections:

$$\omega = \gamma QS / w \tag{1}$$

where ω is the stream power per unit bed area (W m^{-2}), γ is the product of the density of water (1000 kg/m^3) and the acceleration caused by gravity (9.8 m/s^2), Q is the discharge (m^3/s), S is dimensionless channel slope, and w is bankfull channel width (m).

In the Willow Slough basin, there is abundant fine sediment available for transport that has a high potential effect on water quality. We assume that suspended sediment concentration is well represented by total measurements of suspended solids (TSS). Weekly TSS measurements were collected and dried at 103–105 °C following method 2540D (APHA, 1995). Using data collected during a period of Q and TSS measurement overlap between February and September 2006, we examine data for the lowland sample site. The instantaneous concentration of TSS, determined as the ratio of the dry weight of sediment to the volume of water–sediment mixture sampled (Guy, 1969), and their associated discharge values were used to generate a power law regression equation for suspended sediment concentration (*SSC*):

$$SSC = aQ^b \tag{2}$$

where flow Q is discharge and a and b are empirical coefficients. Potential problems with use of the rating curve method to calculate daily suspended sediment load (Q_s, kg/day) are well documented and include presence of hysteresis associated with variable sediment supply seasonally and during rising and falling limbs of the hydrograph (Ferguson, 1986; Asselman, 2000; Horowitz, 2003). Errors in estimates of sediment load using this method may range from 15% (Horowitz, 2003) to 50% (Ferguson, 1986). To account for bias in the rating curve method from factors identified by Ferguson (1986), sediment load analysis was conducted using the U.S. Geological Survey LOADEST software (Runkel et al., 2004). First, daily TSS loads were estimated. Because the TSS concentration data are more sparse than the riverine discharge data, daily TSS loads cannot be calculated directly by multiplying concentration and discharge. Instead, a relationship between daily discharge (Q) and daily load (L) was investigated:

$$lnL = a_0 + a_1\ lnQ \tag{3}$$

where a_0 and a_1 are coefficients determined by linear regression of ln$Q$ and ln$L$, and ln$Q$ is given as ln(Q) − center of ln(Q) in which 'center of ln (Q)' is an automatic function within LOADEST used to eliminate any colinearity between explanatory variables (Runkel et al., 2004). Because the period of concentration data is shorter than the period of daily discharge measured, the method selected does not include a trend term and thus estimates load conservatively to prevent overestimation of daily TSS loads. We discuss other potential causes of uncertainty in this relation in the results section.

Calibration data used by LOADEST were prepared for two hydrologic seasons in 2006: the irrigation season (May to October) and non-irrigation season (November to April). LOADEST was run separately for each of these 6-month periods using daily discharge values. The LOADEST output (daily loads) were then summed to calculate monthly loads. We used monthly values to clarify temporal trends during the dry, storm (including winter baseflow between storms), and irrigation periods relevant to this study; investigation of shorter-term variation is beyond the scope of the work presented here. Total annual load in Willow Slough is estimated as the sum of the monthly data for each period:

$$Total\ Load = Storm\ Load + Irrigation\ Load + Dry\ Season\ Load \tag{4}$$

Because the geology, topography, and climate trends are similar along swaths parallel to the Coast Ranges, we assume that the upland field site on Cottonwood Creek and the TSS and discharge sample site Chickahominy Slough, with correspondingly similar drainage area of ~27.8 km^2, are mutually representative of upland system processes. Similarly, we assume that the lowland field site and TSS and discharge sample site, just upstream of the field site and with similar drainage areas, correspondingly represent lowland processes; data take into account hydrologic differences imposed by placement of a summer dam between May and September that separates the two lowland sites.

The total annual load – or the erosion rate, E (kg/year), normalized by drainage basin area – reflects the rate of removal of a mass of sediment from a unit area within the basin, r (kg/km^2/year):

$$r = E / A \tag{5}$$

where A is basin area (km^2). The lowering rate, L (mm/year), is calculated as the unit erosion rate divided by the density of sediment, ρ_s (g/cm^3):

$$L = r / \rho s \tag{6}$$

where densities of soil and rock are estimated as 1.28 and 2.5 g/cm^3, respectively.

4. Conceptual model of a depositional system prior to agricultural landscape modification

Our synthesis of historical maps and documents (Sprague and Atwell, 1870; U.S. Geological Survey, 1907; Gilbert, 1917; Bryan; 1923, Marchand and Allwart, 1981; Graymer et al., 2002) suggests that, prior to nineteenth and twentieth century anthropogenic landscape modification, tributaries that form Willow Slough flowed eastward toward their terminus in the Yolo flood basin, maintaining a dynamic system where sediment deposition dominated over erosion. River flow interacted with surficial deposits along a longitudinal gradient from the Coast Ranges toward the Sacramento River exhibiting Quaternary terraces, alluvial fans, floodplains, channel mouth bars, and flood basin sediment. A conceptual sediment mass balance model illustrates dominant erosion and deposition processes along with spatial distribution of sediment sinks for the preanthropogenic disturbance system (Fig. 3).

Historical evidence suggests that overbank flooding occurred and presumably supplied sediment that contributed to lowland floodplain accretion. Early accounts (Sprague and Atwell, 1870) reported that during storms that generated high magnitude discharges, overbank flow from the Cottonwood Slough tributary and Cache Creeks joined and flowed through the Willow Slough watershed: "During one of these periodical floods, in March, 1847, Joe Buzzy got into his canoe … and sailed through the tules and up Willow Slough to Gordon's Ranch, on the north side of Cache Creek." A merging of the Willow Slough–Cache–Putah depositional systems is evident in geologic maps of Holocene units that show former channel-levee deposits trending from Putah and Cache Creeks into the Willow Slough lowlands (see Fig. 2). Low elevation channel-levee deposits from Cache and Putah Creeks formed dynamic northern and southern watershed boundaries of Willow Slough and the Yolo flood basin formed the transitional eastern boundary with location dependent on relative flood levels in these hydrologically connected systems.

Historical accounts also documented the presence of riparian vegetation: "Along the slough… the banks are well wooded, the trees and undergrowth thickly interlaced with wild grape and other vines, forming a pleasant shady retreat…" (Sprague and Atwell, 1870). Similarly, Vaught (2003) reported characteristics of the nineteenth century Willow Slough: "Three miles to the north [of Putah Creek] lay Laguna Callé (renamed Willow Slough by Anglo settlers), a long, narrow, and deep lake fed by the creek's annual overflows. Both suggested an abundance of water in this otherwise dry grassland region ('California's Kansas,' as one ecologist has described it), and both created dense riparian forests upwards of two miles wide." Such riparian zones may have provided stability and habitat that that likely minimized bank erosion and provided large woody material (e.g. see Florsheim et al., 2008) in turn influencing sediment storage and transport dynamics along the Willow Slough system.

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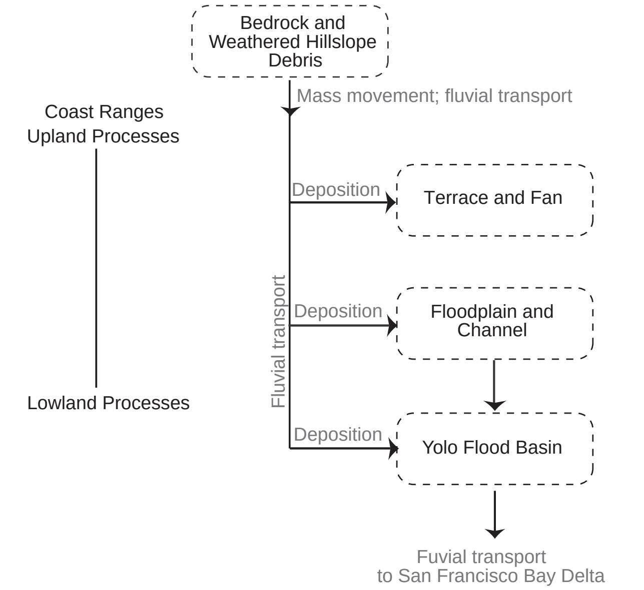

Fig. 3. Conceptual model illustrating dominance of depositional processes in fans, floodplains (some that later become terraces), channels, and the flood basin in the Willow Slough system prior to agricultural activities. Dashed boundaries indicate sediment storage areas; arrows indicate direction of sediment transfer.

