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ARTICLE

Estimating floodplain sedimentation in the Laguna de Santa Rosa, Sonoma County, CA

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Abstract We present a conceptual and analytical framework for predicting the spatial distribution of floodplain sedimentation for the Laguna de Santa Rosa, Sonoma County, CA. We assess the role of the floodplain as a sink for fine-grained sediment and investigate concerns regarding the potential loss of flood storage capacity due to historic sedimentation. We characterized the spatial distribution of sedimentation during a post-flood survey and developed a spatially distributed sediment deposition potential map that highlights zones of floodplain sedimentation. The sediment deposition potential map, built using raster files that describe the spatial distribution of relevant hydrologic and landscape variables, was calibrated using 2 years of measured overbank sedimentation data and verified using longer-term rates determined using dendrochronology. The calibrated floodplain deposition potential relation was used to estimate an average annual floodplain sedimentation rate (3.6 mm/year) for the ~11 km^2 floodplain. This study documents the development of a conceptual model of overbank sedimentation, describes a methodology to estimate the potential for various parts of a floodplain complex to accumulate sediment over time, and provides estimates of short and long-term overbank sedimentation rates that can be used for ecosystem management and prioritization of restoration activities.

Keywords Floodplain · Overbank sedimentation · Sediment deposition potential · Laguna de Santa Rosa · Russian River

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Introduction

Most floodplain environments experience unsteady flow conditions during overbank events and sediment transfer across floodplains occurs through a combination of diffusion and convection processes (Pizzuto 1987; James 1985). Floodplain aggradation may occur laterally or vertically (Schumm and Lichty 1963) and the spatial variability of sediment accumulation tends to be complex (Asselmann and Middlekoop 1995; Middelkoop and Asselman 1998). The rates and patterns of overbank sedimentation depend upon a range of hydrologic and landscape variables including: magnitude, frequency and duration of inundation, sediment supply, and floodplain topography and roughness (Middelkoop and Van Der Perk 1998; Harter and Mitsch 2003; Phillips et al. 2007; Kiss and Sandor 2009; Schenk and Hupp 2010; Kiss et al. 2011). Generally, an increase in any of these factors could lead to an associated increase in the likelihood, or potential, of sediment deposition.

Whether floodplain sedimentation is considered desirous or deleterious depends upon local conditions and the dominant physical processes controlling both short and long term storage of floodplain sediment. Whereas traditional studies of overbank sedimentation primarily focused on floodplain morphology (Wolman and Leopold 1957; Lewin 1980; Brakenridge 1984; Brierly 1991; Nanson and Croke 1992), more recent studies investigate the rates and patterns of sediment deposition using sediment traps (Asselmann and Middlekoop 1995; Steiger et al. 2003), artificial markers (Kleiss 1996; Hupp 2000; Ross et al. 2004; Hupp et al. 2008), dendrochronology (Hupp and Bornette 2003; Ross et al. 2004), and radionuclide analyses (Walling and Woodward 1992; Goodbred and Kuehl 1998; Blake et al. 2002; Matisoff et al. 2005). The measured data can then be extrapolated using regression models (Lecce 1996; Heimann and Roell 2000). Although use of numerical models that

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characterize overbank sedimentation studies is becoming more common (Bridge and Leeder 1979; James 1985; Pizzuto 1987; Howard 1992; Middelkoop and Van Der Perk 1998; Heimann 2001; Nicholas et al. 2006), the ability of these models to accurately simulate rates and patterns of floodplain sedimentation has not been well established (Hupp et al. 2008).

Floodplain geomorphologic studies identify linkages between form and process necessary for predicting floodplain sedimentation. Although geomorphological prediction is an emerging science (Wilcock and Iverson 2003), when implemented within a GIS framework predictive models can be a powerful tool for determining potential responses to geomorphic processes that vary widely in time and space. Also the use of GIS for prediction and verification of geomorphic responses directly leads to an understanding of the geomorphic system in a spatially explicit way (Mitasova et al. 1996; Curtis et al. 2005). Although Haff (1996) recognized a general lack of predictive geomorphic studies, forecasting the effects of geomorphic processes on observable timescales is critical for making informed decisions about land management and hazards. Currently there are few floodplain deposition studies that explicitly incorporate a full suite of hydrologic and landscape variables determined to influence sedimentation (Hupp et al. 2008) and even fewer studies that produce process-oriented, spatially-distributed and empirically-verified estimates of sediment deposition potential for large floodplains (Asselmann and Middlekoop 1995; Lecce 1996; Heimann and Roell 2000; van Proosdij et al. 2006).

This study introduces a new first-order approach for characterizing and quantifying sediment deposition in a highly complex floodplain environment. We provide a conceptual and analytical framework for predicting the spatial distribution of overbank sedimentation within an 11 km^2 portion of the Laguna de Santa Rosa floodplain (Laguna), located in Sonoma County, CA (Fig. 1). We assess the role of the floodplain as a sink for fine-grained sediment and investigate concerns regarding the potential loss of flood storage capacity due to historic sedimentation. We do not address streamflow or hydraulics directly, alternatively we focus on assessments of hydrologic and landscape variables that are widely available and understood to control overbank sedimentation.

We begin with a conceptual framework for understanding overbank sedimentation processes and use measured sedimentation data, collected during a post-flood survey, to determine the relative importance of a suite of hydrologic and landscape variables. We then characterize the potential, or likelihood, for floodplain deposition, by geoprocessing of raster files and development of a sediment deposition potential map. The deposition potential map is then calibrated and verified using short and long-term sedimentation rates and used to predict the spatial distribution of overbank sedimentation and net floodplain deposition for the 2-year study period. Although our sediment deposition potential map is intrinsically heuristic, the merit and value of our method is that widely available landscape and hydrologic datasets can be used to understand and identify areas of the floodplain likely to experience sedimentation thus making the methodology highly transferrable.

Study Area

The Laguna de Santa Rosa (Laguna), located in Sonoma County, CA, drains a 660-km^2 watershed and is the largest tributary to the Russian River (Fig. 1a). The mainstem is composed of a 23-km long channel and wetland complex, with a narrow western floodplain and a much wider eastern floodplain that grades into an extensive mountain-front fan complex called the Santa Rosa Plain. The alluvial river classification of Church (2002) aptly describes the Laguna's sediment transport regime and channel morphology: silty to sandy channel, suspension-dominated, minor bedform development, meandering single thread or anastomosed channels, floodplain dominated by vertical accretion, levees are prominent, very low gradient, stable or slowly shifting channels, extensive wetlands and floodplain lakes, located in an inland sedimentary basin.

The study area is located in the lowermost reaches of the Laguna, along the western edge of a tectonic depression formed by the Windsor Syncline, a compressional structure between two tilting crustal blocks composed of highly erodible Plio-Pleistocene sediments (Wilson Grove Formation) and more resistant Cenozoic volcanics (Sonoma Volcanics) (Wagner and Bortugno 1982; McPhee et al. 2007). The western edge of the Laguna floodplain coincides with the boundary between these two crustal blocks. Tilting, uplift, and erosion of these blocks over geologic time periods resulted in aggradation of the Windsor Basin, deposition of the Santa Rosa Plain and sedimentation within the Laguna. Thus, sediment deposition within the Laguna is a natural geologic process; however, historic land use changes altered both the rate and pattern of sediment delivery.

In its natural state, the Laguna effectively regulated water, sediment and nutrients and supported a diverse range of ecosystems that included an upland oak-woodland-vernal pool complex, a riparian forest and a string of emergent freshwater wetlands. During pre-settlement time periods, deposition of sediment supplied from the upper watershed was distributed across the Santa Rosa Plain (Fig. 1a). However, exponential growth in agricultural production (ca. 1855) and urbanization (ca.1940) lead to increased surface runoff, larger storm peaks, and greater runoff volumes. These effects dramatically altered storm hydrographs and

