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Landscape and Urban Planning xxx (2007) xxx–xxx
LANDSCAPE AND URBAN PLANNING
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A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design

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Received 13 March 2006; received in revised form 4 December 2006; accepted 10 January 2007

Abstract

An alluvial river channel typically meanders by eroding its outer banks and depositing sediments on the inside of bends, producing new land surfaces. Over time the landscape pattern created by these processes is important to the understanding of riparian plant ecology and the spatial structure of riparian forest development for restoration planning and design as well as other purposes. The middle sector of the Sacramento River is an actively meandering channel that deposits sediments in discrete new areas from fluvial geomorphic events creating a land age gradient. Newly formed land undergoes a primary succession by woody species such as willow and cottonwood communities that provide habitat for important conservation target species in California. Conservation and restoration of primary and secondary successional processes is an important management goal on the Sacramento River. The objectives of this paper were: (1) to develop and codify new methods to track the surficial chronological patterns of floodplain land age in a meandering river system, and (2) to analyze land production and the spatial distributions of gravel bars, riparian vegetation communities, and forest structure in relation to the land age gradient. Results from the ecological analysis indicate 71% of extant riparian vegetation was located within the 101-year meander zone; willow (18%) and cottonwood (31–43%) had the highest proportional canopy cover on lands aged 1–9 and 10–44 years, respectively. Potential applications of this approach for conservation and restoration planning and design of alluvial river floodplains are discussed.

Keywords: Meander migration; Floodplain age; Primary succession; Canopy structure; GIS cartographic modeling; Sacramento River; Ecological cascade effect

1. Introduction

1.1. Background

The riparian landscape of a meandering river system is a heterogeneous land mosaic that can change rapidly through time in response to fluvial geomorphic factors (Gregory et al., 1991; Malanson, 1993; Bayley, 1995; Steiger et al., 2005). This study addresses key questions that are important to help guide the rehabilitation of alluvial riparian ecosystems and to show how documenting the chronological development of floodplain deposits can elucidate ecological patterns of riparian vegetation for purposes of restoration planning, design, and management.

The concept of "the landform system composed of a nested hierarchy of subsystems each having different levels of sensitivity and recovery, the whole being subject to a temporal stream of input (i.e., process) changes" (Petts and Bravard, 1996 quoting Chorley et al., 1984) is fundamental to understand riparian landscape dynamics (van Coller et al., 2000; Dixon et al., 2002; Turner et al., 2004). Malanson (1993) argued that riparian systems are a shifting mosaic of patch dynamics in a continuous state of multi-dimensional (space–time) change. Therefore, a method of analyzing riparian vegetation structure and development (i.e. succession) should reflect the effects of temporal sequences and spatial patterns of fluvial geomorphic disturbances (Benda et al., 1998).

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doi:10.1016/j.landurbplan.2007.01.002

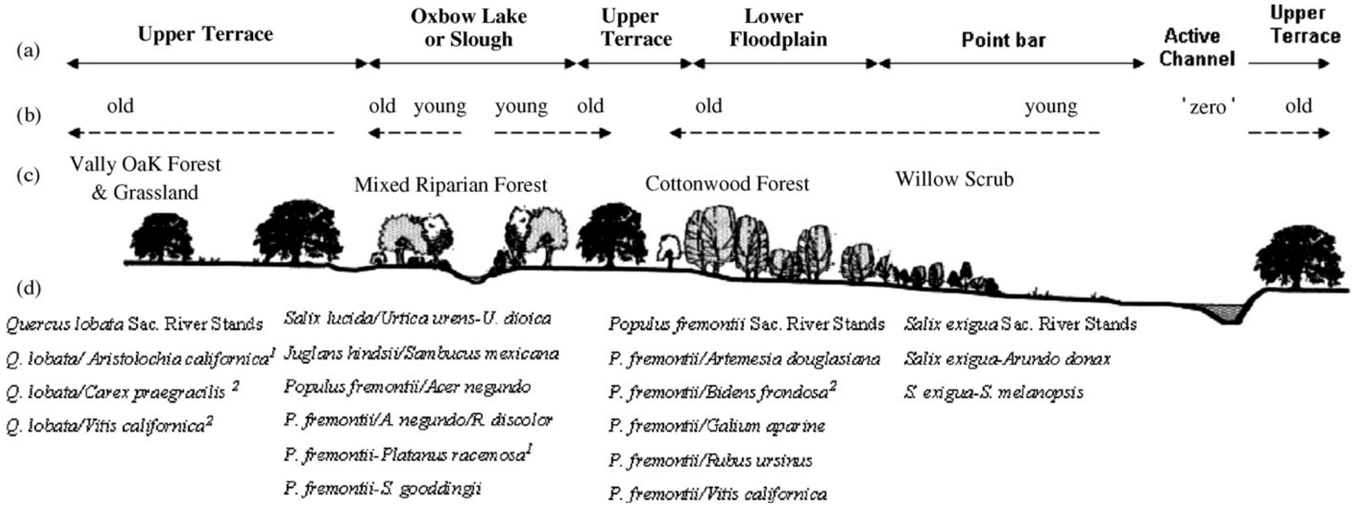

Fig. 1. A cross-section of the Sacramento River floodplain depicting an idealized riparian toposequence: (a) solid lines show the extent of fluvial geomorphic floodplain zones, (b) dashed lines indicate generalized floodplain age gradients, (c) plant communities identified by Holland (1986), and (d) plant species associations described by Vaghti (2003) and others. 1, Rivas-Martinez et al. (1999); 2, Tu (2000). Illustration adapted from Vaghti and Greco (2007) and Conard et al. (1980).

The typical geomorphic structure of a floodplain in a low-gradient or piedmont alluvial river includes eroding cut banks, depositing pointbars, frequently inundated lower floodplains, and infrequently inundated upper terraces (Fig. 1a). The sinuous pattern created by erosion of banks and deposition on pointbars is self-maintaining over time through progressive bend migration (Leopold et al., 1964; Hickin, 1974; Ferguson, 1977). Land reworked through erosion and deposition processes of an active channel creates new land surfaces devoid of vegetation. Bend evolution and channel migration rates are largely a function of local flow magnitude, sediment characteristics, and bank properties (Hughes, 1977; Johannesson and Parker, 1989; Larsen, 1995; Larsen et al., 2006). Human influences on river flows (from dams and diversions) and on bank erosion (i.e. riprap or other revetment) can significantly reduce channel migration rates. However, it should be noted that due to uncertainty and the degree of interactions among those human influences, determination of a single causality can be difficult to achieve (Piégay and Schumm, 2003). Inter-annual climatic variation can produce a range of runoff volumes from a watershed and result in episodic rates of channel migration (Hickin, 1977; Larsen et al., 2006). High flow events can cause large deposits on the margins of pointbars or can initiate meander bend cutoff events to create oxbow lakes (i.e. floodplain water bodies) (Hooke, 2004). Over time oxbow lakes undergo a gradual terrestrialization process due to sediment deposition and accumulation of organic matter (Malanson, 1993; Morken, 2002; Piégay et al., 2002).

To effectively plan, manage, and restore degraded alluvial river systems, there is a need to develop quantitative models to describe and predict geomorphic processes and riparian vegetation community patterns. For a review of some new tools in fluvial geomorphology see Kondolf and Piégay (2003) and for riparian ecology and conservation see Naiman et al. (2005). An approach to quantifying the spatial patterns of meander migration that takes geomorphic processes into account is the mapping of low-flow channels at various time intervals to produce a 'floodplain surface age' map (Gilvear and Bravard, 1996). A good example of this approach was an analysis of the development of alluvial floodplains from ca. 1840 to 1980 in the River Dane Valley in Cheshire, N.W. England by Hooke et al. (1990). The analysis depicted five floodplain age classes representing the time periods: 1840–1870, 1870–1910, 1910–1947, 1947–1968, and 1968–1980. However, Hooke et al. (1990) did not present a formal method for creating the map of floodplain surface ages. To our knowledge, there is not a study in existing literature that formalizes a method to document floodplain surface age for meandering rivers. There is much information regarding the input data for such a map. Historical maps and photographs are typical sources of information for geomorphic studies of channel change, but have limitations in terms of availability, accuracy, and interpretation (Gurnell et al., 2003). Lewin (1977) noted how graphical representation of low-flow channel data can vary from historical maps and photographs and that river stages are rarely recorded. Most of these problems were overcome in this study by acquiring a long time series of photographs and maps, controlling for spatial resolution, employing consistent interpretation rules, and linking photograph dates to historical flow records (see Greco et al., 2003; Greco and Alford, 2003a,b).