Prior to modification of the system, fluvial processes such as floodplain deposition differed from processes apparent today in the agricultural landscape. Bryan (1923) observed that in addition to building natural alluvial levees sediment deposition in the floodplain–channel system sometimes raised channel beds such that bed and banks together formed a 'double crested ridge' above the surrounding lowland. However, because of the gentle outward slopes of the levees, these sediment deposits were not visible until floods made them topographically prominent, when levee crests protruded above the overbank flood water. Levee breaches formed new branching channels, leaving floodplains with lower surface elevation in intervening areas. Such floodplain deposits occurred in both the lowland alluvial floodplain and across the transitional boundary into the Yolo flood basin. Bryan (1923) observed levees in the west side of the Yolo flood basin adjacent to Willow Slough that included some channels that were abandoned and permanently dry, while others contained intermittent streams that drained storm flows—sometimes eroding their beds, despite the dominance of deposition in the system. The broad shallow area of the Yolo flood basin was dry most of the year, and sometimes for the entire year. However, during wet periods, floodwater from the Sacramento River mixed with flow from Cache and Putah Creeks and Willow Slough forming a tule wetland with water that flowed toward the San Francisco Bay-Delta Estuary. Alluvial channel and levee deposits terminating within this wetland in the Yolo flood basin likely formed as prograding channel mouth bars (Fig. 2). Similar deposits are active along the Cosumnes River east of the Sacramento River where bedload transport on a restored area of the floodplain extends alluvium, thereby extending channel length, during overbank floods (Florsheim and Mount, 2002).

The preanthropogenic disturbance conceptual model (Fig. 3) illustrates a dynamic transport-limited sediment system where the sediment supply from the uplands was transferred to the low-gradient floodplain and flood basin where deposition rates were high enough over the long term to fill the subsiding Central Valley. In Willow Slough, the significant temporal and spatial variability of sediment pathways, sources, sinks, and fluxes that occurred throughout the fluvial system, as agricultural land use practices beginning with farming in the mid-1800s modified geomorphic processes, are demonstrated below.

5. Alteration of drainage system configuration and sediment pathways

Analysis of historical maps highlights changes between the preagricultural and current drainage system configuration and sediment pathways. These changes are significant with respect to sediment routing and storage sites throughout the watershed. The 1854 map of Laguna de Santos Callé shows a prominent sinuous lake in place of a creek, with the eastern edge of the lake in the 'Tulares,' or tule wetlands in the Yolo flood basin. Similarly, early accounts (Sprague and Atwell, 1870) suggested that during the dry season, Willow Slough was characterized by spring-fed ponds separated by dry channels. Further, instead of a continuous channel system, historical U.S. Geological Survey topographic maps from the early 1900s illustrate discontinuous channel segments throughout the lowland portion of the Willow Slough system. From these maps and documents we infer that scour during winter floods may have created deeper channel reaches that intersected the groundwater table, thus creating ponds that were linked together during winter runoff but discontinuous during the dry season.

Substantial modification of the drainage pattern began with farming activities in about 1840, with former fluvial channels and ditches collectively employed as an irrigation conveyance system. The original multiple distributary and anastomosing channels were concentrated into single channels draining to a fixed point at the head of a constructed flood bypass channel; numerous additional ditches were incorporated into the drainage network. In the bypass channel, flow is routed across the lowland area that was once part of the Yolo flood basin wetland. The Yolo flood basin itself is confined and operated as a flood bypass system for the Sacramento River. Analysis of topographic maps illustrates realignment and straightening of the channels and introduction of 90° bends and linear segments that follow roads, fields, and property boundaries (Fig. 4). The presence of such features, that are not common in natural systems, are used to quantify channel alteration (Table 1). Results show an approximately twofold increase in channel straightening during this period; although, channel straightening had already commenced by 1907.

Alteration of drainage system configuration and sediment pathways indicated by the straightening and convergence of flow and sediment pathways were compounded by incision of the channel. Bed lowering by ~4.3 m in the lowland study reach (discussed in Section 6.2) led to ~0.0001, or a 33% increase in the lowland channel slope between

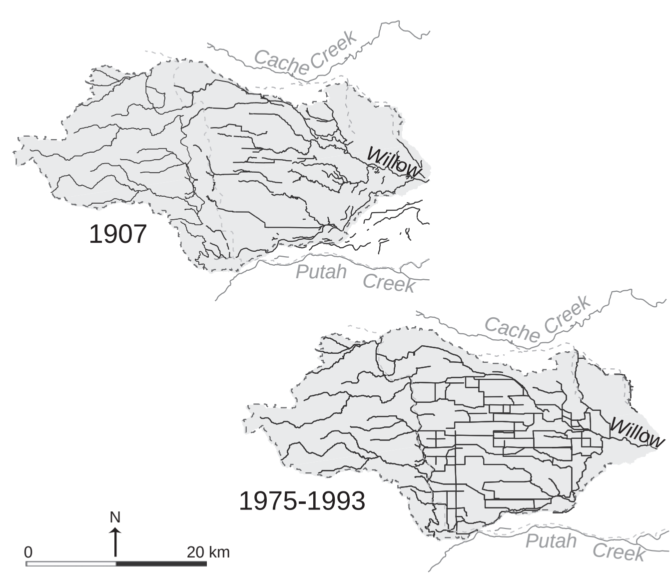

Fig. 4. Map analysis of blue-line channels between 1907 and 1993 illustrates realignment, straightening, and introduction of 90° bends upstream of the confluence. Linear channel segments follow roads, fields, and property boundaries.

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Table 1
Channel pattern alteration between 1907 and the 1990s.

	Linear (km^2)	% of total	90° bends (#)
1907	16.7	17	1
1993	37.8	39	67

~20 km downstream of the Winters–Capay canal and the confluence of Dry and Willow Sloughs. Together with the loss of riparian vegetation, these changes likely decreased roughness, increased flow strength, and contributed to a more efficient transport capacity.

6. Modified morphology, sediment storage, and sediment sources

6.1. Upland field site

Characterization of the upland field site on the Cottonwood Creek tributary to Willow Slough illuminates interactions between human modification and sediment contributions from Quaternary alluvium and active hillslope erosion processes that provide a ready source of fine sediment to the downstream drainage system. The upland field site includes a partially straightened channel (Fig. 5A–D; Table 2) incised into friable shale bedrock of the tilted Great Valley complex that underlies the Tehama Formation. Quaternary alluvium exists as terraces adjacent to the creek. Along the west channel bank, exposed shale bedrock forms a strath terrace that is overlain by Quaternary sediment that forms an alluvial terrace above it; together these units comprise a nearly vertical stream bank where the alluvial terrace stands at a height over 4.4 m above the thalweg (Fig. 5C). Another terrace surface exists ~7.4 m above the channel thalweg on the east bank. The geomorphic map and profile illustrate the discontinuous and relatively narrow (3–17 m wide) floodplain inset between Quaternary terraces. Average floodplain height ranges from ~1.0 to 1.3 m above the thalweg, and large boulders exposed at the base of some of the floodplain deposits are likely lag deposits derived from the Tehama Formation.

The gradient of the reach is 0.014, and channel morphology is characterized by alternate bars and riffles (Fig. 5A–B). Coarse sediment visible in channel beds and bars is supplied from adjacent hillslopes and the upstream watershed. The profile illustrates that residual depth of shallow pools in the reach averages only 0.35 m with one deeper pool with residual depth of 0.85 m scoured into bedrock exposed near the upstream end of the reach. The reach was mostly dry during the time of the survey in July 2006.