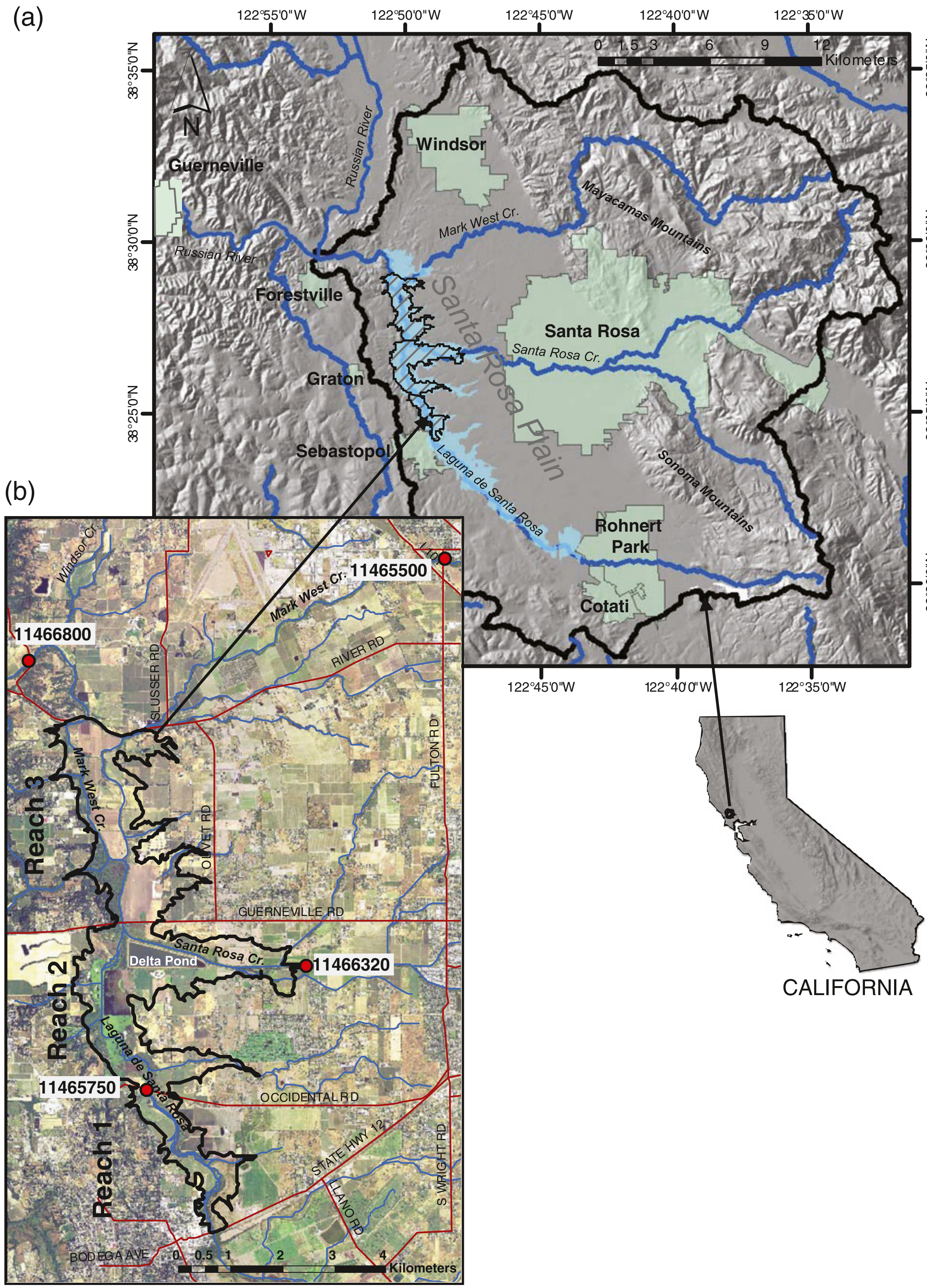

Fig. 1 Maps of (**a**) Laguna de Santa Rosa floodplain (*in blue*) within the Santa Rosa watershed, Sonoma Country, CA and (**b**) study area boundary (*in black*) extending from River Road to State Hwy 12, and USGS gaging station locations

when coupled with widespread channelization resulted in increased sediment production and delivery rates. Channelization also caused the loci of sediment deposition to shift away from the Santa Rosa Plain where previously sediment was dispersed by a series of distributary channels. Currently, a few large engineered channels convey upland sediment directly to the Laguna where dramatic changes in hydraulic geometry (decreased slope and velocity, increased width and depth) and backwater effects from the Russian River promote deposition. Aggradation of the Laguna channel and floodplain equates to a reduction in channel capacity and storm water storage and as a result increases flood risk for local and downstream communities.

The altered rate and pattern of upland sediment delivery nearly doubled Laguna floodplain sedimentation rates over the last 50 years (Sonoma County Flood Control and Water Conservation District SCFCWCD 1965) and lead to water quality and biota deterioration (Smith 1990). Although the trend began to reverse in the 1990s, the Laguna remains listed as impaired under the federal Clean Water Act for sediment, nitrogen, phosphorus, temperature, mercury, and dissolved oxygen, rendering it the most impaired water body on the North Coast of California (Laguna de Santa Rosa Foundation, Library Archives, 2006). Even with a large historical reduction in biological resources, the Laguna currently provides wildland habitat for over 200 species of birds, threatened and endangered salmonid species, and a diverse range of small and large carnivores making it the most biologically diverse part of Sonoma County (Sonoma County Community Foundation SCCF 2009).

Streamflow conditions in the Laguna are highly variable due to the Mediterranean climate. During the dry summer season the Laguna consists of a narrow low-flow channel that connects a series of wider slackwater reaches. During the winter storm season the annual floodplain is frequently inundated for extended periods of time thereby creating a large continuous slow-moving water body. Annual stagnant water conditions are further exacerbated by backwater effects generated by the Russian River such that the Laguna functions as a stormwater retention basin, capable of storing over 98 million m^3 of surface water runoff, thereby mitigating flood risk within local and downstream communities.

The study area extends from Highway 12 to River Road (Fig. 1b) and encompasses the area inundated by a flood peak with an estimated 30-year recurrence interval (December 31, 2005, New Year's Eve flood). We separated the study area into three reaches based on floodplain and channel characteristics. Reach 1 extends from Hwy 12 to Occidental Rd. and receives surface runoff from several small tributaries that flow through Rohnert Park and Sebastopol. This reach has a narrow floodplain and a slope of 0.002 m/m. Reach 2 extends from Occidental Rd. to Guerneville Rd. and includes streamflow from Santa Rosa Creek, which conveys surface runoff from the City of Santa Rosa. During the 1960s the City of Santa Rosa straightened and leveed portions of Santa Rosa Creek as part of the Santa Rosa Flood Control Channel and in 1984 the city installed a large ~2.3 million m^3 (~600 million gallons) reclaimed water storage pond (Delta Pond) . This reach has a wider floodplain, an average channel gradient of 0.00005 m/m, and a significant portion of this low gradient reach is covered by permanent shallow lacustrine environments. Reach 3 extends from Guerneville Rd. to River Rd., has a wider floodplain than Reach 1 but narrower than Reach 2, a greater amount of riparian woodland vegetation, and a average channel gradient of about 0.0008 m/m. This reach includes discharge from Mark West Creek, which drains a less urbanized portion of the Laguna watershed. Prior to 1915 the Mark West Creek-Laguna confluence was diverted and the current confluence lies ~2 km upstream of the historic confluence. The Windsor Creek confluence is located ~1.5 km downstream of the study area boundary and the Laguna flows into the Russian River ~6 km downstream from the study area boundary.

Methods

Data collection

Post-flood survey - inundation extent and sediment deposition

The 2005 New Year's Eve flood event, with an estimated 30-year recurrence interval and a peak flow of greater than 200 m^3/s, inundated ~50 % of the floodplain and provided an opportunity to map the inundation extent and spatial distribution of associated overbank sedimentation. Two weeks after the peak flow during a post-flood reconnaissance, we surveyed the location and elevation of high water marks, location and depth of sediment deposition, and made observations such that channel and floodplain processes controlling the spatial distribution of overbank sedimentation could be interpreted. High water marks (HWM) were identified based on floatable debris or veneers of fine-grained sediment covering fences and riparian vegetation. Coordinates of each HWM and water depth were determined using a stadia rod and kinematic GPS with a post-processed differential correction of less than 10 m. Surveyed data points were superimposed on an available digital elevation model (DEM, Gesch et al. 2002) with a 10-m grid spacing and the inundation extent for the New Year's Eve flood event was interpolated in ArcGIS using measured points and anecdotal information available from on-site observations collected during the flood peak (Honton 2008). Measurements of overbank sedimentation were collected along transects that extended from the edge of the active channel upslope to the edge of high water. Recently deposited sediment was identified by color, lack of structure (e.g. soil peds), grain size, and deposition atop stratigraphic markers (soil surfaces and leaf litter). At each field site the relative importance and correlation of six hydrologic and landscape variables to measured sediment deposition was assessed. Variables included: slope, proximity to main stem or tributary channel, availability of local erodible sediment sources, location relative to inundation extent of New Year's Eve 2005 flood, soil drainage or surface ponding, and roughness due to topography or vegetation.