A suitable approach to represent the phenomenon of surficial floodplain chronology, or floodplain age, is cartographic modeling using a geographic information system (GIS). Cartographic modeling is a map overlay process that uses functions to combine the features and attributes of multiple map layers into a single map layer (Tomlin, 1990; Lo and Yeung, 2002). Temporal GIS data structures and models to track geographic changes over time are becoming more prevalent in resource management (Ott and Swiaczny, 2001; Peuquet, 2002), such as the development of the ArcGIS Tracking Analyst Software Extension (ESRI, 2003a). Several GIS methods to detect and quantify landscape change are reviewed in Mitchell (1999). In particular, the 'space–time composite' modeling approach described by Langran (1993) uses a series of time slice overlays (time interval snapshots) of the same geographic area to systemati-

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cally map discrete changes in land cover over time. This paper presents new mapping methods to track the cumulative surficial (or chorographic) patterns of landforms created over time in an alluvial meandering river system and relates those patterns to geomorphic and ecological variables. We adopted a time slice overlay method, similar to the space–time composite approach, to identify and quantify the chronology of alluvial floodplains and terraces on a meandering river and used it as a tool for analyzing the spatial patterns of riparian forest ecology. The method tracks land cover properties and the associated fluvial process that created the landform.

1.2. *Riparian ecology*

Riparian ecosystems and the processes that structure, support, and regenerate them are valuable natural resources. These ecosystems support a greater variety of wildlife than any other habitat type in California (Smith, 1980): nearly a third of Pacific Coast wildlife species (Kelsey and West, 1998) and 225 species of birds, mammals, reptiles, and amphibians (Knopf et al., 1988; Dobkin, 1994; Saab et al., 1995). Wildlife in riparian systems responds to numerous environmental variables. Typically, riparian generalist species are less affected by ecosystem changes than riparian obligates. However, specialist species (i.e. riparian obligates) can be highly sensitive to plant species composition and successional stage changes (Kelsey and West, 1998) and this is a management concern (California Resources Agency, 2000).

Alluvial landforms created by flood and channel meander processes provide new substrates for plant species to colonize. Steiger et al. (2005) describe the hydrogeomorphic processes structuring riparian zones. Commonly noted features on meandering rivers are scroll bar topography and striated forest patterns on pointbars that increase in age and size with increasing distance away from the channel (Hickin, 1974; Hickin and Nanson, 1975). With the passage of time, plant growth and environmental conditions typically change vegetation structure and species composition of the riparian landscape. This development through time is commonly distinguished as: (1) ‘primary succession’, which consists of pioneer plant species invading newly created substrates, forming primary successional riparian forests, that we refer to as ‘early seral riparian forests’; and (2) ‘secondary succession’, which is the process of progressive change in species dominance and structure over time on land previously colonized (Mueller-Dombois and Ellenberg, 1974; Bormann and Likens, 1979; Barbour et al., 1987; Pickett and Cadenasso, 2005; Naiman et al., 2005). The conservation of primary successional processes is a critically important management objective because the habitat it creates frequently supports specialist species and a high degree of biodiversity, and it sets the foundational structure for secondary successional riparian forest development (Naiman et al., 2005). Altering ecosystem processes to exclude primary succession could have profound negative consequences for future forest structure, species composition, and habitat function for numerous wildlife species dependent on early and mid-seral forests (Webb, 1997).

On meandering alluvial rivers early seral riparian forests typically occur on recently deposited younger substrates (Fig. 1b) that are dominated by allogenic forces (i.e. physical disturbance acting from outside the community). Pioneer woody plant species colonize in this pointbar area in the fundamental niche space known as a “recruitment box,” as a function of: available substrate, relative elevation, flow drawdown rate and timing, propagule release timing, and root growth rate (Mahoney and Rood, 1998). The temporally striated forest pattern is the result of successful colonists within the realized niche space of the recruitment box and creates a series of even-aged forest stands. Marston et al. (1995) reported that riparian vegetation development on the Ain River in France shifted from a “pulse-like” disturbance regime to one that is more terrestrial and lacking fluvial disturbances.

A chronosequence method studies the process of vegetation succession by substituting space for time (Mueller-Dombois and Ellenberg, 1974; Barbour et al., 1987; Pickett and Cadenasso, 2005), and compares vegetation patch attributes (i.e. species composition and vegetation structure) at different geographic locations at a single point in time since known disturbance events. Studying vegetation development on abandoned agricultural land, Foster and Tilman (2000) found the chronosequence approach was a valid and accurate predictor of relative species abundance but not of species richness. Fremier (2003) used a chronosequence approach to document riparian forest successional stages and pathways on the Sacramento River.

Riparian landscapes are frequently described using a topographic cross-section called a toposequence (Barbour et al., 1987; Luken, 1990) that describes the spatial distribution of dominant plant species and/or communities relative to distance from the channel and depth to groundwater (Fig. 1). This functional relationship between the topographic position of floodplain landforms and vegetation zonation results from the interaction of groundwater patterns and surface flooding patterns of varying intensities within the complex topography created by past fluvial geomorphic events (Mitsch and Gosselink, 1986; Swanson et al., 1988). Topographic position of the floodplain is frequently used as a guideline for species selection in riparian community restoration design. Floodplain age is another variable that in combination with topographic position could help restoration practitioners interpret reference conditions for community type and structural characteristics at a particular site.

1.3. *Study objectives*

The objectives of this paper were: (1) to develop formalized methods to track and quantify the surficial chronological patterns of floodplain land age in a meandering river system, and (2) to analyze land production rates and the spatial distributions of gravel bars, riparian vegetation communities, and forest structure in relation to the land age gradient. Our study was conducted to gain a greater understanding of riparian plant habitats on a meandering portion of the Sacramento River and how community type and structure are distributed in space and change through time. This is important information for conservation, restoration, and management of meandering alluvial rivers because it provides a baseline for natural community structure and a basis for floodplain planting design. These data can be

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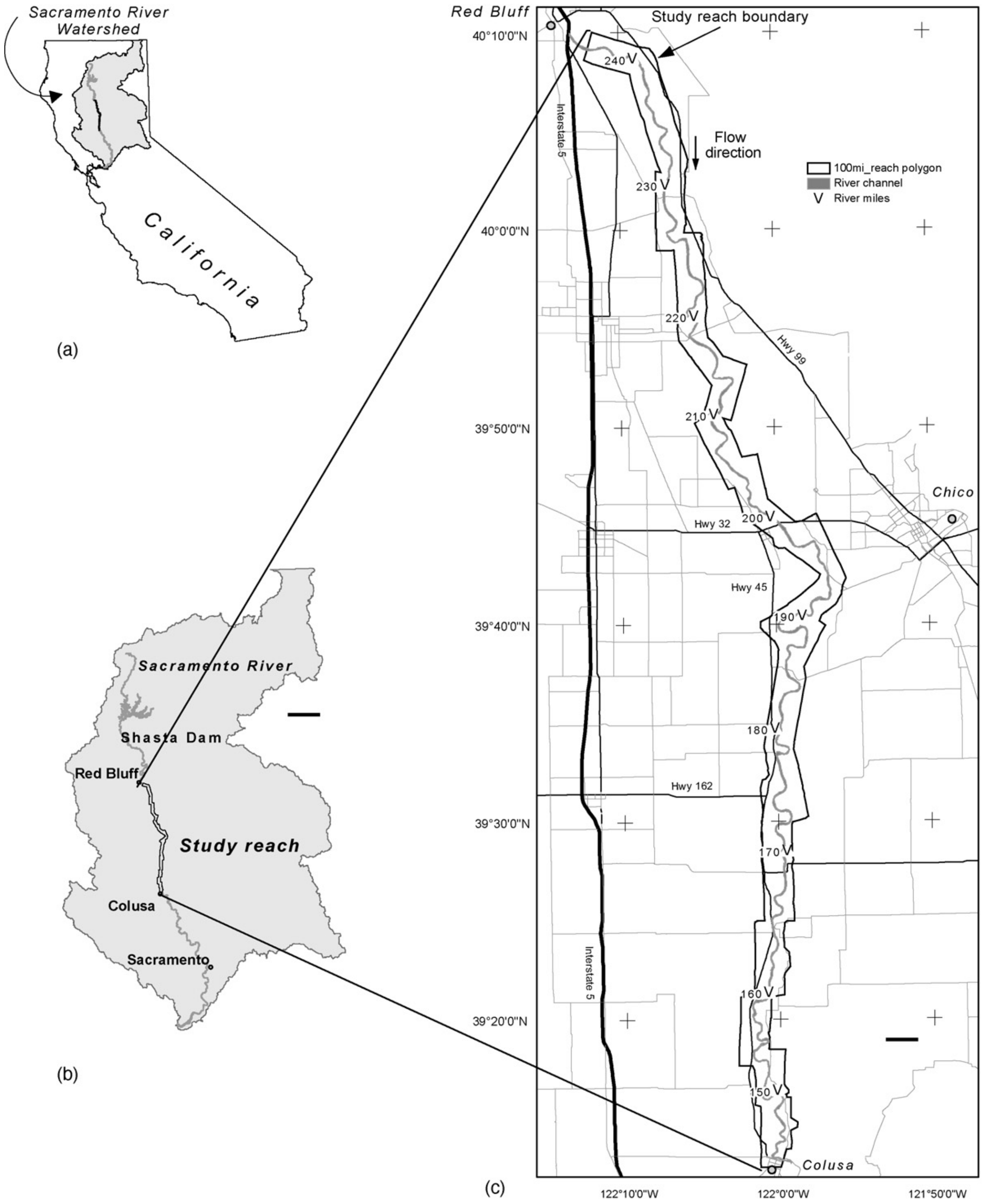