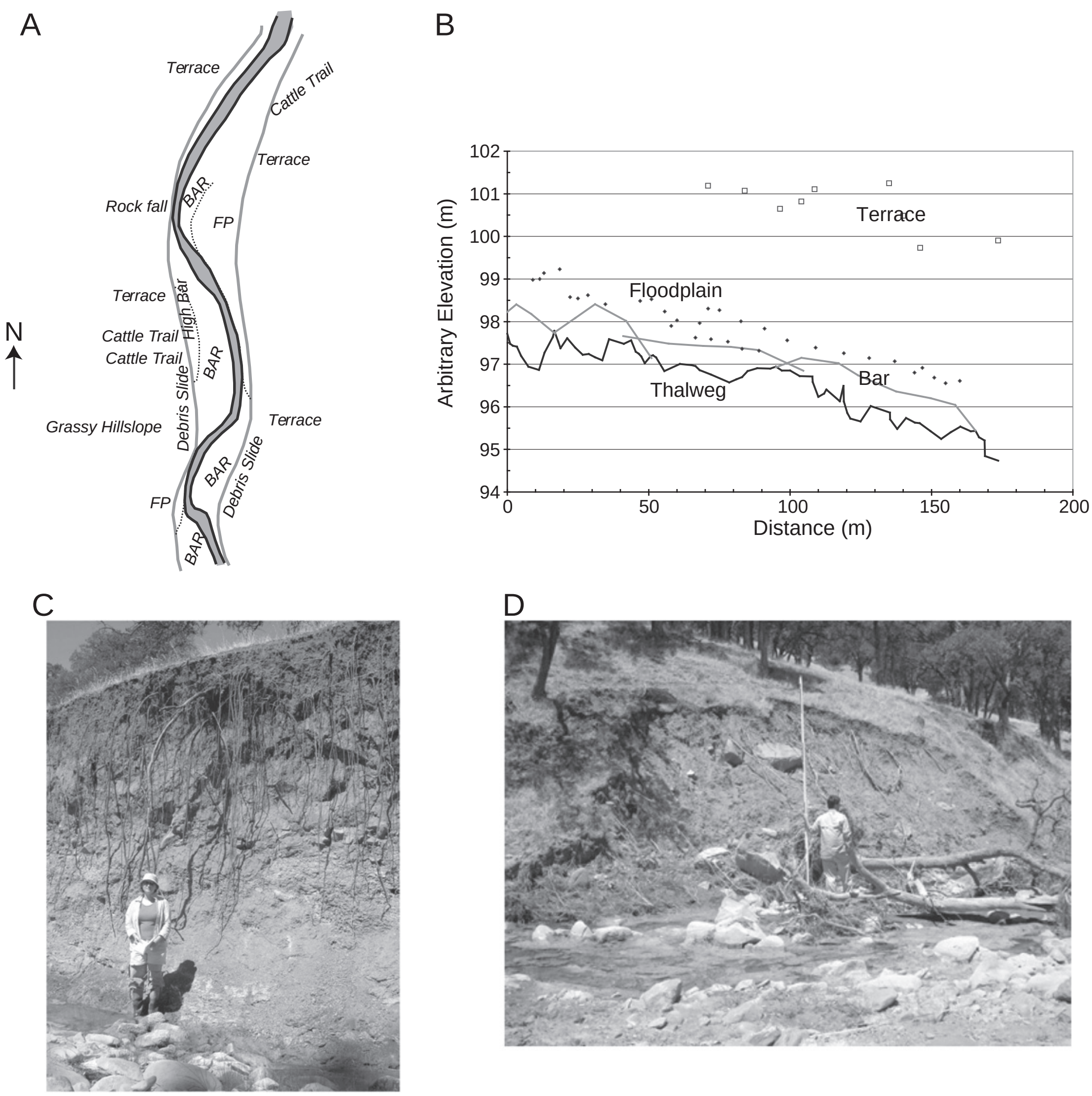

Fig. 5. Upland field site. (A) Geomorphic map; (B) longitudinal profile; (C) bank erosion of Quaternary Alluvium underlain by Great Valley complex shale; strath terrace indicated by dashed line; (D) photograph showing hillslope debris slide contributing sediment directly to channel.

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Table 2
Geomorphic characteristics of field sites.

Site	Drainage area (km^2)	Reach average slope	Height floodplain above thalweg (m)	Height terrace above thalweg (m)
Upland	21.3	0.014	0.6	4.4; 7.4
Lowland	425.3	0.0004	2.1[a]	4.3[b]

[a] Floodplain is excavated into terrace (historic floodplain).
[b] Modern terrace is former historic floodplain.

Bank erosion is prevalent in the upland reach with ~60% of banks actively eroding. On the nearly vertical west bank, dry season slaking of shale was evident; however, erosion processes also likely include lateral retreat of the basal shale by fluvial flows and subsequent collapse of the overlying terrace sediment. Quaternary sediment deposits that comprise vertical channel banks are devoid of vegetation and are easily eroded by both fluvial and mass movement processes and provide a ready source of fine sediment to the basin's yield. Roots of oak trees (*Quercus lobata*) set back from the top of bank are exposed and cattle trails and associated sloughing are evident.

Active hillslope erosion processes also contribute sediment directly to the drainage network. Debris slides, identified on the 2005 NAIP imagery, allow estimation of slide frequency; in a subset of Cottonwood Canyon, debris slide frequency is 0.69/km^2 (4.0/5.8 km^2). Similarly, gullies contribute sediment to channels, with a frequency of 2.76/km^2 (16/5.8 km^2) and a density of 180 m/km^2. Debris slides contribute a range of sediment grain sizes from large boulders to silt and clay directly to the upland channel (Fig. 5D).

6.2. Lowland field site

Field examination of the lowland site on Willow Slough downstream of the confluence with Dry Creek illustrates the human transformation of lowland drainage system morphology and processes. The lowland field site is in an artificial bypass channel excavated into Quaternary Alluvium and is currently the dominant flow path carrying water from Willow Slough to the Yolo flood basin (Fig. 6A–C; Table 2). The bypass includes an excavated floodplain adjacent to the north side of channel that stands ~2.1 m above the channel thalweg. This excavated channel–floodplain system is contained within a zone about 60 m wide between constructed levees. Beyond the constructed levees, the height of the extensive historical floodplain surface is ~4.3 m above the bypass channel thalweg, similar to the elevation difference between the thalweg and terrace in the upland reach. However, in the lowland reach the drop reflects a baselevel change associated with excavation of the bypass channel.

The gradient of the lowland reach is 0.0004 and the excavated channel bed and banks are relatively uniform. Little sediment is stored in within this reach over the long term. Within the channel, bars are not present in this relatively homogeneous reach. Sediment deposition on the order of a few centimeters thick was observed in patches on the excavated bypass channel floodplain following its inundation during storm flows in water year 2006, with long term storage is dependent on flood control maintenance. A few small benches exist along the base of the north bank; they appear to be small slump blocks that have not yet been eroded.

Although grassy, past bank erosion is evident in the scalloped shape of the banks that suggest that mass movement processes such as slumps or small slides with arcuate scarps contribute sediment to the channel (Fig. 6C). About 30% of the channel banks lack vegetation and are actively eroding. Thus, Quaternary sediment stored in the lowland floodplain deposit that forms the bed and bank material in the bypass channel is supplied through bed incision and bank erosion processes and is available for transport downstream.