Suspended-sediment measurements and mass balance

In a companion study streamflow and suspended-sediment were measured at four USGS gaging stations (Fig. 2; Table 1) during water years 2006, 2007, and 2008. We used estimated annual suspended-sediment loads (Flint et al. 2012) to calculate changes in channel storage using a standard mass balance approach. The sum of estimated loads at the Laguna (USGS 11465750), Santa Rosa Creek (USGS 11466320), and Mark West Windsor (USGS 11465500) gages represents the annual mass of suspended-sediment delivered to the study reach. Sediment loads estimated at the Mark West Mirabel (USGS 11466800) gage represent the annual mass of suspended-sediment delivered out of the study reach.

Floodplains on low gradient rivers like the Laguna are depositional features that typically function as fine-grained sediment sinks. We assumed a negligible amount of the suspended-sediment load was deposited within the active channel and inferred that annual changes in floodplain storage of suspendable-sized sediment could be estimated as the difference between incoming and outgoing suspended-sediment. Our assumption and related inference are valid in light of the Laguna's sediment load and hydraulic geometry.

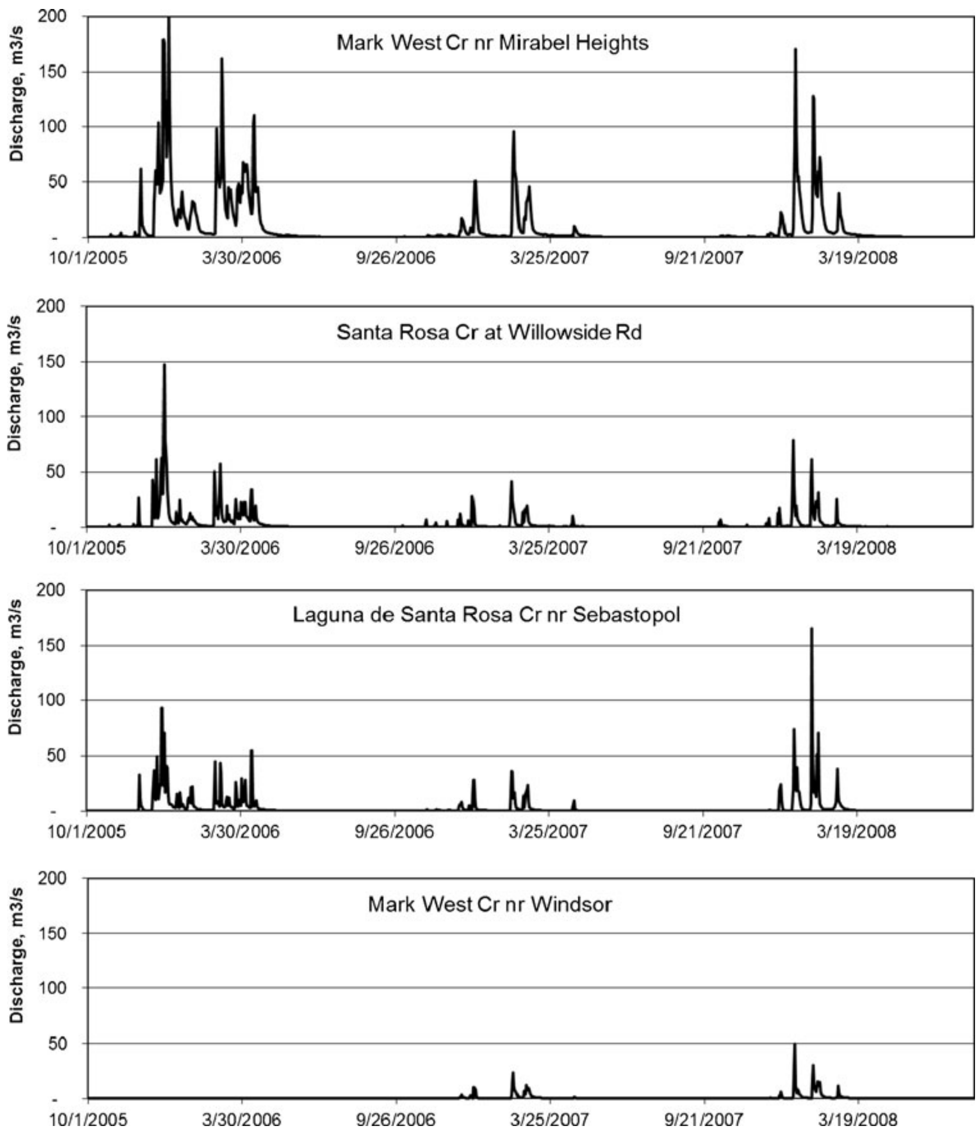

Fig. 2 Mean daily stream discharge for water years 2006 to 2008

Table 1 Streamflow and suspended-sediment data collected at four USGS gaging stations and estimates of changes in channel storage within the Laguna de Santa Rosa, CA.*

USGS Site ID	Description	Drainage Area (km^2)	WY2006			WY2007			WY2008			Summary	
			Annual Mean Discharge (m^3/s)	Annual Suspended Sediment Load (tons)	Annual Suspended Sediment Volume (m^3/yr)	Annual Mean Discharge (m^3/s)	Annual Suspended Sediment Load (tons)	Annual Suspended Sediment Volume (m^3/yr)	Annual Mean Discharge (m^3/s)	Annual Suspended Sediment Load (tons)	Annual Suspended Sediment Volume (m^3/yr)	Annual Suspended Sediment Load (tons)	Suspended Sediment Volume (m^3/yr)
11465750	Laguna	261	4.3	7,690	2,630	1.2	1,850	635	2.8	5,880	2,000	4,541	2,160
11466320	Santa Rosa Creek	255	5.2	24,100	8,260	1.3	283	97	2.0	878	300	9,400	2,950
11465500	Mark West Creek	141	–	**84,400	28,900	1.0	997	341	1.6	3,530	1,209	28,800	10,400
11466800	Mark West Mirabel	824	15.1	26,400	9,000	3.6	4,390	1,500	5.8	9,100	3,100	13,100	5,500
	Mass balance estimate of changes in channel storage			**89,800	30,700		(2,250)	(773)		(2,340)	(800)	29,641	10,010

*A full description of the gaging station data is available in Flint et al, 2012

**Mark West Creek WY2006 suspended sediment load estimated in Flint et al., 2012

Measuring Floodplain Sedimentation

Long-term Sedimentation Rates: Dendrochronology Dendrochronology is widely used to assess wetland and floodplain sedimentation rates in locations where riparian woodlands exist (Sigafoos 1964; Hupp 1988; Hupp and Bornette 2003). The age of a tree with a buried trunk can be determined by collecting an increment boring as low on the tree base as possible such that even the earliest years of growth are sampled. The total number of tree core growth rings is counted and the depth of sediment deposition estimated by excavating the base of the trunk below any adventitious roots and down to the original major radiating roots system. Depth of burial equals the distance from the ground surface to the original radiating root system, the date of burial is determined by analysis of the borings, and the depth and age of burial are used to estimate sedimentation rates.

Dendrochronology samples were collected at five forested wetland locations distributed throughout the study area (Fig. 3a). Trees within the active annual floodplain and protected from surface disturbances were selected and surveyed using kinematic GPS. At each location a total of three to eight oak or ash trees were sampled and a total of 24 cores were collected throughout the study area. The cores were surfaced, measured and dated in the laboratory. Ring counts, made from the biological center to the outside ring, provided the tree age at the height of coring. Depth of burial was divided by tree age to determine an average annual net sedimentation rate and these values were averaged for each sampling location and for each of the three study reaches.

Short-term Sedimentation Rates: Clay pads Overbank sedimentation can be directly measured using sediment traps, plates or marker horizons (U.S. Army Corps of Engineers USACE 1993; Asselmann and Middlekoop 1995; Heimann and Roell 2000; Harter and Mitsch 2003. Steiger et al. 2003) designed to function in a variety of sampling environments and over different spatial and temporal scales. In this study we utilized feldspar clay pads as bright white marker horizons upon which present-day sediment could settle and be subsequently sampled. The feldspar clay provides a natural surface similar to the sampling environment, and in depositional areas that do not experience erosion the clay pad may stay intact for several years.

Clay pads were installed and used to estimate average annual sediment deposition at 10 sampling sites (Fig. 3a) during water years 2007 and 2008. The 10 sampling sites, located within the active annual floodplain, were selected to represent a variety of land use, habitat, and surface roughness factors including several agricultural (crops, dairy pasture, and reclaimed pasture) and wetland (forested and emergent) environments. At each site, representative areas of the active annual floodplain were selected and three to six pads were installed in either a cluster or transect pattern to detect lateral and longitudinal variations in overbank sedimentation. A total of 34 pads were installed throughout the study area and their locations were surveyed using kinematic GPS. Each pad covered a surface area of ~0.25 m^2 to a depth of ~20 mm.