Fig. 2. Study site location map: (a) Sacramento River watershed within the state of California, (b) the selected study reach between river mile 144 (near Colusa) to river mile 245 (near Red Bluff), and (c) the spatial extent of the study reach.

used to help plan and design restoration projects by interpreting site potential, for example, the expected proportion of plant community types (or plant species) associated with a particular mosaic of variously aged lands at a particular site on the river (e.g. cleared agricultural land). Using the surficial floodplain age tracking approach we substituted space for time to examine these ecological patterns. A 100 river mile study reach was analyzed in the upper reaches of the middle Sacramento River (Fig. 2).

2. Study area

The Sacramento River is California's largest flowing river and it provides a majority of the water produced by the state (USACOE, 1986). The study area for this research was located along 157 km in the upper reaches of the middle Sacramento River (RM 143.5–244) in the Great Valley of California (see Table 1) and was approximately 3–5 km in width. This section of the river exhibits a meandering main channel and the flood-

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Table 1
Average values for the Sacramento River study reach (RM 144–245)

Study reach characteristic	Average value
Channel slope	Ranges from 0.0002 to 0.0007 m m^{-1}
Low-flow channel width	120 m
Channel sinuosity	1.36
Climate type	Mediterranean
Mean annual rainfall (valley)	Ranges from 250 to 500 mm year^{-1}
Mean annual rainfall (mountains)	Ranges from 500 to 2500 mm year^{-1}
Catchment size (whole river)	2,305,100 ha

ing regime of wide floodplains (Fig. 2). Conservation of the meander zone, or "meander belt" as it commonly called, and its associated riverine and riparian habitats has been identified as a major conservation and restoration goal of the state of California (CALFED, 1999; California Resources Agency, 2000). The inner river zone is a conservation area defined as the 100-year meander zone plus a 50-year meander projection under current channel management conditions (California Resources Agency, 2000). Conservation and restoration of this management area is a high priority among state, federal and private agencies. Land acquisition and active restoration has been a goal for over two decades and progress has been made (Golet et al., 2003). This research provides scientists and managers with spatial data that tracks the development of floodplains on the Sacramento River over the past 127 years and relates that to natural riparian forest communities.

The riparian forests along the Sacramento River are a valuable natural resource and a heritage to the state of California with a long history (Thompson, 1961). They are highly productive and host great biological diversity, however, it is estimated that 95% of the riparian forests in the Sacramento River system have been lost to agricultural land conversion, flood control projects, and urbanization since settlement of the valley in the mid-1800s (Katibah, 1984; Bay Institute, 1998; GIC, 2003). The remnant riparian forest patches of the Sacramento River are now located within an agricultural landscape matrix consisting mainly of irrigated orchards and annual cropland. A concerted effort by numerous public and private interests to secure conservation lands and restore forests for many threatened and endangered species in the region has resulted in some large-scale acquisition and restoration projects such as the establishment of a US Fish and Wildlife Service National Wildlife Refuge on the river.

Several studies over the past two decades have documented natural history information on the riparian forest ecology of the Sacramento River (Roberts et al., 1980). The riparian flora of the Sacramento Valley was described by Conard et al. (1980) using an association algorithm to derive five community classes for observed plant species sampled along gradients of various topographic and hydrologic zones. The five community types they identified were: valley oak woodland, riparian forest, gravel bar thicket, open floodplain, and hydric communities. Similarly, Holland (1986) described seven riparian plant communities occurring in the Great Valley: valley oak riparian forest, mixed riparian forest, cottonwood forest, elderberry savanna, willow scrub, buttonbush scrub, and freshwater marsh (Fig. 1c). Plant species associations have been described by Rivas-Martinez et al. (1999), Tu (2000) and Vaghti (2003) (Fig. 1d). A review of Great Valley riparian systems and a detailed species list of native and non-native plants was compiled by Vaghti and Greco (2007).

Habitat for the many types of vegetation communities found on the Sacramento River is provided by channel and floodplain morphology shaped by fluvial processes (i.e., erosion and deposition). Channel meander bend cutoff dynamics also produce floodplain water bodies such as backwater sloughs and oxbow lakes. These floodplain geomorphic features produce large early seral riparian forests through primary succession over relatively short time scales (Morken, 2002; Greco and Plant, 2003). Oxbow lakes and islands present challenges to the floodplain age mapping process and are discussed further in Section 3 and Appendix A.

An extensive levee system was completed in the 1920s that channelized the Sacramento River's main stem from RM 0 to 144 at the city of Colusa. From RM 145 to 176 the levees are set back from the river channel between 0.4 and 1.6 km allowing portions of the channel to migrate within the floodplain. From RM 176 to 244 levees are intermittently distributed and most are set back from the main channel of the river.

Shasta Dam was completed on the Sacramento River in 1945 in response to public calls for flood control and water storage and is the state's largest dam (Kelley, 1989). The downstream effects of dams on the physical and ecological processes of rivers are well established (Ligon et al., 1995; Shields et al., 2000). Flow regulation since construction of Shasta Dam has had a dramatic effect on the frequency and timing of historic flow regimes (Fig. 3). A flow analysis of several gage locations conducted by the California Department of Water Resources found extensive alteration to the volume and timing of flows using the indicators of hydrologic alteration (IHA) method (Richter et al., 1996) on the Sacramento River (CDWR, 2001). A flow frequency analysis of the longest and most continuous historic hydrographic record for the Sacramento River (the Bend gage, USGS ref. no. 11377100, located at RM 267) by Lowney and Greco (2003) found the pre-Shasta Dam 2-year recurrence interval (RI) discharge ($Q_2 = 3300\,\mathrm{m^3\,s^{-1}}$) was greater than the post-Shasta Dam 5-year RI discharge ($Q_5 = 3256\,\mathrm{m^3\,s^{-1}}$). And furthermore, the pre-Shasta Dam 5-year RI discharge ($Q_5 = 4446\,\mathrm{m^3\,s^{-1}}$) was nearly equal in magnitude to the post-Shasta Dam 20-year RI discharge ($Q_{20} = 4417\,\mathrm{m^3\,s^{-1}}$). Despite the Bend gage's location

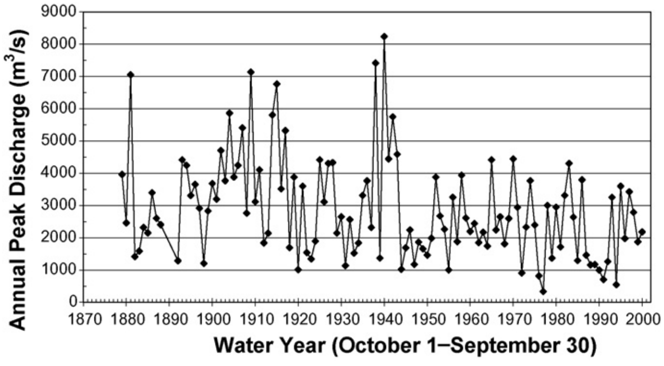

Fig. 3. Annual peak discharge—Sacramento River at Bend Bridge (1879–2000).

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upstream of the study area, it remains a good indicator of stream power lost from the upper watershed flows in the main channel due to storage (impoundment) behind Shasta Dam. However, it should be noted that the largely unregulated tributary streams that flow into the lower reaches of the Sacramento River (within the study area) contribute stream power and bed load to the production of new floodplains. Bed load in the study reach is primarily derived from local bank erosion and tributary inputs, and is largely unaffected by bed load losses blocked by Shasta Dam (Buer et al., 1989).