Field reconnaissance throughout adjacent lowland areas of the Willow Slough system illustrate that lowland channels, enlarged by

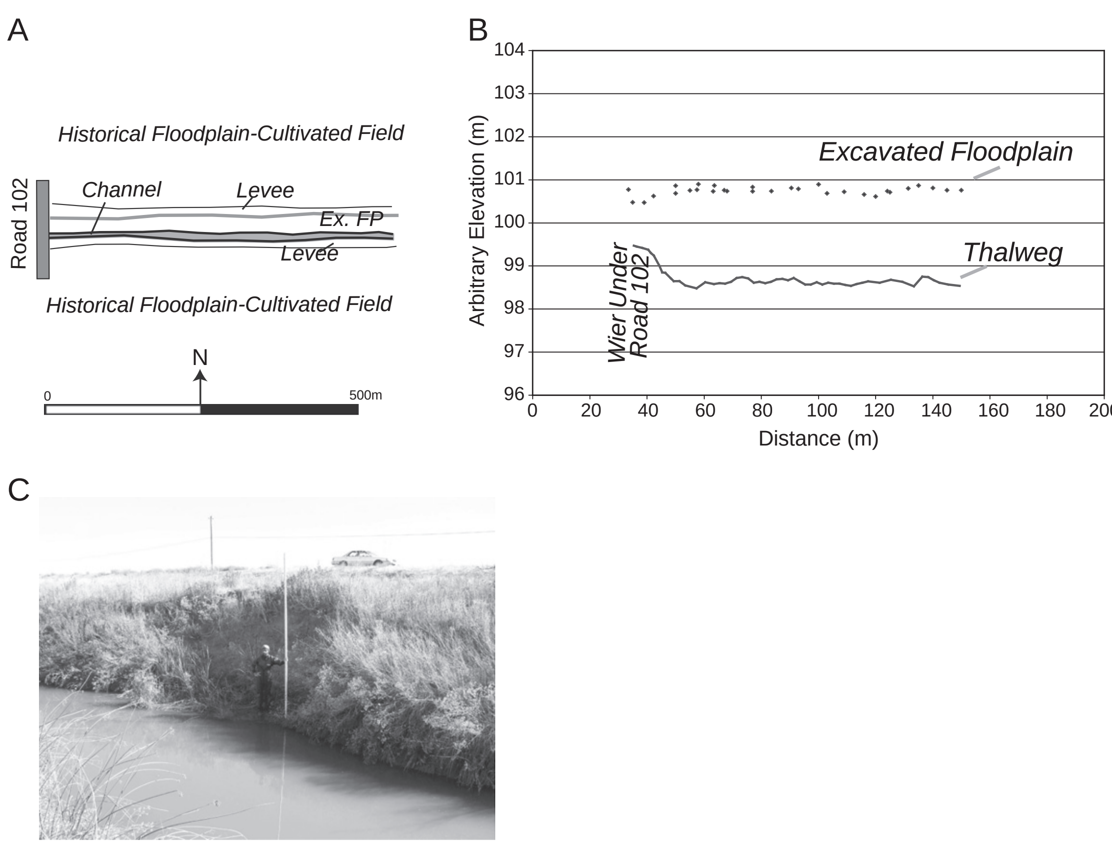

Fig. 6. Lowland field site. (A) Geomorphic map; (B) longitudinal profile; (C) photograph showing bank slumping with dashed line along scarp.

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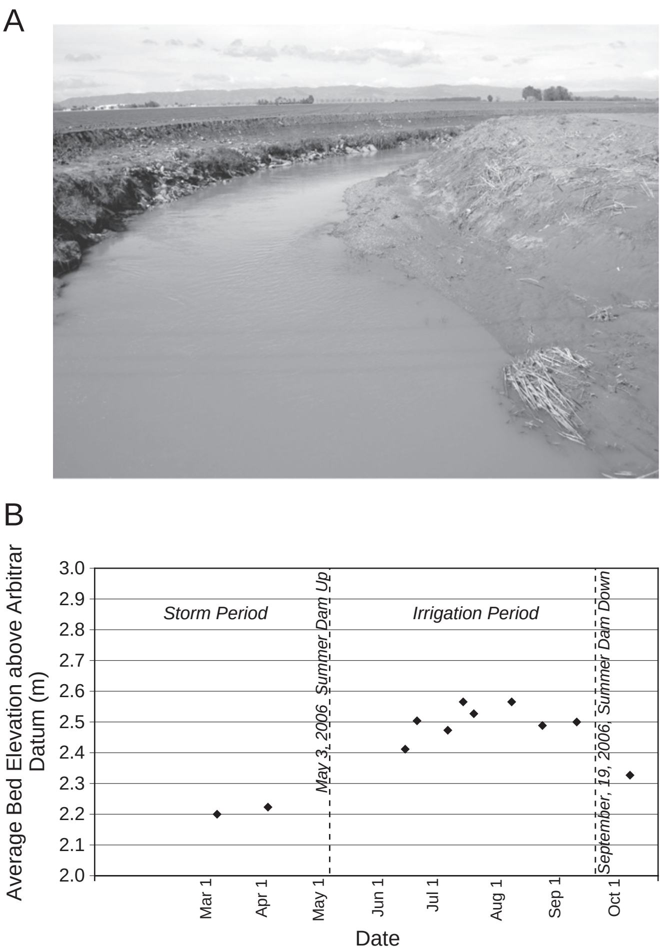

Fig. 7. (A) Photograph of Willow Slough in lowland reach cleared of vegetation with concrete rubble on bank. Channel enlarged by excavation of small bench, erosion, and dredging is confined between low levees <1.0 m in height above adjacent floodplain. Coast Ranges in background; (B) **s**hort-term lowland sediment storage upstream of temporary summer flow diversion dams. Average bed elevation increases ~0.3 to 0.4 m after construction of an upstream dam. Material was partly eroded during later part of irrigation season following dam removal.

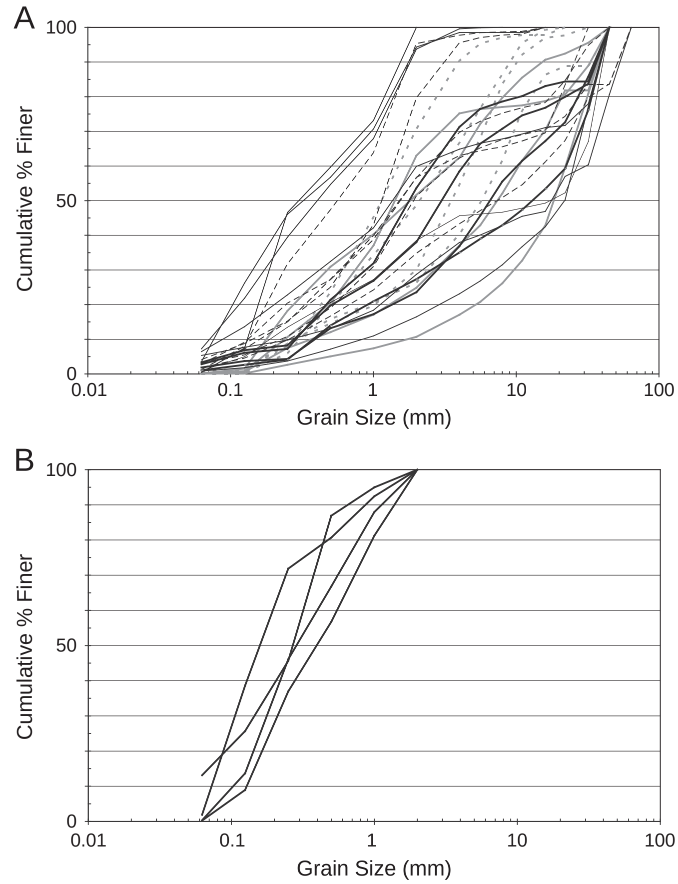

Fig. 8. Grain size distribution of sediment showing difference in range of distribution between upland and lowland areas. (A) Size distribution of sediment stored in the banks and slide debris, floodplains, and channel bed in upland reach; (B) size distribution of bank material in lowland reach.

erosion and dredging, are confined between low levees constructed on the order of a few meters or less above the adjacent floodplain (Fig. 7A), similar to the bypass channel. Banks are sporadically armored with broken concrete or other hard material, and riparian vegetation is absent throughout much of the lowland area. Over the short term, fine sediment composed of silt and clay is deposited in association with temporary structures such as summer flow diversion dams (Fig. 7B). This fine channel bed deposit has a short residence time and is partly transported once the dam is removed during the later portion of the irrigation period.

6.3. Grain size characteristics

Grain size distributions of sediment derived from eroding Quaternary Alluvium deposits in upland and lowland areas are relevant for understanding characteristics of sediment sources supplied to the modern Willow Slough system. Upland sediment deposits exhibit a large range of grain sizes from boulders to silt and clay, with median grain sizes ranging from ~0.30 to 22 mm (Fig. 8A). All sediment sources, including slides and eroding terraces composed of Quaternary Alluvium, contain <10% silt + clay (Fig. 9). In the upland area, the percent clay and silt in channel deposits such as bars and pools is <1%, whereas the floodplain and terraces store a greater percentage of fine material.