Annually at the end of the wet season each pad was sampled with a hand trowel to determine cumulative overbank sedimentation. Three samples were collected in a single quadrant of the pad in 2007 and an additional three samples from each pad were collected in 2008 in a different quadrant to prevent overlap of sampled area. Average annual sediment deposition at each pad was determined and used to estimate the annual deposition rates for each of the ten sampling sites. These data were then used to calibrate a sediment deposition potential map and estimate the average annual deposition rate within each of the three study reaches

Development of conceptual model and sediment deposition potential map

Although the body of literature that describes overbank sedimentation is robust, there appears to be a lack of studies that explicitly utilize suites of physical characteristics to predict the likelihood of floodplain deposition (Hupp et al. 2008). In this regard we used field observations and measurements collected during a post-flood reconnaissance to define a set of six hydrologic and landscape variables subsequently used to develop a conceptual model of sediment deposition potential. Observations of hydrologic and landscape variables that were positively correlated with floodplain deposition within the study area are presented in the results section and were used to develop a conceptual model, which was transferred to a GIS framework. Raster files describing the spatial variability of datasets determined to control overbank sedimentation were created and scaled numerically. The relative importance of each scaled variable was incorporated using weighted factors and an equation developed to calculate a spatial representation of the potential, or likelihood, for sediment deposition. The uniqueness of a study area is represented in the raster data and also by a departure from equal weights in the relative weighting system. Hydrologic and landscape variables observed to be highly correlated with overbank deposition within the Laguna were assigned larger weighting factors.

Rates and patterns of overbank sedimentation generally depend upon a range of hydrologic and landscape variables

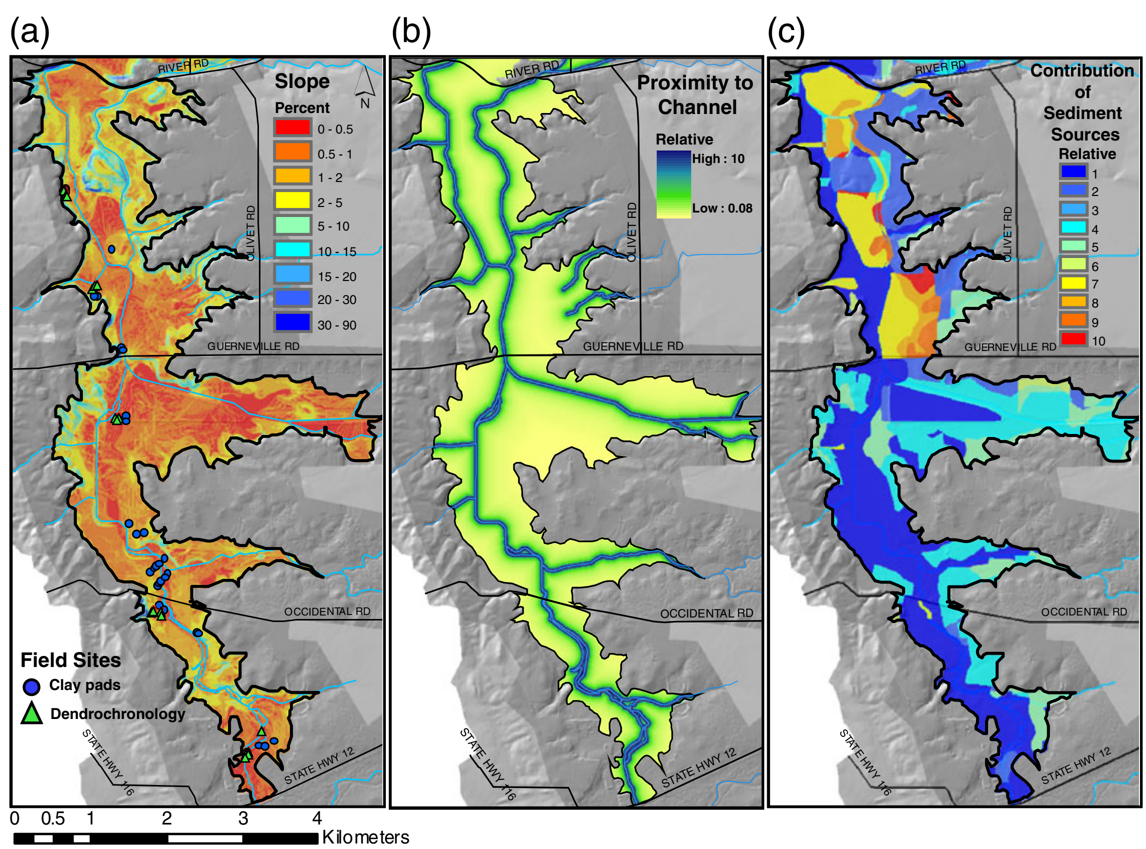

Fig. 3 Maps of processes used to develop a sediment deposition potential map including (**a**) percent slope and overbank sedimentation sampling locations, (**b**) proximity to channel and (**c**) relative contribution of floodplain sediment sources based on land use and soil erosivity with higher numbers indicating greater relative influence on sediment deposition

that include: magnitude, frequency and duration of inundation, sediment supply, and floodplain topography and roughness (Middelkoop and Asselman 1998; Middelkoop and Van Der Perk 1998; Harter and Mitsch 2003; Phillips et al. 2007; Kiss and Sandor 2009; Schenk and Hupp 2010; Kiss et al. 2011). Our method requires selection of a suite of raster datasets to represent these variables. We chose datasets that are widely available such that our methodology is easily transferrable. Inundation extent and duration was characterized by the extent of permanent wetland, annual floodplain extent, and a soil drainage parameter. Sediment supply was characterized by proximity to channel (a surrogate for upland sediment supply) and contribution of erodible floodplain sediment sources (estimated based on land use, soil erosivity, and erodible sedimentary deposits). The variability of floodplain topography was characterized using slope and roughness was described based on land use and field observations of vegetation density. Using Raster Calculator (ArcGIS Spatial Analysis), these datasets were either scaled linearly from their original range and assigned values that ranged from 1 to 10 or assigned presence-absence values (either 0 or 10), with 10 representing the highest likelihood for floodplain sediment deposition (Figs. 3 and 4). The scaled values are intended to represent the likelihood or potential for sediment deposition.

The following describes the process for creating raster datasets and assigning scaled or presence-absence values. Percent slope was calculated in ArcGIS using a 10-m DEM (Gesch et al. 2002). The range of slopes (0 to 40 %) was scaled and inversed such that high slopes have low sediment deposition potential (Fig. 3a). A cost-distance calculation tool (ArcGIS Spatial Analyst) was used to develop the proximity to channel grid using buffered channel vectors and the 10-m DEM. The proximity to channel grid was scaled and inversed such that low distance values had high scaled values (Fig. 3b). The spatial extent of permanent wetlands and the annual floodplain were mapped using a 2005 aerial photograph and 10-m DEM (Fig. 4a). Criteria for delineating the annual floodplain included vegetation type, landscape lineations and slope. Water inundation grids were developed by assigning presence-absence values with 10 assigned to areas within the inundation zone and 0