Due to the meandering nature of the river channel on the Sacramento River (between RM 143 and 245) private landowners and irrigation districts have sought federal and state assistance to prevent erosion of their river-front properties. Rock revetment (riprap) was installed on numerous eroding banks at great expense to prevent the channel from meandering, and succeeds to varying degrees only with regular, costly maintenance (Kraemer, 1984). Riprap prevents lateral expansion of pointbars and reduces or eliminates the production of new land and thus impacts the regenerative capacity of primary successional processes to produce and sustain early seral riparian forest stages. Approximately 34% of the study reach between RM 143.5 and 194 was revetted with rock (i.e. riprapped) and concrete from the 1960s through the 1980s to prevent the erosion of crop land and orchards planted up to the river's edge (USACOE, 1986; CDWR, 2005). Brice (1977) noted that bank revetment has caused substantial "deformations" of the meander bends and that in most cases removal of vegetation was detrimental to preventing erosion on the banks of the Sacramento River. Locally constraining the channel with riprap can: (1) prevent both the formation of new fluvial geomorphic land surfaces and their associated early seral riparian forests, (2) prevent gravel recruitment critical to anadromous fish spawning, and (3) cause incision to the bed of the river (Buer et al., 1989).

In the parts of the river that are free to migrate, Larsen et al. (2006) found a significant relationship between stream power and bank erosion rates on the middle reaches of the Sacramento River. Over time, the drastic reduction in flow volume from impoundment and flow regulation, and the subsequent reduction in stream power, in combination with channel restraints, such as riprap, has ecological implications for limiting the potential of the river to create new land through channel migration and to regenerate early seral riparian forests. As a result of the cumulative effects of both natural channel movement (i.e. unrestrained) and human influences acting to reduce or prevent channel movement of the Sacramento River, the surficial floodplain age gradients and the forests produced from them are visually intriguing and complex landscape patterns to observe.

3. Methods

This section has two parts. The first part describes the background of two algorithm-based cartographic modeling processes to calculate surficial floodplain land age gradient maps from a set of discrete low-flow channel-edge maps and from buffered centerlines (objective 1, above). Additional detailed information on the methodology for the algorithm-based methods is available in Appendix A. The second part describes three analyses conducted with the results of the modeling in the first part. In this study, 'land' is defined as any floodplain exposed during low-flow conditions during the dry season in California (flows <351 m^3 s^{-1} [12,400 ft^3 s^{-1}]). 'Floodplain age' is defined as the time period elapsed (years) since a low-flow channel changed state from water to land (Greco, 1999; Fremier, 2003).

3.1. Part 1: Floodplain age mapping and cartographic modeling

The GIS cartographic modeling processes we developed to track and calculate a cumulative surficial floodplain age map from historical channel dynamics from 1870 to 1997 utilized a combination of vector and raster-based methods in ArcGIS (version 8, ESRI, 2003b). There were three stages in the calculation of a floodplain age surface map: (1) delineation of a time series of low-flow channel-edge and centerline maps, (2) preprocessing the channel maps into 'land year' maps, and (3) calculating cumulative floodplain age.

The first step in the process of calculating the land age gradient surface is to create a set of vector-based channel-edge maps at low-flow. In this study, "low-flow" is defined as discharge on the Sacramento River between 83 and 351 m^3 s^{-1} (2940–12,400 ft^3 s^{-1}) as measured at the Bend gage (USGS Gage #11377100, located at RM 267) and these flows typically occur in the dry season (May–October). The definition of floodplain age as previously discussed depends on the transition of water to land at the low-flow conditions. However, floodplain water bodies such as oxbow lakes (i.e. lentic features) and sloughs can vary significantly in their water levels inter-annually and intra-annually (from early spring and late summer) and thus can confound land age calculations in those areas. Fremier (2003) described three types of cartographic models to calculate floodplain chronology: (1) floodplain history with lotic and lentic features, (2) floodplain history with lotic features only, and (3) floodplain age with a subset of lotic features.

In this study, two approaches were implemented to calculate land age gradients using the first and third model types described above. The first model type retains the greatest amount of spatio-temporal resolution of water feature changes within the floodplain history map and was implemented for the analysis of plant distributions. It employed a time series of 10 natural low-flow channel-edges and all associated floodplain water bodies. The third model type was chosen for the geomorphic analysis of new land production to take advantage of additional data available only as centerlines (i.e. 1920) to increase the temporal resolution of the time series. That analysis used a time series of 12 centerlines buffered 60 m on each side to create a consistent channel width (120 m) for the analysis of land production. The 120 m average width was determined by averaging lateral width measurements of multiple years of low-flow channels according to the low-flow definition discussed above. Only low-flow channel-edges delineated from aerial photography were used for measuring channel widths. The centerline approach also has the advantage of maintaining low-flow channel width consistency between historical maps and aerial photographs. Pre-dam

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Table 2
Land and water classes for low-flow channel-edge maps (from Greco et al., 2003)

Land cover class	Description
River channel	Active flowing channel of water (lotic)
Side channel	Distinguishable from main channel yet still connected—lotic water features
Tributary	River or creek flowing into main channel (lotic)
Lacustrine	Lentic water features either adjacent or set back from river channel (lentic)
Land	All other features were labeled non-water

(before 1945) channel low-flow widths, as observed from 1938 aerial photography taken in the dry season, show similar widths, or in some cases narrower widths, because of lower flows in summer prior to flow regulation. Therefore, an assumption in this floodplain age modeling approach is that no significant change in channel width has occurred between pre-dam and post-dam conditions and that low-flow channel width is low in variation. Based on the pre-dam photography we believe these are reasonable assumptions for our analysis on the Sacramento River. The automated portion of each model was implemented using ArcInfo Arc Macro Language (AML; a copy of the AML is available from the author upon request) (ESRI, 2003b).

Low-flow channel-edge and centerline maps for this project were created using historical maps and aerial photography (see Greco and Alford, 2003a,b; Greco et al., 2003). Channel delineation from aerial photography employed a 20 m minimum mapping unit criterion. Water features in all channel maps were classified to distinguish between the main channel and other floodplain water bodies (Table 2). Channel centerlines were derived from the low-flow channel-edges as described by Greco and Alford (2003a,b). Six historical channel maps and nine sets of aerial photography were utilized as input to create the low-flow channel-edge and centerline maps for the floodplain age modeling process (Table 3). Full coverage of the river channel was achieved for most but not all time periods. Two channels in the time series are temporal composites consisting of a portion of the river channel in two different years, but close in age. Those two channels are 1938 and 1966, which respectively have portions of channel-edges from 1937 and 1938, and 1964 and 1966. The 1920 centerline is a composite between two different studies (see Table 3).

A more detailed description of the methodology for the preparation of 'land year' maps and the floodplain age calculation process is provided in Appendix A. A discussion of potential sources of error of the surficial floodplain age maps is also included in Appendix A.

3.2. Part 2: Floodplain age surface analyses

3.2.1. Ecological analyses

Using the results from the buffered centerline floodplain age model we measured the area and rate of new land production between each time period. Since there are an unequal number of years between each time interval of available channel data, we calculated the mean annual rate of new land created for each time period. From the floodplain age model that used low-flow channel-edges as its input we measured the proportional land cover responses to the surface land age gradient. Land cover mapping was conducted by the Sacramento River Riparian Mapping Project (GIC, 2000) on lands bordering the Sacramento River and its major tributaries. The project used 1999 true color aerial photography at a scale of 1:9000 in order to map riparian vegetation community types, species, and other land cover types (Table 4). For the land cover analysis we quantified the respective relative proportions of areal cover of each land cover class within each floodplain age class. We selected a subset of the five most abundant land cover classifications (Table 4) to show the relationship to each floodplain age class.