Lowland sediment deposits exhibit a smaller range of sizes with a median size <1.0 mm and that exclude grains >2.0 mm (Fig. 8B). The alluvial bed and banks of the modern channels in the lowland area are composed of fine sediment derived from Quaternary Alluvium and Flood Basin deposits. Channel bank samples reflect variable percentages of fine sediment, indicating the dynamic nature of the lowland floodplain processes active when the sediment was deposited. These deposits that provide a lowland source via bank erosion are composed of between 9% and 40% fine material with the percent of clay and silt ranging from <1% to about 13% (Fig. 9).

Examination of the grain-size characteristics of mean diameter and sorting in upland versus lowland areas (Fig. 10) shows that sorting and average grain size in upland and lowland areas plot in different fields. The relatively coarser and poorly sorted character of upland sediment reflects the higher energy depositional environment, whereas the relatively finer and well-sorted character of lowland sediment reflects the low energy depositional environment of the floodplain and flood basin portions of the Willow Slough system.

7. Temporal and spatial variability of stream power and sediment load and erosion and lowering rate estimates

7.1. Precipitation variability

Precipitation records illustrate the strongly seasonal contributions to stream flow (Fig. 11A): 2006 was the ninth wettest year, and 2007

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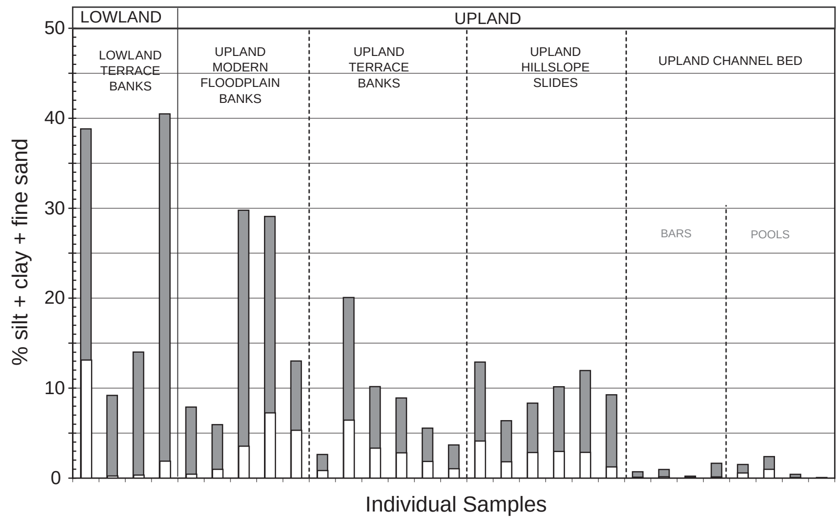

Fig. 9. Fine fraction of sediment deposits contributing to and within upland and lowland reaches. White portion of bar represents percentage clay and silt; gray portion of bar represents percentage fine sand.

was the eighth driest year on record. Rainfall governs runoff and stream hydrology in upland areas, and the water year is characterized by two periods: (i) the dry season, and (ii) the storm season—with the length of each period having variable duration depending on actual precipitation. During the storm season, upland channel flow returns to baseflow levels between storms that generate runoff. In contrast, in lowland areas flow hydrology is not solely dependent on climate; instead, flow hydrology is affected by both rainfall and agricultural irrigation water imports.

7.2. Stream power variability

Calculation of average monthly stream power per unit bed area, ω, proportional to discharge, illustrates temporal variation and trends for the lowland sample site in response to changes in flow discharge from 2006 to 2008 (Fig. 11B). The variation is characterized by three disparate periods of the agricultural water year: (i) the dry season—after irrigation from the previous season ceases until the subsequent

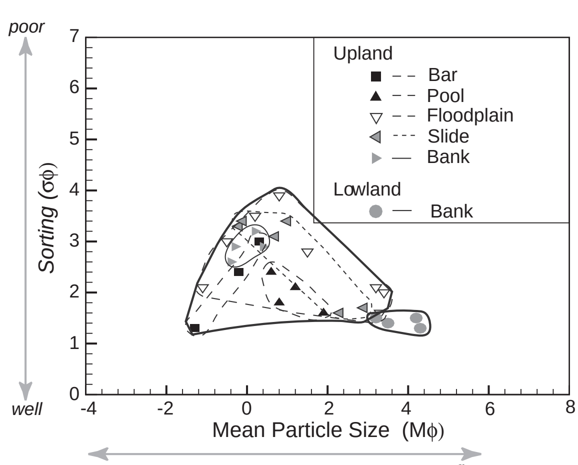

Fig. 10. Sorting, $\phi\sigma = (\phi 84 - \phi 16)/2$ as a function of mean grain size; $M\phi = (\phi 84 + \phi 16)/2$ for sediment in deposits in upland and lowland areas. The larger number of samples in the upland site is used to illustrate the variability of sediment sizes in the greater range of different upland fluvial deposits present.

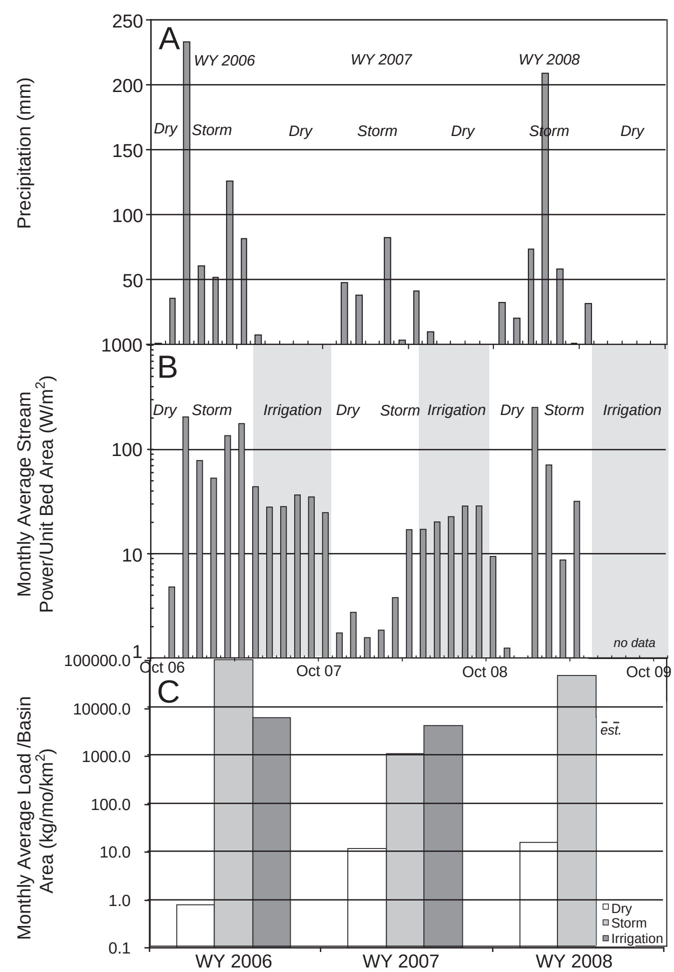

Fig. 11. (A) Precipitation at the lowland station indicating dry and storm seasons (CIMIS, 2010); (B) estimates of monthly stream power per unit bed area showing temporal variability. Because of the addition of irrigation water to Willow Slough, patterns of stream power do not directly reflect precipitation patterns. For comparison, upland data are shown for months where available; (C) relative sediment load during the storm, irrigation, and dry periods. Data unavailable for the WY 2008 irrigation period—dashed line shows an estimate calculated as the average of the two prior years.

Table 3
Comparison of average stream power per unit bed area during the storm and irrigation periods at the lowland sample site.

	Average ω[a] storm period	Average ω irrigation period
2006	130	33
2007	2.3	24
2008	91	na[b]

[a] Average ω is calculated using monthly discharge values shown in Fig. 11B.
[b] Data not available during 2008 irrigation period.