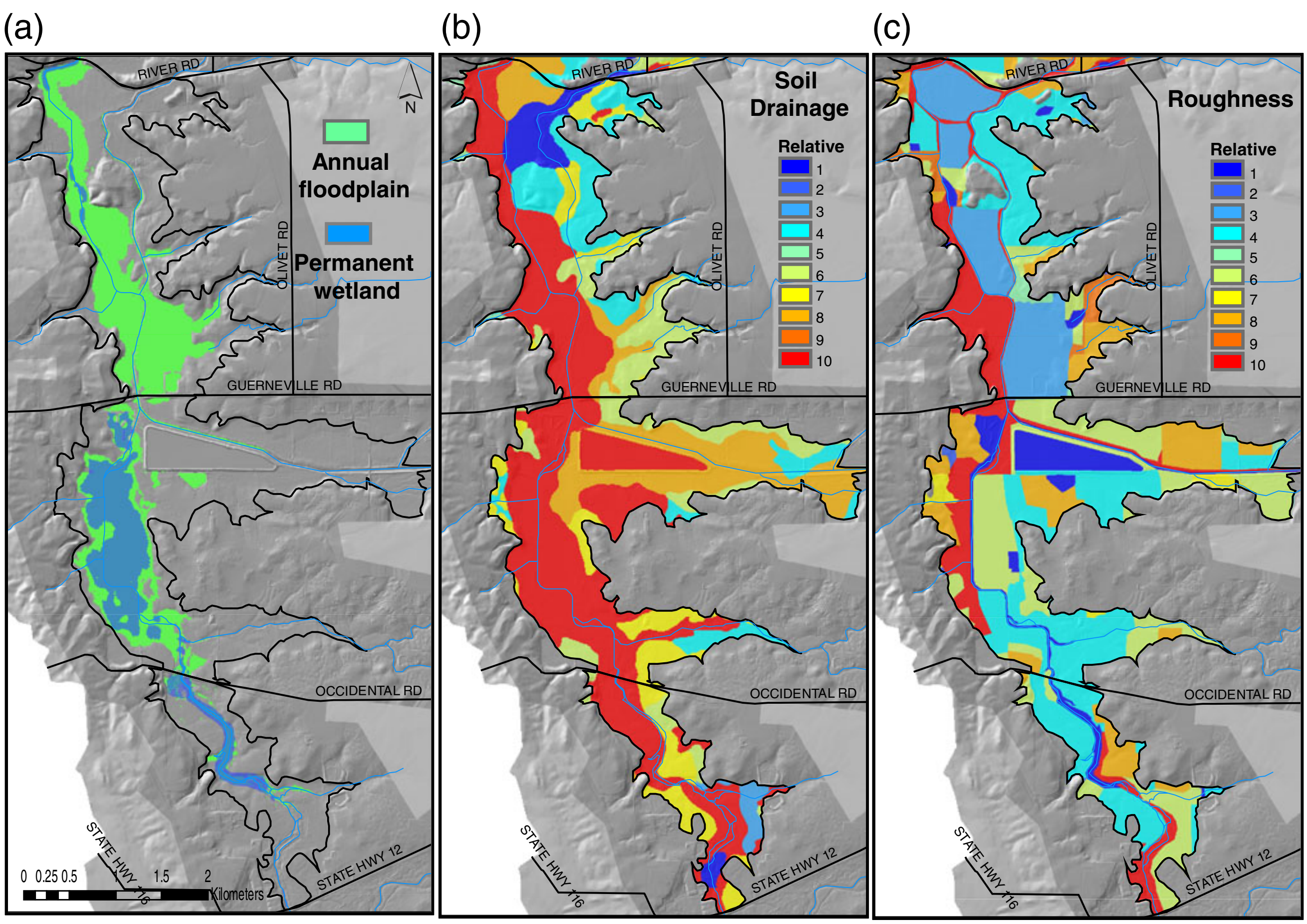

Fig. 4 Maps of processes used to develop sediment deposition potential map including (**a**) extent of annual floodplain and permanent wetlnads, (**b**) relative soil drainage and (**c**) relative roughness based on vegetative cover and land use, with higher numbers indicating greater relative influence on sediment deposition

assigned to areas outside the inundation zone. Soil permeability (Natural Resources Conservation Service 2007) was used as a surrogate for soil drainage and the range of permeability (1.5 to 75 cm/h) was scaled such that soils with low permeability have high sediment deposition potential (Fig. 4b).

The contribution of erodible floodplain sediment sources raster represents the relative importance of erodible floodplain sediment sources and was developed using land use (National Land Cover Database NLCD 2001), erodible sedimentary deposits (field observations), and soil erosivity (Natural Resources Conservation Service 2007). Areas with native and agricultural vegetation were delineated using land use data. Areas that experience annual deposition of sand, delivered from small western tributaries draining highly erodible uplands, and areas prone to cutbank erosion were mapped during the post-flood survey.

A scaled-raster file was developed by assigning values to represent the relative importance of the mapped floodplain sediment sources. Potential floodplain sediment sources were assigned the following scaled values: erodible sediment deposit =10, channel bank erosion=9, row crops=6, vineyards=4, native vegetation=2, and water surfaces=1. Soil erosivity, a dimensionless value ranging from 0 to 0.43, was rescaled from 0 to 10 and multiplied by the sediment source assignments. The final raster was rescaled again from 1 to 10 to generate a representation of the relative contribution and potential for sediment deposition from each floodplain source (Fig. 3c).

Field observations, collected during the post-flood survey, indicate that sediment deposition potential is positively correlated with vegetation type and density (biological trapping) and small scale topographic texture (roughness). We combined the effects of vegetation density and topographic texture to estimate a roughness parameter analogous to Manning's n but derived heuristically. Land cover (National Land Cover Database NLCD 2001) and field estimates of vegetation density and topographic texture were used to define a raster dataset with the following scaled values: golf courses, residential, and urban=1; row crops=2; mixed-native vegetation and pasture=3; row crops=4; low emergent shrub native vegetation=5; high emergent shrub native vegetation=6; orchards and vineyards=7; native vegetation or forest=8; and denser mixed riparian forest=9 (Fig. 4c).

Once the conceptual model was fully rendered in a GIS, an additive equation was developed that included all variables contributing to the likelihood of overbank sedimentation and a sediment deposition potential map was created using Raster Calculator. The equation form used for the sediment deposition potential raster was [slope*A]+[proximity to channel*B]+[permanent wetlands*C]+[annual floodplain*D]+[erodible floodplain sediment sources*E]+[roughness*F]+[soil drainage*G], where the letters A–G represent weighting factors. This equation was used to calibrate the deposition potential map using measured sedimentation rates. Initial weighting factors were assigned based on observations and measurements collected during the post-flood survey. Variables observed to be highly correlated with sediment deposition potential were assigned larger weighting factors. During the calibration process, the weighting factors were changed iteratively until a final solution was defined. During each iteration an estimated sediment deposition potential (SDP) was extracted from the map for each clay pad location and the SDP-measured data relation evaluated for outliers. The coefficients were adjusted based on the correlation between measured deposition data and variables used in the SDP calculation (Fig. 5), SDP was recalculated to minimize outliers and optimize the SDP-measured data relation. The final data were log-transformed and fit with a power function and the final equation describing the SDP-measured data relation was extrapolated and used to predict sediment accumulation on the 11 km^2 floodplain over the 2-year study period.

Results and Discussion

Post-flood survey - inundation extent and sediment deposition

In the lowermost portion of the study area the maximum inundation extent of the New Year's Eve flood (Fig. 6) coincides with the 100-year flood boundary estimated by Federal Emergency Management Agency (FEMA) (2002), whereas flooded elevations were greater than 10 m lower than the 100-year flood boundary in the upper study area between Hwy 12 and Guerneville Rd. This reflects backwater effects from the Russian River, which in this case extended upstream to the Santa Rosa Creek confluence, and possibly as far as Occidental Rd. The elevation of the flood peak at Occidental Rd. was well above the road bed and measured velocities at the gaging station were abnormally low.

The following observations and measurements collected during the post-flood reconnaissance provided the framework for our initial conceptual model and were used to define the initial relative weights for the SDP analysis. Although sedimentation throughout the floodplain varied dramatically, we documented positive correlations with variables used in our GIS analysis and highlight these correlations here. Widely dispersed thin veneers of sediment were located beneath compressed mats of annual grasses and in agricultural fields, (e.g. roughness and floodplain sediment sources), thicker patchy deposits were measured within topographic depressions (e.g. soil drainage and slope), more continuous deposits at the