Table 3
Low-flow channel mapping datasets with map attributes, data sources, and river mile extents (from Greco et al., 2003; Greco and Alford, 2003a,b)

Year	Format	Scale	Source	River miles
1870	Hist. map	1:94,000	UCD	145–245
1887	Hist. map	1:125,000	CADE	145–245
1896	Hist. map	1:6,000	USACE	145–245
1904	Hist. map	1:63,360	USGS	145–245
1920	Hist. map	[a]	USGS Rpt.	143–192
1920	Hist. map	1:4,800	USACE	192–246
1937	b/w photo	1:20,000	NARA	145–201
1938	b/w photo	1:20,000	NARA	201–245
1942	b/w photo	1:15,840	USBOR	145–245
1952	b/w photo	1:20,000	USDA	145–245
1964	b/w photo	1:20,000	USDA	145–202
1966	b/w photo	1:20,000	USDA	202–245
1976	color photo	1:24,000	DWR	145–245
1987	b/w photo	1:24,000	DWR	145–245
1997	Color photo	1:12,000	DWR	145–245

Note: CADE: State of California Department of Engineering; DWR: California Department of Water Resources; NARA: National Archives; UCD: Shields Library, Map Collection, University of Califonia, Davis; USBOR: U.S. Bureau of Reclamation; USACE: U.S. Armry Corps of Engineers; USDA: U.S. Department of Agriculture; USGS: U.S. Geological Survey; USGS Rpt.: see Brice (1977).

[a] Undocumented.

Table 4
Selected land cover types from the GIC (2000) vegetation map analyzed with the floodplain age gradient

Land cover classification	Description
Gravel and sand bars	Annual and perennial herbland plant species with less than 50% vegetation coverage (appears un-vegetated on photos)
Great Valley riparian scrub	Young primary succession (presumably willow dominated stands with young cottonwood)
Great Valley cottonwood riparian forest	Cottonwood (*Populus fremontii*) canopy cover greater than 80% including one or more tree willows (*Salix goodingii*, *S. laevigata*, and *S. lasiandra*) and when conspicuous, California grape (*Vitis californica*)
Great Valley mixed riparian forest	A mixture cottonwood and willow containing Valley oak (*Querus lobata*), black walnut (*Juglans* spp.), Oregon ash (*Fraxinus latifolia*), Chinese tree of heaven (*Ailanthus altissima*), sycamore (*Platanus racemosa*)
Valley oak	Canopy cover of Valley oak (*Querus lobata*) less than 60%

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Riparian forest structure of the Sacramento River corridor from Red Bluff to Colusa, RM 143.5–245 was mapped using 1997 color aerial photography at a scale of 1:12,000 by the Landscape Analysis and Systems Research Laboratory at the University of California, Davis (Greco et al., 2003). Three canopy height classes of low, medium, and high (<6, 6–20, >20 m, respectively) were visually delineated using a stereoscope along with land cover classifications, such as riparian forest, oak woodland, orchard, disturbed, lacustrine, and side channel. Our analysis focused on the canopy height classification of the natural vegetation, i.e. riparian vegetation (excluding annual grasslands) and oak woodland. An accuracy assessment of this dataset conducted by Greco (1999) found canopy heights were classified approximately 87% correctly in a 37 km subreach (RM 196.5–218) of the project study area. Raster-based cartographic modeling was used to quantify co-occurrence between the floodplain age surface map and the ecological variables (species composition and canopy height) using a “combine” function and summarizing value attribute tables generated by the Spatial Analyst extension of ArcGIS (ESRI, 2003b).

4. Results

4.1. Floodplain age surface map

The floodplain age surface map derived from the sequential raster overlay process of low-flow channel data between 1870 and 1997 is presented in Fig. 4. It shows the year (i.e. time period) that each portion of the 1997 floodplain was created within the study reach and clearly illustrates the dynamic nature of the Sacramento River over the past 127 years within the study reach. Table 5 forms a matrix of the area (ha) of each land age class for each time period (i.e. model iteration). The table tracks the progressive age structure of the land and thus can be considered an accounting tool for the analysis of “floodplain demography.” An example application of floodplain demography is the examination of the fraction of new land created with each iterative step of the floodplain age mapping process as shown in the diagonal values of Table 5. The length of each river channel centerline is also reported in Table 5.

Table 6
A summary of the new land area created in each time period and the mean annual rate of new land production

Time span	Year	New land (ha)	Time difference	Rate (ha year^{-1})
1870–1887	1887	3243	17	191
1887–1896	1896	3044	9	338
1896–1904	1904	1507	8	188
1904–1920	1920	1659	16	104
1920–1938	1938	1040	18	58
1938–1942	1942	1096	4	274
1942–1952	1952	837	10	84
1952–1966	1966	891	14	64
1966–1976	1976	1008	10	101
1976–1987	1987	1091	11	99
1987–1997	1997	584	10	58

4.2. Ecological analyses

The respective land area and rate of new land production for each time period (Table 6) is shown in Fig. 5. The time periods from 1870 to 1904 exhibit high rates of land production that ranged from 188 to 388 ha year^{-1} (mean = 239, S.E. = 49, n = 3) whereas the time period from 1904 to 1938 shows a marked decrease (mean = 81, S.E. = 23, n = 2). The time period from 1938 to 1942, which included two large flood events, shows a spike in land production (274 ha year^{-1}) similar in magnitude to the 1870–1904 time period. The time periods after 1942 show a land production rate without a clear trend that ranged from 58 to 101 ha year^{-1} (mean = 81, S.E. = 9, n = 4) and was similar in magnitude to the 1904–1938 time period. Overall results of the riparian vegetation analysis indicate that 71% of the extant riparian vegetation within the study reach was found to be located within the 101-year meander zone in 1997, as measured by flood-

Table 5
Results from the floodplain age model of buffered channel centerlines showing the land area (ha) in each land age class

Land age year	Channel length (km)	Cumulative age range in 1997	Area of floodplain age class (ha) by mapped year											
			1870	1887	1896	1904	1920	1938	1942	1952	1966	1976	1987	1997
1870	156.0	>127	32,172	28,978	26,692	26,008	25,273	24,923	24,648	24,367	24,091	23,781	23,461	23,336
1887	151.8	111–127	0	3,243	2,297	2,066	1,867	1,772	1,687	1,611	1,571	1,468	1,391	1,360
1896	166.5	101–110	0	0	3,044	2,551	2,156	2,022	1,873	1,805	1,757	1,690	1,608	1,557
1904	158.3	93–100	0	0	0	1,507	1,140	1,047	981	942	913	861	812	795
1920	161.1	77–92	0	0	0	0	1,659	1,320	1,154	1,083	1,033	972	898	850
1938	159.4	59–76	0	0	0	0	0	1,040	742	677	638	590	546	522
1942	154.0	55–58	0	0	0	0	0	0	1,096	863	789	743	680	650
1952	153.6	45–58	0	0	0	0	0	0	0	837	706	638	564	530
1966	155.6	31–44	0	0	0	0	0	0	0	0	664	546	475	445
1976	151.7	21–30	0	0	0	0	0	0	0	0	0	891	753	690
1987	153.3	10–20	0	0	0	0	0	0	0	0	0	0	1,008	888
1997	152.1	1–9	0	0	0	0	0	0	0	0	0	0	0	584
Water	na	0	1,958	1,909	2,098	1,998	2,034	2,007	1,948	1,946	1,968	1,950	1,934	1,922
Total area	na	na	34,130	34,130	34,130	34,130	34,130	34,130	34,130	34,130	34,130	34,130	34,130	34,130

Column year values represent the same year ranges as the cumulative age range values.