Table 4
Ratio of load during each period of the agricultural water year to total annual load.

Period	% of total annual load
2006 dry	$\ll 1$
2006 storm	94
2006 irrigation	6
2007 dry	$\ll 1$
2007 storm	21
2007 irrigation	79

rainy season begins, (ii) the storm season—related to runoff generated between November and April, including winter baseflow between storms, and (iii) the irrigation period—dominated by water exports from Cache Creek that generally contribute flow for 6 months between May and October.

During storm periods, variability in flow discharge and ω, even averaged on a monthly timescale, is relatively high; in contrast, during irrigation periods flow and ω are relatively constant. The duration of each portion of the agricultural water year differs greatly on an interannual basis, depending on the magnitude and variability of local precipitation and on the management of initiation and cessation of irrigation water supply. During 2006, a relatively wet water year, average ω during the irrigation period was ~25% of the average ω during the storm period (Table 3). In contrast, during the relatively dry 2007 water year, average ω during the irrigation period was ~10 times greater than that during the storm period. Thus, the importance of the agricultural irrigation water contribution relative to storm flows, with respect to the potential for erosion and sediment transport, depends on the seasonal precipitation and runoff variation.

Two anthropogenic factors affect ω at the lowland sample site: (i) hydrologic modification, and (ii) channel alteration that steepened channel slope. Assuming that all of the flow in the lowland system during the dry season is from irrigation contributions and that the average of irrigation flows measured during water years 2006 and 2007 (~5,186,200 m^3/month or ~2.0 m^3/s) represents the average long-term irrigation addition, it follows that ω increased from 0.0 to an average of ~46 kg/s^3/month for 6 months/year. The increased channel slope in the lowland area from channelization and baselevel lowering increased the stream power by ~7% over the historical period. Both factors raise the potential for erosion and elevated sediment loads in the Willow Slough watershed.

7.3. Sediment load variability

Fig. 11C illustrates the relative magnitude of average monthly sediment load during the three distinct periods of the agricultural water year. Similar to discharge and stream power, loads are relatively constant during the irrigation period. In contrast, storm period loads are variable depending on climatic conditions. Thus, the ratio of irrigation load or storm load to annual load is variable depending on climate conditions. During the wet agricultural water year 2006, the storm period dominates total load; in contrast, during the dry agricultural water year 2007, the irrigation period dominates the total load (Table 4). The average sediment load during both the 2006 and 2008 storm periods is an order of magnitude larger than the average load during the irrigation period.

The smallest discharge and associated sediment loads occur during the dry season between when crops are irrigated and when the subsequent rainy season begins. High variability can be seen in a comparison of the load carried by flow during the dry period relative to the storm period; the ratio is <1 to 25%. The duration of the dry period is inversely related to the duration of the storm season, whereas the duration of the irrigation season is fixed by management decisions and water rights. Estimates of total annual load during 2006 and 2007 exhibit large interannual variability: total load during the relatively wet 2006 water year was ~108,500 kg/km^2/year, whereas the total load during the 2007 water year was 5950 kg/km^2/year, only 5% of that during the previous year. This difference of two orders of magnitude illustrates significant variability between wet and dry years.

The total annual sediment load estimated for 2006 and 2007 represents the erosion rate per unit area during those 2 years. We used these estimates to approximate basin scale lowering rates that integrated upland and lowland areas and yielded a similarly large range (assuming $\rho = 2.5$ and 1.28, respectively, in the values that follow): 2.3×10^{-3} to 4.5×10^{-3} mm/year for the dry year and 4.3×10^{-2} to 8.4×10^{-2} mm/year for the wet year. Because these estimates are based on sediment load at the lowland sampling site, they integrate surface lowering and channel erosion.

Spatial variability of sediment load is evident during the dry season when there is no flow in the upland tributaries during the dry season; for example, upland field and sample sites contributed 0% of the load measured downstream during much of the period when irrigation water dominated lowland watershed hydrology. Comparison of the upland and lowland TSS and discharge sample sites is possible during a part of the storm period from mid-February through April 2005 when discharge and TSS data were collected at both sites. Despite being only 7% of the watershed area, the daily load at the upland sample site was 42% of the load measured downstream during this period, on average. Normalizing daily load by watershed area illustrates the importance of the uplands in contributing to watershed sediment loads during the storm season (Fig. 12). In contrast, during the irrigation season, the entire load was produced from lowland areas as there was no flow contribution from the upland portion of the watershed.

Fig. 13 illustrates a difference in the sediment rating curves generated for the lowland sampling site that includes data measured during storm flows versus data combining storm and irrigation flows. The equations of the two sediment rating curves are similar, with the combined curve slightly steeper than the storm curve. However, the R^2 values are significantly different, with $R^2 = 0.94$ for storm data but $R^2 = 0.51$ for the combined storm and irrigation data. This comparison suggests that scatter in the irrigation flow data raises uncertainty in the rating relation. Quantification of uncertainty in the combined curve including the irrigation data yields ± 0.0012 on the slope and ± 0.008 on the intercept. The uncertainty in this rating relation may be caused by water reuse during the irrigation period and by the relatively few high discharge measurements available during the study period. The irrigation water reuse cycle – where water is used on a field, and then returned to channel, and reused for irrigation in a downstream field – may occur several times. Thus, SSC may be large or small for a given irrigation flow discharge depending on how many times the water has been used and the sediment yield contributed from individual fields. Confidence in both relationships could be improved in future work that includes monitoring during wet years with high magnitude flows and by quantifying sediment yield, erosion, and deposition related to cultivation of fields.

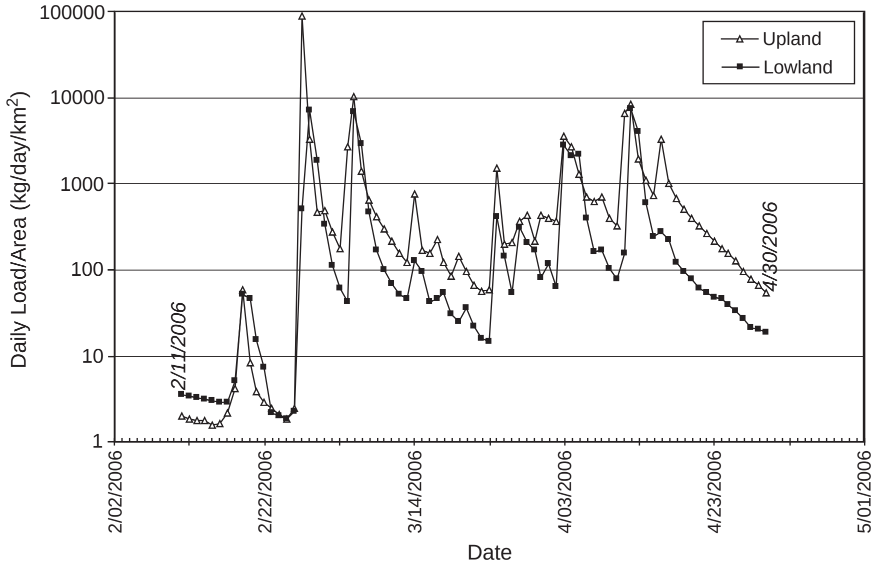

Fig. 12. Comparison of daily sediment load normalized by drainage basin area at the upland and lowland TSS and discharge sample sites over a short period from mid-February through April 2006 showing the significance of sediment contributions from upland areas.

8. Discussion

8.1. From deposition to erosion and transport

Results presented in this study suggest that the preagricultural Willow Slough watershed was a transport-limited system characterized by sediment deposition and that the modern system has become an effective transport system despite a large supply of sediment easily eroded from Quaternary Alluvium. A conceptual model (Fig. 14) illustrates the nature of the sediment sources, storage, and transport pathways in the Willow Slough watershed after ~150 years of land use changes. The change from deposition to erosion and transport likely occurred because of a combination of factors: (i) an increase in transport capacity from channelization and increased slope, and (ii) hydrologic alteration that extended the duration of flows with potential for sediment transport.