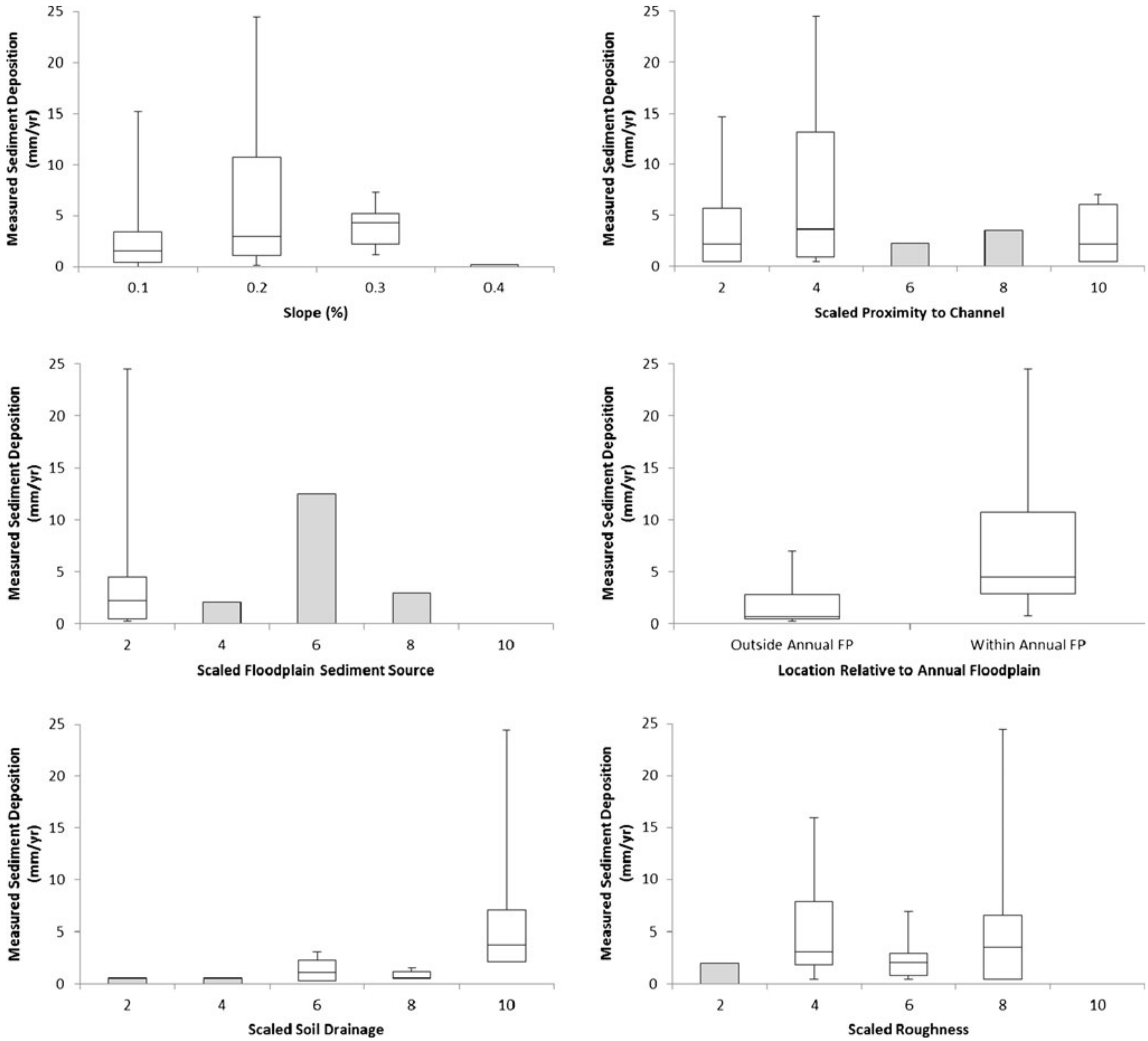

Fig. 5 Box plots represent the correlation between sediment deposition measured at clay pad locations and variables used in sediment deposition calculation shown in Fig. 7. Boxes indicate 25th and 75th percentiles and lines denote the 50th percentile. Capped bars represent the minimum and maximum values. Shaded boxes represent variables with only one sampling location

confluence of Santa Rosa Creek where backwater effects are inferred to have reached an equilibrium with tributary flow (e.g. inundation extent and proximity to channel), to much larger alluvial fan deposits from steep western tributaries draining uplands underlain by the highly erodible Wilson Grove Formation (e.g. floodplain sediment sources and proximity to channel). Measured sediment deposition generally ranged from 0 to 2 mm and can best be described as a pervasive veneer of sedimentation. Deposits located in topographic depressions were 2 to 5 cm thick, whereas flow expansion and deceleration at tributary confluences resulted in thicker deposits that ranged from 5 to 25 cm. The most extreme sedimentation occurred at a break in slope where a series of steep western tributaries flow out of the uplands and across the floodplain. A dramatic change in slope and high sediment loads in this region of the study area result in favorable conditions for alluvial fan development and estimated deposition during the flood event ranged from 0.5 to 1.5 m. These data indicate that depth of sedimentation was positively correlated with slope, proximity to channels, floodplain sediment sources, roughness related to vegetation density and type and small-scale topographic texture, and inundation duration and extent. These observations highlight the validity of the hydrologic and landscape variables used in our analyses.

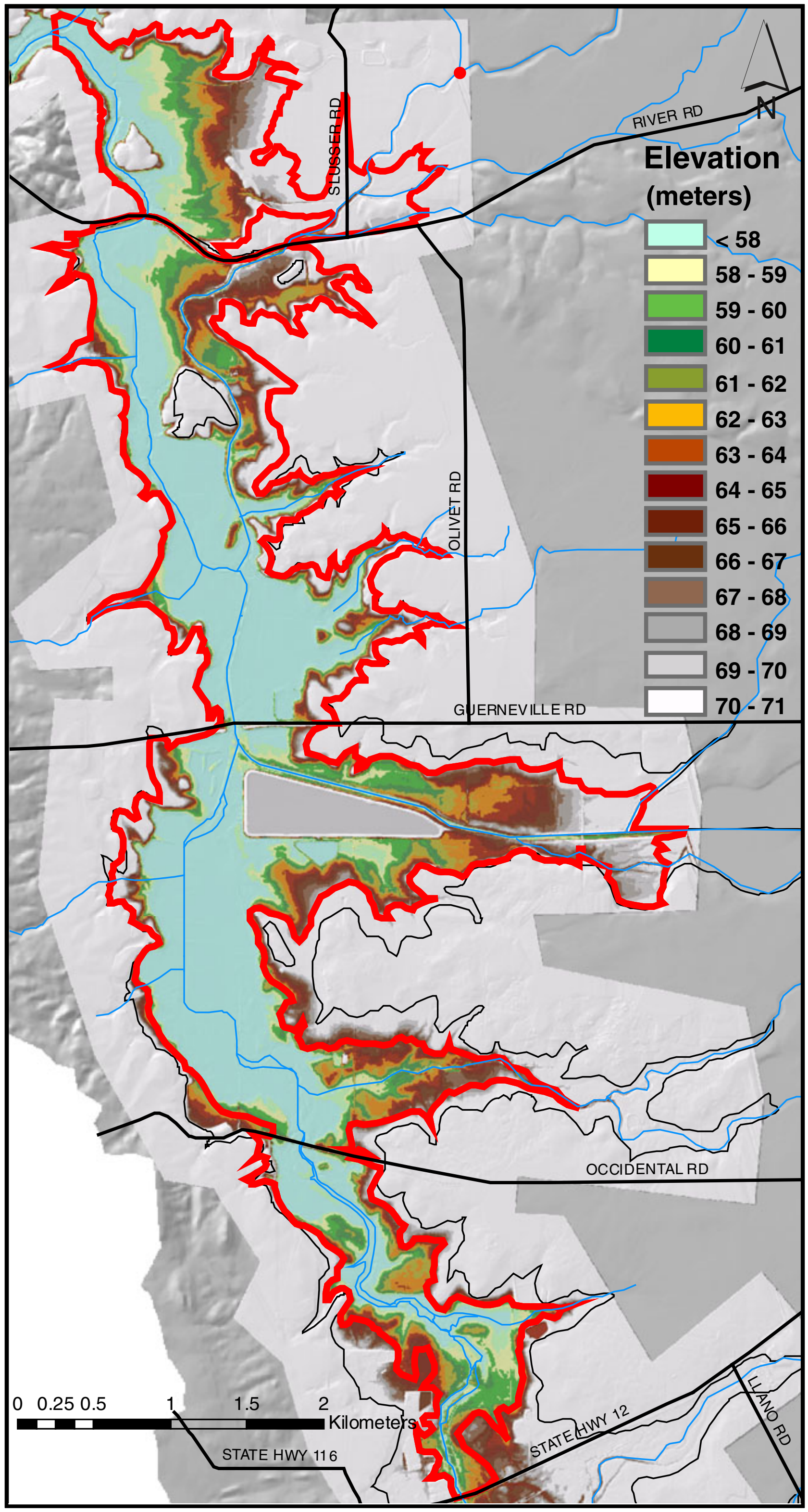

Fig. 6 Floodplain map showing elevation and inundation extent (*red*) for the New Year's Eve 2005 flood and FEMA (2002) 100=yr flood boundary (*black*)

Stream discharge and suspended sediment concentration

Peak discharge for the study period (320 m^3/s) occurred on December 31, 2005 at the Mark West Mirabel gage (Table 2) and the mean annual stream discharge at the Mark West Mirabel gage during water year 2006 was ~15 m^3/s. Based on historic streamflow records from 1940 to 2009 measured at the USGS Russian River gaging station located nearby in Guerneville, CA (USGS 11467000), water year 2006 was a wet year with streamflow at 200 % of normal, whereas water

Table 2 Overbank deposition rates measured using dendrochronology and clay pads and estimated using sediment deposition potential map shown in Fig. 7

Method	Deposition Rate												Floodplain Sedimentation (m^3/year)
	Reach 1*			Reach 2			Reach 3			Study Area			
	Mean (mm/year)	SD	n	Mean (mm/year)	SD	n	Mean (mm/year)	SD	n	Mean (mm/year)	SD	n	
Dendrochronology													
All years	3.2	1.6	13	3.6	1.7	5	4.9	1.1	6	3.7	1.6	24	48,100
Post-1950	4.7	1.5	5	3.5	1.2	3	4.9	1.1	6	4.5	1.3	14	
Pre-1950	2.4	1.1	8	3.7	2.8	2	-	-	-	2.7	1.4	10	
Clay Pads													
2007 to 2008	2.2	2.3	9	4.8	5.1	15	6.5	7.6	10	4.6	5.5	34	49,300
Sediment Deposition Potential Map													
2007 to 2008	2.9	7.5	-	4.5	8.5	-	3.1	5.9	-	3.6	7.2	-	38,200

*See Fig. 1 for reach locations

years 2007 and 2008 were drier with streamflow 40 % and 60 % of normal respectively.