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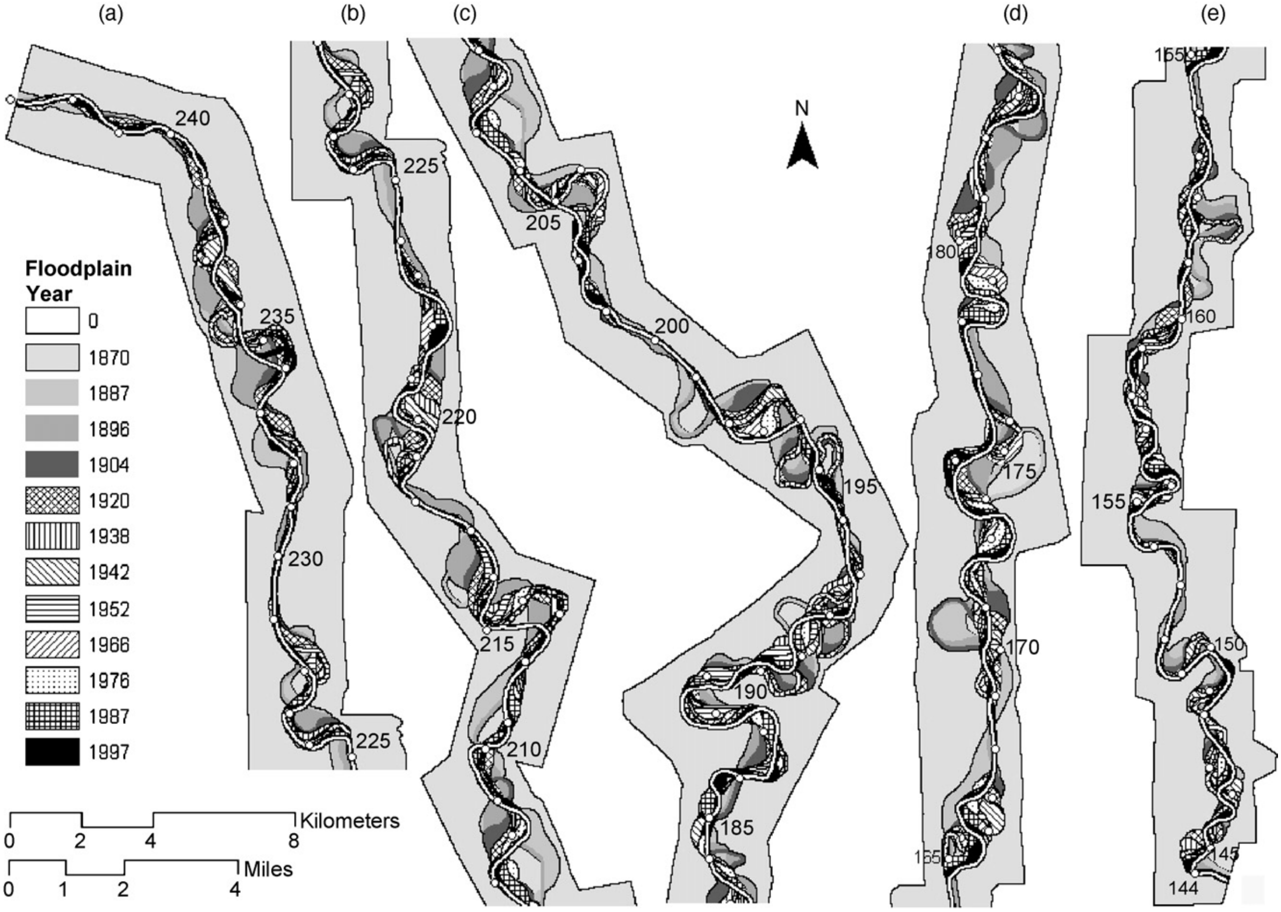

Fig. 4. Results from the floodplain age GIS model presented in five river reaches from north to south (a–e) of the middle Sacramento River. Patterns and shades indicate the time period when the land was created. River mile markers are indicated by open white dots.

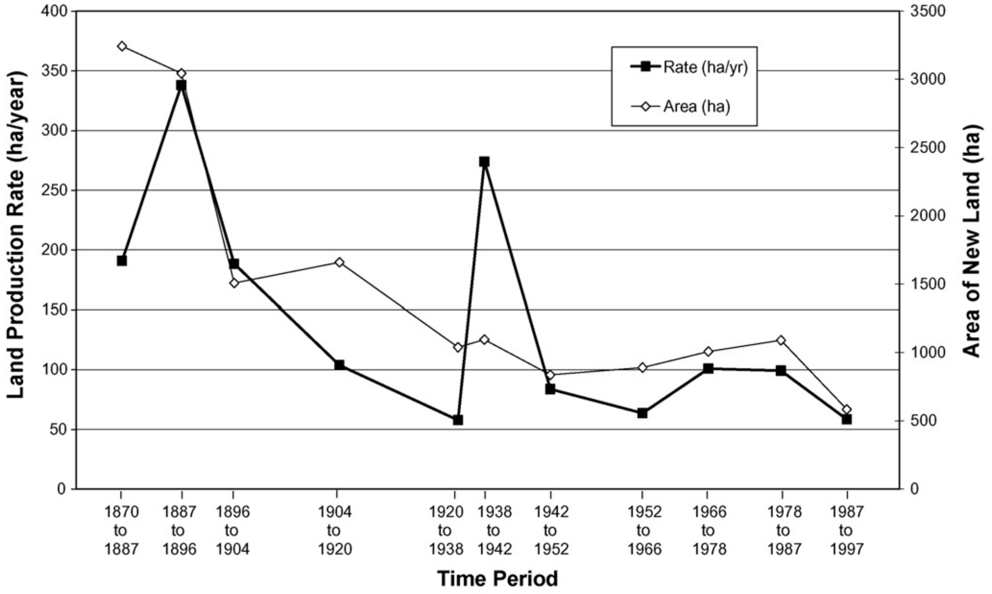

Fig. 5. New land area production rate (ha year^{-1}) and area (ha) created for 11 time sequences between 1870 and 1997 on the Sacramento River.

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plain age classes less than 101 years (1896–1997; Table 7). The remaining 29% of the riparian vegetation was located in floodplains older than 101 years.

The "proportion of land cover type area" per floodplain age class is shown in Fig. 6 (note that for each floodplain age class the land cover proportions of each land cover type in that floodplain age class sums to 1). Proportional cover of each land cover type was derived from the land area measurement results in Table 7. Analysis of plant community spatial distributions over the age gradient indicate that the riparian scrub category, i.e. dominated by willow communities, had the highest proportional land cover (18%) on lands aged 1–9 years and cottonwood communities had the highest proportional land cover (31–43%) on lands aged 10–44 years (Fig. 6). Gravel was found to be the dominant proportional land cover type (33–56%) on lands aged 1–20 years (Fig. 6).

Riparian forest canopy height class patterns over the land age gradient (Fig. 7 and Table 8) indicated that 52–62% of proportional land cover on lands aged <21 years was dominated by low canopy height vegetation (<6 m in height). A notable pattern developed in the 21–30 year floodplain age class where nearly equal proportions of all the canopy height classes are represented. This pattern changes rapidly on lands aged >31 years where high canopy vegetation (>20 m in height) was clearly dominant in floodplain age classes between 31 and 101 years and in the 111–127 year age class. The decline of dominance of high canopy in the 93–110 year age classes could be a result of cottonwood communities becoming decadent in the later stages of the primary succession. We have observed that *Populus fremontii* is gradually replaced by understory tree species such as *Juglans califonica* var. *hindsii*, *Fraxinus latifolia*, *Acer negundo*, and *Quercus lobata* in floodplain age classes >100 years (see Fremier, 2003 and Vaghti, 2003).

5. Discussion

In this study, we successfully developed and implemented a new tool to understand the geomorphic dynamics of an alluvial river floodplain in relation to the spatial distribution of riparian plant communities and forest canopy structure. The floodplain age cartographic modeling approach employed an automated GIS environment to track the areal chronology of floodplain development. This formalization of the cartographic modeling methods and the assumptions into computer code allows repeatability in a timely manner and enhances scientific interpretation of the methods and results. From the resultant land age surface we were able to measure land production rates and develop spatial relationships between vegetation communities and the land age gradient. This new tool can help to inform scientists and natural resource managers about the potential impacts of human influences (e.g. dams and channel restraints) on downstream forests, and provides important information about reference site characteristics for the restoration of degraded alluvial riparian ecosystems. For example, given the floodplain age state (or gradient) of a site on the Sacramento River, the relative proportions of specific plant communities can be estimated and used as parameter in the design of the restoration of the site. Another

Table 7
Results from the analysis of the co-occurrence of land cover (vegetation types and gravel bars) and surficial floodplain age classes

		Area (ha)											
		FPA range (years)											
		>127 (1870)	111–127 (1887)	101–110 (1896)	93–100 (1904)	59–92 (1938)	45–58 (1952)	31–44 (1966)	21–30 (1976)	10—20 (1987)	1–9 (1997)	Total
Vegetation types												
1	Blackberry scrub	20.4	4.8	2.0	1.9	1.8	0.1	0.5	0.3	0.3	0.4	32.4
2	Cottonwood forests	171.5	57.0	91.7	64.5	206.5	199.4	203.2	246.5	254.0	58.6	1552.9
4	Giant reed	5.9	0.6	2.6	0.3	4.1	4.5	1.7	3.3	5.1	0.7	28.6
5	Grassland	189.2	41.1	183.1	59.4	139.9	98.3	77.3	50.2	55.7	20.3	914.5
6	Marshlands	24.1	1.4	1.5	3.1	4.7	2.1	1.7	4.4	9.5	9.0	61.3
7	Mixed riparian forest	718.8	245.2	397.1	263.5	465.9	203.5	105.9	107.9	75.3	42.5	2625.6
9	Riparian scrub	154.3	47.1	61.8	43.2	94.8	53.2	43.3	74.6	149.6	90.5	812.4
11	Valley oak	53.8	1.3	6.1	0.1	2.3	0.1	0.0	0.1	0.0	0.5	64.2
13	Disturbed riparian	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
Subtotal		1339.6	398.6	745.8	436.0	920.0	561.0	433.5	487.2	549.4	222.4	6093.4
Non-vegetation types												
14	Gravel and sand bars	62.8	13.8	50.2	23.6	83.6	84.5	51.2	87.8	268.2	283.4	1009.2
Total		1402.3	412.4	796.0	459.6	1003.6	645.5	484.7	575.1	817.6	505.8	7102.6