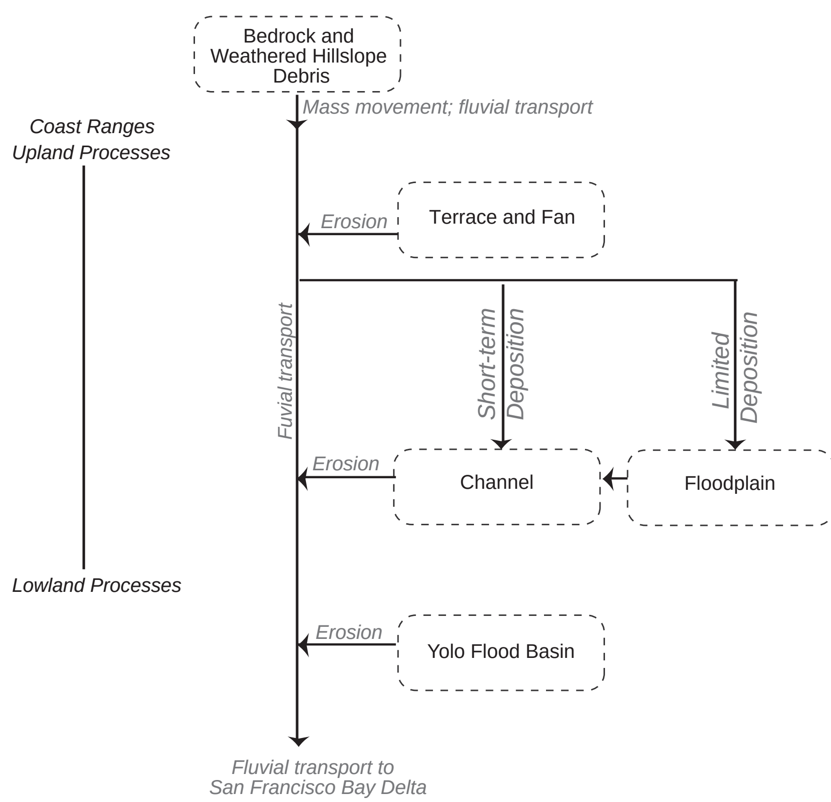

Fig. 13. Sediment rating curve for storm data (solid line) and combined storm and irrigation data (dashed line). Irrigation data show scatter that raises uncertainty in the rating relation.

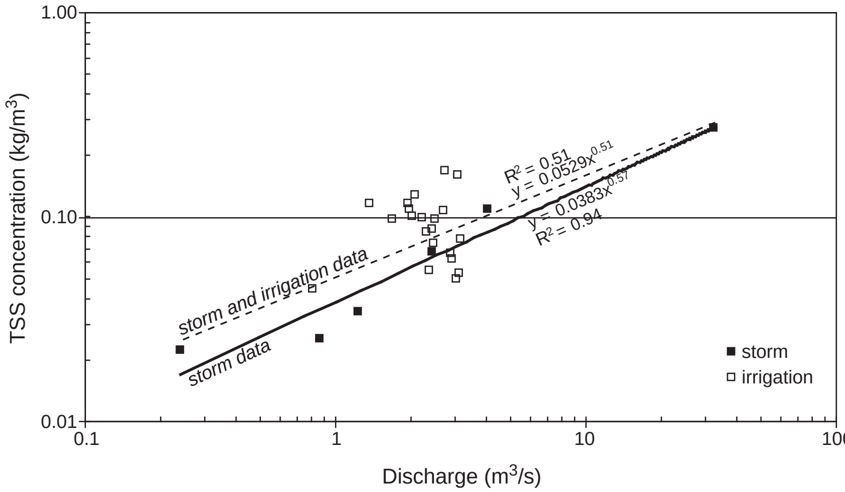

Fig. 14. Conceptual model illustrating dominant sediment sources, depositional areas, and transport processes as a result of agricultural land use changes in the Willow Slough watershed. Over the past two centuries, bank erosion, channel incision, and fluvial transport dominate processes. Areas with dashed boundaries indicate sediment storage reservoirs; arrows indicate direction of sediment transfer.

8.1.1. Variation in transport capacity

The increase in transport capacity that in turn increased erosion and transport in Willow Slough resulted in part from activities related to channelization, such as straightening drainage system patterns, levee construction, and removal of riparian vegetation and woody debris—that decreased channel roughness and increased flow velocity. In combination with dredging, these factors increased flow depths, in turn reducing frequency of overbank floodplain flow and associated sediment deposition. A second factor contributing to the increase in transport capacity resulted from a decrease in baselevel elevation from excavation of the bypass channel near the mouth of Willow Slough, together with incision from channelization, that increased lowland channel slope and increased stream power by about 7% during the historical period.

Slattery and Phillips (2011) similarly report that transport capacity controlled by slope is a critical factor in moderating the balance between sediment storage and yield in lowland rivers. Recent research shows numerous analogs where prior to anthropogenic modifications, sediment transport-limited systems were characterized by deposition in floodplains that moderated sediment yield to coastal environments (Walling, 1983; Brizga and Finlayson, 1995; Fryirs and Brierley, 1999; Fryirs and Brierley, 2001; Phillips, 2003; Phillips et al., 2004). In other systems, despite large sediment supply, floodplain deposition rates were limited by high lateral channel migration rates that returned sediment back into transport (Aalto et al., 2008; Swanson, et al., 2008). In Willow Slough, the dynamic transport-limited sediment system that existed prior to anthropogenic disturbances was transformed by changes in transport capacity, and the addition of irrigation water that altered hydrology, as described below.

8.1.2. Hydrologic alteration

Hydrologic alteration in Willow Slough gives both winter storm flows and dry season irrigation flows significance with respect to lowland sediment transport. In contrast, prior to irrigation, the lowland portion of the watershed often lacked dry season flow. Thus, irrigation extends the period with flows exceeding the threshold for bed and bank erosion and transport of sediment by about 6 months each year. Although projections for changes in the annual precipitation this century are relatively small (<10%, Cayan et al., 2007), shorter-term variability, such as the occurrence of extreme winter storms or drought that characterize California's climate (Malamud-Roam et al., 2006, 2007; Dettinger et al., 2011) would have a significant impact on the threshold for bed and bank erosion and transport.

8.2. Spatial and temporal variability of sediment sources, storage, and transport and erosion

8.2.1. Changes in sediment sources

Historical data suggest that prior to the onset of channelization and irrigation in the Willow Slough system, sediment was once dominantly derived from upland hillslope erosion processes occurring during winter storms. Similarly, our field measurements documenting relatively high modern sediment loads contributed from upland areas during the storm period are consistent with results of modeling conducted in Willow Slough (Kavvas et al., 2010). Their work shows that for a portion of the storm period during the 2006 agricultural water year, between 5 December, 2005 and 6 January, 2006 (prior to the period illustrated in Fig. 12), sediment load produced in the upland portion of the watershed was over 100 times the load produced in the lowlands (upland load reached 12.5 kg/ha, whereas lowland areas produced loads <0.1 kg/ha).

Field data suggests that significant sediment sources are present in both upland and lowland alluvial sources in the modern Willow Slough system. These new sources include channel bed incision and bank erosion into Quaternary Alluvium. In addition, surface erosion of this deposit occurs in lowland areas where cultivated fields and orchards are the dominant land use. Erosion of fine material from Quaternary Alluvium provides sediment to a modified system where increases in transport capacity effectively route sediment, such that modified fluvial processes structure river and floodplain morphology and grain size distributions. A similar consequence of Quaternary sediment on modern sediment yields has been documented in rivers in British Columbia (Church and Slaymaker, 1989).

8.2.2. Changes in sediment storage

Fine sediment deposition on floodplains often accounts for a significant component of a lowland river's suspended sediment budget (Walling et al., 1992). In the Willow Slough watershed, however, levee construction diminished channel–floodplain connectivity and the function of lowland floodplains and the flood basin to store fine sediment. Residence time of sediment stored in the historic floodplain is reduced because of incision and bank erosion documented in this study. Nevertheless, some uncertainty exists related to the residence time of floodplain sediment related to the role of surface erosion on floodplains: in lowland areas lacking continuous levees within the watershed, some sediment is still deposited during overbank floods; however, overbank floods may instead erode floodplain sediment. Similarly, irrigation runoff may both deposit and erode sediment from cultivated floodplain areas. Thus, as irrigation runoff from upstream fields is reused downstream, some sediment redistribution is likely through erosion and deposition. The volumetric change in surface elevation because of either deposition or erosion has not been quantified and further work is warranted to address this uncertainty.