Suspended-sediment data were analyzed in a companion study (Flint et al. 2012) but are presented as support information here. Although suspended-sediment concentration generally increases with increasing streamflow, significant scatter in the mainstem relations indicates varying suspended-sediment supply conditions. At the mainstem Laguna gage (11465750), sediment transport is relatively steady-state until discharge reaches bankfull at ~30 m^3/s. At flows below 30 m^3/s suspended-sediment concentrations are highly variable and range from 12 to 210 mg/l and at higher flows suspended-sediment concentrations begin to increase exponentially with streamflow. Notably, the suspended-sediment concentration at the Laguna gage is typically higher than at the mainstem Mark West Mirabel (11466800), located downstream of the two primary tributaries (Santa Rosa Creek and Mark West Creek). Even under low flow conditions (< 0.3 m^3/s) suspended-sediment concentrations at the Laguna gage range between 12 mg/l and 137 mg/l indicating an abundant sediment supply and transport-limited conditions. Whereas at the Mark West Mirabel gage, low flows

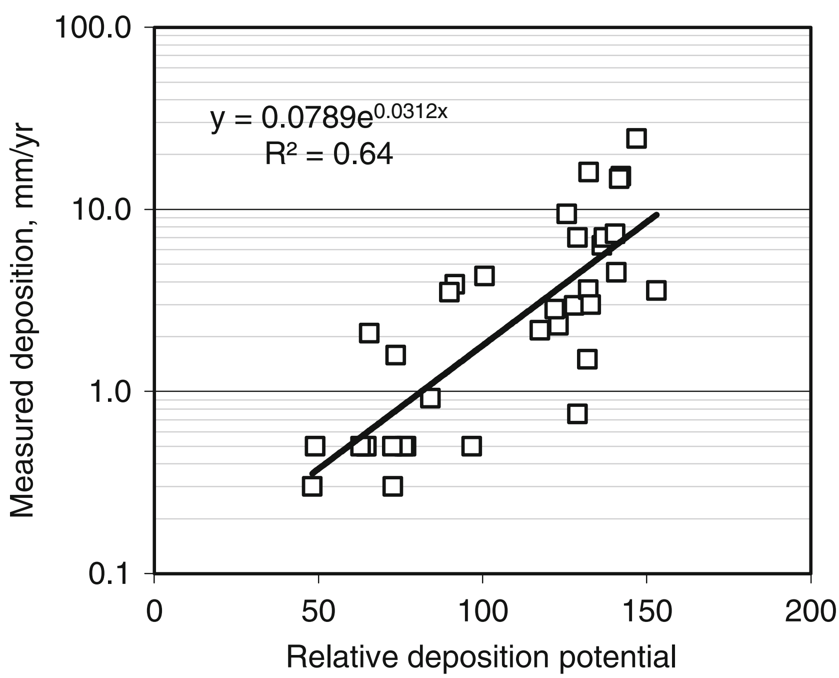

Fig.7 Regression relation between clay pad sedimentation measurements collected during water years 2007 and 2008 and sediment deposition potential estimated at the same locations using a GIS calculation (Eq. 1)

(<0.3 m^3/s) correspond to lower suspended-sediment concentrations ranging from 3 to 39 mg/l. The observed downstream decrease in suspended-sediment concentration could indicate sediment deposition between the two gages or dilution caused by the addition of sediment-free tributary discharge.

There is less scatter in the suspended-sediment rating relations for tributary gaging stations located in Santa Rosa Creek and Mark West Creek (Windsor gage). The tributary gaging relations indicate relatively low rates of suspended-sediment transport during low to average flows but exponentially greater transport during above average flows. The dramatic increase in suspended-sediment delivery at higher flows indicates erosion of sediment sources that are unavailable under lower flow conditions.

Measured floodplain sedimentation rates

Short and long-term sedimentation rates measured within the Laguna floodplain generally increase with increased downstream distance, with the highest rates of historic and present-day deposition occurring in Reach 3 (Table 2). The positive trend with distance downstream is expected as the number of tributaries supplying sediment increases with distance downstream. Long term estimates of overbank sedimentation, estimated using dendrochronology, indicate nearly a doubling of the deposition rate during the last 60 years, with pre-1950 estimates averaging 2.7 mm/year and post-1950 estimates averaging 4.5 mm/year. Sediment deposition estimated from clay pad measurements averaged 4.6 mm/year for water years 2007 and 2008 and the general trend of increased deposition with increasing downstream distance is more pronounced in the clay pad dataset. The clay pad sites represented a broader range of conditions as their placement was not limited to forested locations, which may have biased the dendrochronology measurements.

Measured sedimentation rates in this study are low in comparison to estimates from two recent studies. Philip Williams and Associates, Ltd. (PWA) (2004) estimated an average annual floodplain sedimentation rate of 9.9 mm/year based on a comparison of cross sections surveyed in 1956 and 2002. Aalto (2004) estimated an average annual sedimentation rate of 14.5 mm/year at a single forested floodplain site based on ^{210}Pb analysis of eight cores collected along a single transect and sampled to a depth of 0.5 to 1.5 m. We believe the differences in the rates can be attributed to intrinsic spatial and temporal variability. The relatively low short-term sedimentation rate estimated using clay pads in this study (4.6 mm/year) can be explained by less than average streamflow during the study period. The longer term rates estimated using dendrochronology should be more comparable to those estimated using radionuclide and historic cross section analysis. The long term sedimentation rates estimated in this study ranged from 2.7 to 4.5 mm/year, compared to 9.9 mm/year (Philip Williams and Associates, Ltd. PWA 2004) and 14.5 mm/year (Aalto 2004). The order of magnitude differences likely represent inherent spatial variability.

Predicting floodplain sedimentation using a calibrated deposition potential model

Here we present the final deposition potential model, with weighting factors representing the relative importance of variables for controlling floodplain deposition:

$$\begin{aligned}\text{Sediment Deposition Potential(SDP)} &\quad (1)\\ = [\text{slope*7}] &\\ + [\text{proximity to channel*7}] + [\text{permanent wetlands*1}] &\\ + [\text{annual floodplain extent*7}] &\\ + [\text{erodible floodplain sediment sources*4}] &\\ + [\text{roughness*3}] + [\text{soil drainage*4}] &\end{aligned}$$

Our prediction of spatially distributed average annual overbank sedimentation, estimated for the study period using equation 1 and the regression relation in Fig. 1 is shown in Fig. 8a. The finer scale map in Fig. 8b shows predicted sediment deposition overlaid with clay pads using the same color scheme such that measured and predicted rates can be compared. The range of estimated overbank sedimentation was 0.07 to 120 mm/year and the average annual overbank sedimentation rate estimated using our GIS calculation was 3.6 mm/year (Table 2).

The estimated data do not show the general trend of increased sediment deposition with increased distance downstream. Conversely, the highest reach-averaged estimated rates are in Reach 2, whereas measured data indicate the highest reach-averaged rates are in Reach 3 (Table 2). The higher rates estimated in Reach2 are related to the model assumptions. Reach2 has the widest floodplain, lowest channel gradient, a central permanent wetland that creates slackwater conditions, and recent installation of Delta Pond created an artificial channel constriction at the downstream end of Reach2.