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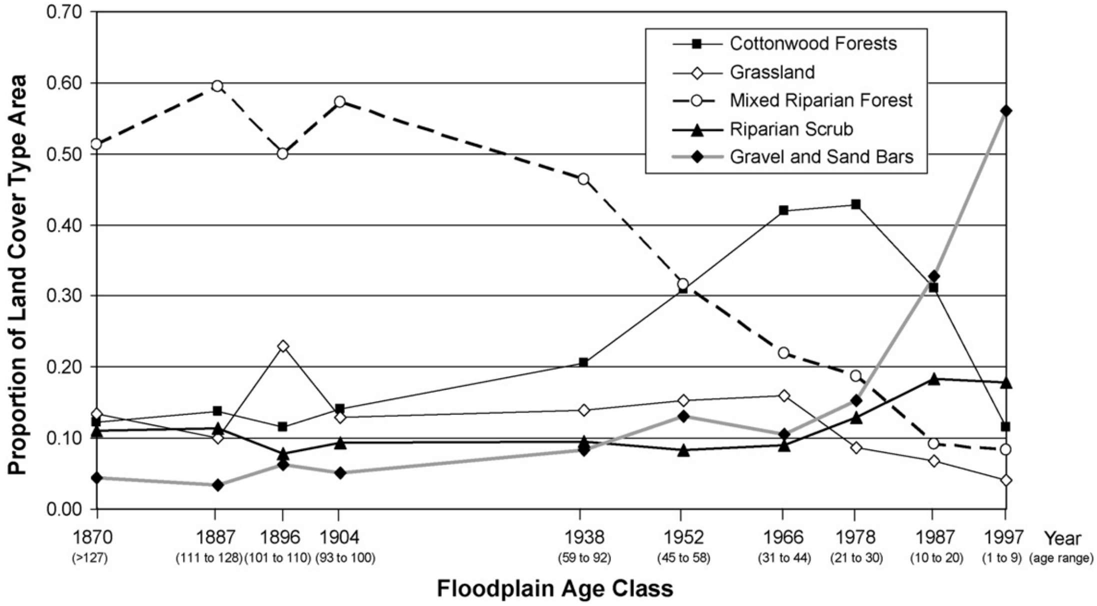

Fig. 6. Results from the land cover analysis showing the relative distributions of gravel bars and riparian vegetation communities on the land age gradient. Note the *x*-axis depicts the land age gradient as decreasing in age from left to right.

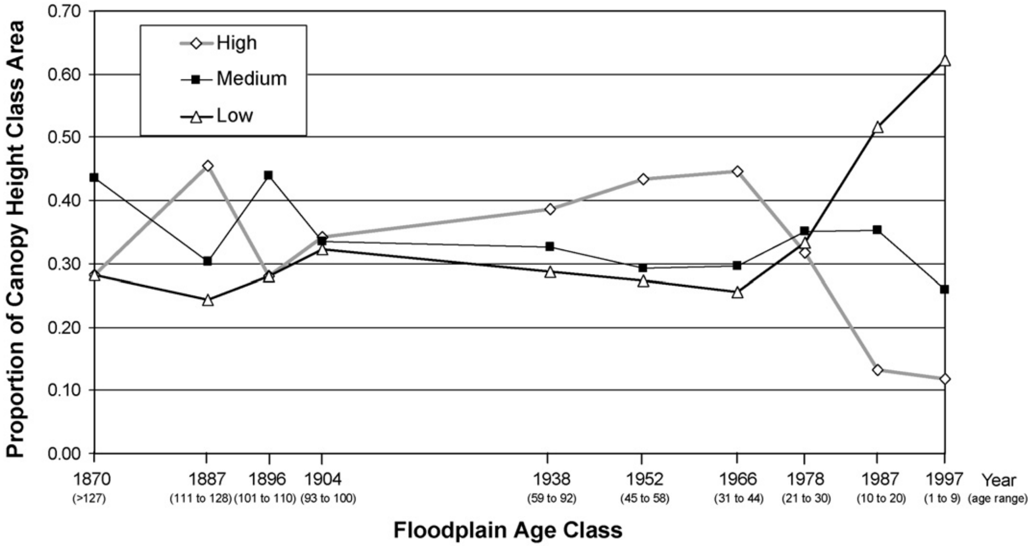

Fig. 7. Results from the land cover analysis of the relative distributions of woody riparian vegetation canopy height classes over the land age gradient.

Table 8
Results from the analysis of the co-occurrence of riparian vegetation size classes and surficial floodplain age classes

Vegetation size class		Area (ha)										
		FPA range (years)										
		>127 (1870)	111–127 (1887)	101–110 (1896)	93–100 (1904)	59–92 (1938)	45–58 (1952)	31–44 (1966)	21–30 (1976)	10–20 (1987)	1–9 (1997)	Total
2	High	447.5	190.4	157.3	146.8	348.3	228.3	176.2	158.4	74.4	32.6	1960.1
3	Medium	689.1	126.7	246.3	143.2	293.6	154.4	117.0	175.0	199.6	71.7	2216.6
1	Low	447.5	101.7	157.3	138.4	259.8	144.3	101.0	166.4	292.4	172.4	1981.0
Total		1584.0	418.7	560.8	428.5	901.7	527.0	394.2	499.7	566.4	276.7	6157.7

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potential application is to use floodplain age vegetation relationships as criteria for assessing success of restored sites as compared to natural reference sites in monitoring applications.

5.1. Conservation of meander dynamics

The sustainable long-term conservation of early seral riparian forest production and other ecological communities – such as oxbow forests – on meandering rivers depends on the ability of the channel to migrate and create new land through fluvial geomorphic processes. The results of this study indicate the rates of new land production on the Sacramento River since ca. 1900 have been altered by a combination of at least four effects: the bank hardening effects of channel bank revetment (riprap) that prevent erosion, impoundment of water due to storage, flow-regulation effects of Shasta Dam, and conversion of natural vegetation to agriculture. Although the impacts on migration rates due to land conversion have been documented (Micheli et al., 2004), it is not possible with our data to separate the flow and riprap effects because there are few, if any, records available of riprap construction on private lands before the 1930s. The precipitous decline of new land production from 1896 to 1938 indicates that something was causing the decrease prior to the dam's construction. Historical flow data alone does not explain the decrease during this time period. The rapid decline could be in part due to channel revetment installed by farmers during this time period, or a series of recorded droughts (e.g. 1912–1913, 1918, 1920, 1922–1925, 1931–1934), or mapping error associated with historical maps. These factors are plausible contributors to sources of error in the results of our study (see Appendix A for further discussion of sources of error). The spike in the new land production rate in the 1938–1942 time period coincides with the largest recorded flood on the Sacramento River in 1940.

It is, however, well understood that peak flows have dramatically decreased since construction of Shasta Dam on the Sacramento River. A reconnaissance study that examined flows on the Sacramento River found a 37% decrease in peak flow between 1879–1945 (mean peak = $3477\,m^3\,s^{-1}$) and 1945–1996 (mean peak = $2175\,m^3\,s^{-1}$) (Graham Matthews and Associates, 1996). And as discussed earlier, the pre-Shasta Dam Q_5 is nearly equal to the post-Shasta Dam Q_{20} (Lowney and Greco, 2003). Loss of cumulative flow results in loss of cumulative stream power (if the channel width, depth, and slope do not significantly change). Flow regulation or impoundment that reduces stream power would tend to reduce land production if the bank erodibility did not change. In addition, bank revetment (riprap) reduces land production rates. These physical constraints set-up an ecological cascade in the Sacramento River ecosystem. The combined effects of the loss of stream power and installation of riprap on meander bends causes the loss of new floodplain surface area for early seral riparian forest regeneration. Consequently, there is less opportunity (i.e. decreased area) for pioneer plant species, such as willow and cottonwood, to colonize those surfaces and implies a concomitant reduction in area of those respective riparian forest types. As a result, specialist riparian or wetland obligate wildlife species that depend on habitats associated with early and mid-seral stages of riparian forests are at great risk from the reduced land and vegetation production. This sequential chain of ecosystem processes that feed into one another and its disruption is an example of an ecological cascade effect.