The residence time of fine sediment stored on the channel bed or its margins may be long, on the order of decades (Skalak and Pizzuto, 2010) or shorter (Owens et al., 1999). In the lowland portion of Willow Slough, the modern residence time of fine sediment within the channel generally appears short – likely because of the increase in channel transport capacity and the absence of roughness or obstacles that influence sediment deposition and transport – obstacles cause backwater reductions in flow strength and promote sediment storage (Lisle, 1986). Thus, removal of riparian vegetation, woody debris, and bends likely decreased deposition and the residence time of fine sediment in Willow Slough channels. Short-term deposition still occurs locally in Willow Slough where roughness is present in association with remaining vegetation, beaver- or human-constructed dams, and in areas where riparian restoration has taken place. Summer dams temporarily trap silty sediment until dams are removed and winter storm flows route the sediment through the system.

8.2.3. Changes in sediment transport and erosion

Fine suspended sediment is easily transported once mobilized, and the addition of irrigation flows facilitates the transport of fine material through the lowland portion of the Willow Slough basin. Thus, the total sediment transport capacity of Willow Slough increases with irrigation water contributions. However, for fluvial erosion of bed and bank material to occur, a threshold must be crossed where $\omega > \omega_c$, with ω_c equal to the critical stream power per unit bed area at the point when erosion occurs. Increases in duration of flows generated by irrigation runoff over a six-month period during the dry season, over the past century and a half, has likely contributed to the bank erosion and channel incision that characterize the modern Willow Slough system. Prolonged flows higher than the threshold for fluvial erosion that promote bank retreat and bed incision also would increase sediment loads. When the duration of relatively high magnitude flow discharge increases and the duration of lower flows that promote deposition decreases, deposition of fine material is likely to be reduced. Further, any rapid drawdown of flow that occurs during irrigation operations may increase bank instability (Thorne et al., 1998).

8.3. Regional significance

8.3.1. Regional sediment loads

Regionally, the significance of a sediment load contributed from small watersheds such as Willow Slough is high when compared to numerous tributaries to the Sacramento system with reduced sediment loads because of dams that trap sediment. Wright and Schoelhammer (2004) reported that major dams in the Sacramento system impound a significant volume of sediment such that downstream sediment yields are reduced: Oroville—99,114 kg/km^2/year; Folsom—272,730 kg/km^2/year; and Englebright—142,850 kg/km^2/year. During a wet year in Willow Slough, the estimated sediment load (~108,500 kg/km^2/year) contributed to the Sacramento system is the same order of magnitude as the average load trapped upstream of the major dams; a dry year in Willow Slough contributes significantly less (~5950 kg/km^2/year). However, it is not possible to deduce a long-term average sediment yield from our short-term data set for comparison to Wright and Shoellhamer's (2004) estimate for the Sacramento (7157 kg/km^2/year for the period 1957–2001).

In large tributaries to the Sacramento system with dams, it is likely that sediment retention upstream of dams reduce overall basin sediment yields, despite the increased conveyance through lowlands. In smaller tributaries without large dams, total basin sediment yield may still not contribute to the downstream system because of local management works, such as trapping in settling basins (R. Beckwith, DWR, personnel communication, 2007; Singer and Aalto, 2009). Further work is warranted to fully understand the effects of the land use changes in Willow Slough and other tributaries on long-term sediment contributions to downstream areas. However, the potential for small watersheds such as Willow Slough to contribute sediment to the Sacramento River and San Francisco bay delta and estuary is significant, at least during wet years, in light of the significant sediment reductions elsewhere in the complex system.

8.3.2. Significance of sediment to water quality

Field data from this study show that both upland and lowland sediment sources contribute fine sediment that increases turbidity. During storm periods, bank erosion is an important source that contributes carbon and metals from both upland and lowland areas. However, during the irrigation season, the source of sediment is less likely to be from bed and bank erosion because peak discharges associated with bank erosion are smaller. Instead, irrigation period sediment contributions are more likely from surface erosion of lowland fields. These lowland agricultural areas are likely to contribute phosphorous and pesticides that degrade habitat during the six-month irrigation season.

In a partner study that investigated soil and sediment as a source of DOC in Willow Slough, suspended sediment in summer yielded twice as much DOC as in winter (Journet et al., 2009) illustrating the significance of disparate sediment sources. From a water quality perspective, any increase in suspended sediment concentration, regardless of source, will also increase concentrations of vascular plant-derived lignin (Hernes et al., 2008), which has implications for foodweb bioavailability as well as the formation of carcinogenic halogenated compounds when disinfected for drinking water purposes (Kraus et al., 2008).

8.4. Strategies for agricultural management of riparian systems

Ecosystem-based management, restoration, and conservation that consider geomorphic processes and sustainability could help minimize effects of agricultural activities that cause erosion. For example, flood management actions that route flood flows onto fallow fields could promote floodplain sediment storage, reduce turbidity, and improve downstream water quality. Whereas other lowland tributaries to the Sacramento–San Joaquin River system have lost their floodplain sediment storage function because of construction of agricultural and flood control levees, management practices such as restoration that allows river flow to flood formerly leveed floodplains promotes sedimentation (Florsheim and Mount, 2003).

Restoration of self-sustaining riparian buffer zones that both accommodate erosion and promote vegetation succession could improve water quality and greatly benefit fish or other aquatic and terrestrial habitats. Minimizing dredging activities through development of alternative irrigation conveyance architecture could reduce disturbance to channel habitat. Actions that promote soil conservation and increase vegetation biomass could increase carbon sequestration. Together, agricultural practices that promote connectivity of the entire drainage network could be facilitated through new governance strategies whereby local farm bureaus, management, and resource agencies aggregate continuous riparian zones longitudinally from uplands to lowlands to provide watershed-scale benefits.

9. Conclusions

We have documented a change in sediment dynamics in the Willow Slough fluvial system that occurred during the past ~150 years. Prior to agricultural activities, Willow Slough was a depositional system where upland sources contributed sediment to a dynamic lowland depositional environment. Alteration of the drainage network pattern and channelization increased slope of the lowland drainage system and together with baselevel change and hydrologic alteration resulting from irrigation flow contributions, increased transport capacity. Quaternary Alluvium present throughout the basin currently acts as a ready source of fine sediment contributed by erosion. Thus, the preagricultural depositional system was transformed to the modern erosion and sediment transport system.

Analysis of stream power per unit bed area quantifies the effects of increased slope on suspended sediment transport capacity, with ω increasing by ~7% over the historical period. Hydrologic alterations from contribution of irrigation flow elevate transport capacity and extend the period of sediment transport and potential for erosion for ~6 months/year. Estimates of suspended sediment load based on field data collected during the relatively dry 2007 water year highlight the significance of irrigation flows in causing erosion and in transporting sediment during drought years when channels would otherwise likely have been dry. In contrast, during the relatively wet 2006 water year, high ω and associated large sediment loads generated in upland areas during wet storm periods emphasize the significance of storm flows. Irrigation water reuse creates considerable scatter in the total suspended solids versus discharge rating curve, a source of uncertainty particular to irrigated agricultural environments.

Because of the increased transport capacity in the watershed, relatively high sediment loads generated during both storm and irrigation periods are less likely to be stored within the modern Willow Slough watershed—instead, sediment is transported from the basin. Regionally, results are important because Willow Slough is representative of other small agricultural watersheds in central California without permanent dams that contribute relatively high sediment fluxes. These results are significant because they aid in understanding effects of agriculture in basins where a legacy of land use activities transformed the landscape and where irrigation modifies hydrology such that sediment is effectively transported rather than stored in lowland floodplain–channel systems.

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