Suspended- Sediment Budget

Although attempts to construct a rigorous sediment budget is deterred by the lack of data from smaller tributaries, a mass balance of measured suspended-sediment loads at the four gaging stations provides an approximation (Table 1). Net changes in storage, estimated as the difference between outgoing and incoming sediment are inferred to represent aggradation or degradation of floodplain deposits based on our assumption that negligible portions of the suspended-sediment budget are deposited in the active channel. During 2006, the annual mass of incoming suspended-sediment was at least 31,800 t. This estimate represents a minimum because it does not include sediment delivered from Mark West Creek,

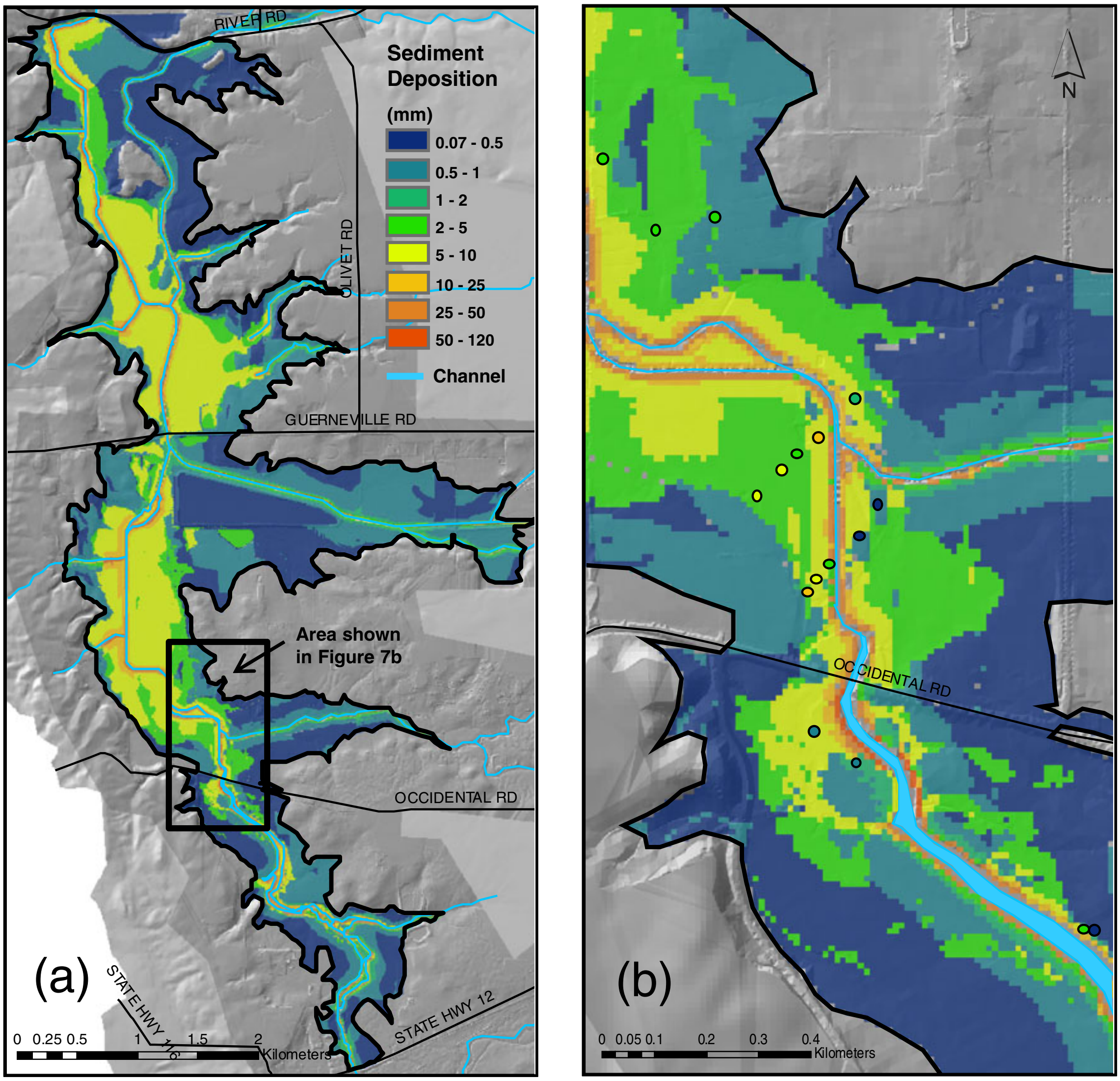

Fig. 8 (**a**) Mean annual overbank sedimentation for WY 2007 and 2008 estimated using regression relation in Fig. 7 and (**b**) finer scale with measured clay pad data collected in 2007 and 2008 color coded for reference

which was ungaged during 2006, nor does it include delivery from smaller tributaries that contribute sediment to the lower Laguna. Flint et al. (2012) estimated that incoming suspended-sediment from Mark West Creek during 2006 could have been as high as 84,400 t. Outgoing sediment, measured at the Mark West Mirabel gage, during 2006 was approximately 26,400 t. Thus at least 5,390 and perhaps as much as 89,800 t of suspended-sediment delivered to the Laguna was not measured at the Mirabel gage and could have been deposited on the Laguna floodplain during 2006.

Water years 2007 and 2008 were significantly drier than 2006 and the sediment budgets were more balanced. Gaging data indicate that during 2007 the study area experienced net degradation with ~2,250 t of sediment eroded from channel or floodplain storage. During 2008 the study area again experienced net degradation with ~2,340 t of eroded channel or floodplain sediment. The summary budget for 2006, 2007, and 2008 indicates at least 875 and as much as 85,300 t of sediment were conveyed into storage representing an average net increase in storage of 290 to 28,400 t/year (~100 to 9,730 m^3/year).

If we compare average annual overbank sedimentation estimated using a mass balance approach (~100 to 9,730 m^3/year, Table 1) with measured clay pad data (~49,300 m3/year, Table 2) for water years 2007 and 2008, the sediment budget estimates represent only ~0.2 to 20 % of the measured data. Although gaging data can provide a first-order approximation of sediment deposition within a reach, the discrepancy between the measured overbank sedimentation data and the mass balance estimates indicates the significance of unmeasured sediment sources and highlights the need to collect direct measurements of overbank sedimentation.

Loss of flood storage capacity

The Laguna, capable of storing over 98,000,000 m^3 (80,000 acre-ft) of stormwater runoff, functions as a flood retention basin for the Russian River. Anecdotal observations of increase flooding from landowners within the Laguna indicate that the annual floodplain is expanding. Our predicted average annual sedimentation rate of 3.6 mm/year extrapolated over 50 years equates to a 0.18 m increase in floodplain elevation or a 2 % reduction in flood storage capacity. Although our observations, measurements and GIS analysis of overbank sedimentation all indicate active floodplain aggradation the rates are low enough to infer that expansion of the annual floodplain is more likely related to changes in storm hydrographs. Within the Laguna the interaction of faster travel times for storm water runoff due to urbanization and tributary channelization with backwater effects from the Russian River has lead to a decrease in channel capacity. During storm conditions the Laguna fills rapidly and backwater effects prevent the downstream transfer of water thereby increasing the elevation and duration of overbank conditions.

Summary

This study documents a method for estimating the potential for various parts of a floodplain complex to accumulate sediment over time. Because overbank sedimentation is highly variable and dependent upon local conditions, we developed a conceptual model using field observations and measurements collected during a post-flood reconnaissance, which also provided an understanding of the hydrologic and landscape variables that influence floodplain deposition. The conceptual model was transferred to a GIS framework and raster files describing the spatial variability of variables determined to influence overbank sedimentation were scaled numerically. The relative importance of each scaled variable was incorporated using weighted factors, an equation was developed to calculate a sediment deposition potential based on local conditions, the deposition potential map was calibrated using measured data, and a spatially distributed map of sediment deposition for the 11 km^2 floodplain was estimated for water years 2007 and 2008. The method is transferable and the uniqueness of a study area can be represented in the raster data and by a departure from equal weights in the sediment deposition potential model such that hydrologic and landscape variables observed to be highly correlated with overbank deposition are assigned larger weighting factors.

Although our results are preliminary and qualitative, they show that our approach has potential to help predict sediment deposition, at least in general terms, and to frame further studies and hypotheses. Although streamflow during the study period was below average, our measured and predicted rates are comparable to those estimated using historic cross section analysis and radionuclide analysis of floodplain cores. Our mass balance analysis indicates that assumptions of sediment trapping on floodplains based on gaging data are not valid in situations where there are significant unmeasured sediment sources and highlights the need to collect direct measurements of overbank sedimentation. This is especially true for regions with multiple land uses, complex topography, and other characteristics that vary spatially and influence floodplain sediment deposition.

Whether floodplains function as short or long-term sediment sinks depends upon local conditions that vary in time and space. The methods outlined here produced a spatial interpretation of floodplain deposition that will support management of the Laguna floodplain for optimum hydrological and ecological performance. Achieving the many interrelated goals of restoration in the Laguna de Santa Rosa, including habitat restoration, reduction of invasive plants, improvement of water quality, as well as maintenance of flood storage capacity, requires a process-oriented approach. The conceptual and analytical framework presented in this study provides a realistic context for prioritizing ecosystem management programs, calibrating future sediment transport modeling efforts, and defining overbank sedimentation rates that can be used to evaluate the effectiveness of future management and restoration activities.

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