In the Sacramento River system the western yellow-billed cuckoo (*Coccyzus americanus occidentalis*) is an exemplary species affected by this ecological cascade effect. The cuckoo was described as a relatively common species in California's Central Valley in the 1940s (Grinnell and Miller, 1944) and today is a California state-listed endangered species due to its severe population decline (Gaines, 1974; Gaines and Laymon, 1984; Laymon and Halterman, 1987; Halterman, 1991). A population census in 2000 found only 67 breeding pairs in the state of California and of those, 34 were located on the Sacramento River (Halterman et al., 2001). The cuckoo is a Neotropical songbird considered to be habitat-limited that nests and forages in large riparian forest patches (>17 ha in area and >100 m in width) of early and mid-seral riparian vegetation consisting of willow and cottonwood forest in its summer range in California (Gaines, 1980; Laymon and Halterman, 1989). Using a geographic time series of six map time slices from 1937 to 1997 on 37 km of the Sacramento River, Greco et al. (2002) found habitat patches meeting the criteria for cuckoo habitat form a shifting mosaic on the Sacramento River; and optimal habitat patches for the cuckoo can form in as few as 9 years and have suitability life spans up to 31 years. Channel cutoff events that formed large oxbow lakes and riparian forests during the study period increased the area of optimal habitats. That study showed that fluvial geomorphic dynamism is essential to the maintenance of riparian landscape heterogeneity and sustainability of the yellow-billed cuckoo's habitat over time.

With greater and greater demands being placed on the existing water supply in the state of California for human uses, the ecological cascade effect described above is likely to increase unless resources are managed to prevent further ecosystem degradation. Two proposed strategies to increase water supply in the state are to increase the capacity of Shasta Dam and to build new off-stream water storage reservoirs. Increasing the capacity of Shasta Dam by increasing its height is likely to cause further reductions in stream power in the river channel by storing more water and its potential energy behind the dam. Off-stream storage sites require diverting water out of the river channel into canals for delivery to the new reservoirs.

Depending on the location of the new off-stream storage sites and the location of the water diversion facilities to fill those sites, the ecological cascade effect could be increased or decreased. If the reservoir or diversion point is located high in the watershed (nearer to Shasta Dam) then the effect is likely to increase and further degrade riparian ecosystem processes on the Sacramento River. However, if the reservoir or diversion point is located low in the watershed (nearer to the San Francisco Bay) and water is permitted to flow in the river channel during winter and spring months, then the ecological cascade effect could be mitigated to restore and enhance riparian ecosystem processes. Studies by state and federal agencies are ongoing to assess storage and conveyance options for these development scenarios (CALFED, 2000).

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5.2. Dynamics and time–space dependency in the riparian landscape

Riparian vegetation communities are evolutionarily adapted to the flood–pulse cycle of the natural hydrograph, but flow regulation due to the construction of dams has changed the seasonal timing, variability and magnitude of flows diminishing establishment of keystone riparian tree species, such as cottonwood (*P. fremontii*) and willow (*Salix* spp.) in California (Strahan, 1984; McBride and Strahan, 1984; CALFED, 2000). The shape of the drawdown hydrograph curve in spring following annual snow melt is especially important to cottonwood establishment because of short seed viability due to small size and susceptibility to desiccation as well as seedling scour (Fenner et al., 1985; Luken, 1990; Mahoney and Rood, 1998). Episodic high flow events that promote meander migration, as well as overbank flow, are beneficial to riparian forest mosaics and a wide array of fish and wildlife species (Brinson et al., 1983; Junk et al., 1989; Bravard and Gilvear, 1996).

The restoration of large river floodplain ecosystems requires the re-establishment of key ecological processes (Stanford et al., 1996). ‘Natural channel design’ (NCD) is a relatively new paradigm in river rehabilitation and restoration that promotes the idea of enhancing natural forms and processes. Gordon et al. (2005, p. 335) stated “The central theme is that NCD is the holistic alternative to the traditional approach of seeking absolute channel stability at the expense of geomorphological and ecological function.” The preservation and conservation of floodplain age gradients and the fluvial processes that maintain them, could be a complementary approach to NCD river restoration planning objectives.

The results from this study are evidence of the dynamic and continual change of the riparian landscape on the Sacramento River and suggest that hydrogeomorphic processes are critical to the maintenance of diverse forest successional stages within the floodplain. Lacking disturbance, riparian forests become dominated by late seral plant species and lose habitat value for species dependent on early seral stages. An important point raised by Pickett and Rogers (1997, pp. 121–122) is that habitat “sustainability must be judged in part on the maintenance of community function.” Webb (1997) argued that to maintain the conservation value of early successional communities, ecosystems require active management for those community types. This is clearly the case on the Sacramento River since new land production is a key process in promoting and maintaining early seral stages of riparian forests formed from primary succession processes. Habitat for the yellow-billed cuckoo have highest suitability on land ages of approximately 10–50 years (corresponding to the peaks in cottonwood and willow scrub distribution) with a mix of low and high canopies (see Greco et al., 2002), while habitat of the endangered songbird, least Bell’s vireo (*Vireo bellii*), would be associated with land ages <20 years with a higher proportion of low and medium height canopy.

We recommend that river managers intentionally seek opportunities to allow and promote channel meander dynamics for the purpose of conserving the temporal land gradient (i.e., creating new land surface through channel migration and channel cut-offs to produce oxbow lakes) and the forest types associated with them. To accomplish this objective, the hydrodynamic processes of the flood–pulse cycle that drive channel meander migration must be restored. Flow patterns must be managed to better resemble historic hydrograph patterns (albeit scaled-down) to maintain heterogeneity within the landscape and increase biological productivity of riverine and riparian ecosystems (Brinson et al., 1983; Junk et al., 1989; Marston et al., 1995; Amoros and Wade, 1996; Gilvear and Bravard, 1996; Large et al., 1996; Scott et al., 1997).

The riparian landscape examined at any one point in time is a reflection of how temporal events in river hydrogeomorphology and individual plant species evolutionary life histories combine to create complex patterns on the landscape (Lytle and Poff, 2004). The floodplain age map shows how the Sacramento River has been consistently reshaping the floodplains over the past 127 years. Riparian vegetation colonization events can persist for many years exhibiting strong community ‘priority effects’ (Bellyea and Lancaster, 1999). For example, establishment of cottonwood stands on pointbars and oxbow lakes can persist for more than 100 years before they are replaced by long-lived floodplain species. Floodplain age modeling can be used to analyze and document the life spans and sequences of plant communities using a chronosequence approach to track various successional pathways of pointbar vegetation and oxbow lake forest development (see Fremier, 2003).

5.3. Plant community restoration design

Several active restoration techniques have been developed in recent decades for riparian ecosystems using agricultural technology. One such planting technique is a “tile” based planting method where a tile consists of multiple plant species placed along lines in a grid that cluster the planting tiles into structural community types (River Partners, 2006). Typically, tile dimensions are 5 rows wide by 10 plants long. This planting technique could be improved by incorporating floodplain surface age as a design variable. Floodplain age could be used as a criterion for selecting species to construct plant communities in proportion to observed natural communities. It could also be used for monitoring of plant communities to assess if actively restored communities resemble natural community types and structural proportions. Ideally, floodplain age would be used in conjunction with other design variables, such as soil texture, soil profile characteristics, and depth to groundwater.

Another important consideration in riparian planting design is vegetation structure. Forest structure is an important planning consideration for both habitat functionality and flood control objectives in large-scale restoration projects. The tile planting technique can incorporate both of these needs through strategic clustered placement of the tiles and plant species selection. Using this technique, River Partners created nesting habitat for the endangered songbird, least Bell’s vireo, in the San Joaquin Valley and observed nesting for the first time in 60 years in the Great Valley of California (River Partners, 2006). More recently, the tile plantings were used to manipulate vegetation structure in the floodplain to reduce floodplain roughness

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and accommodate flood flows on a project on the Feather River.

5.4. Riparian systems modeling

Large-scale restoration and enhancement is needed on many river systems throughout the world and riparian systems modeling is an important tool to assist in the planning and design process of creative solutions to habitat restoration and flood control. Various approaches to modeling ecosystem dynamics have been suggested. The dependency upon process timing and initial conditions to predict landscape states suggest that 'assembly rules' (Lockwood, 1997; Young et al., 2001) might be an appropriate modeling approach for gaming various scenarios to restore riparian landscapes. Given the flux of fluvial geomorphic processes and the strong allogenic patterning associated with this flux, the riparian mosaic may best be modeled using techniques that take into account intermediate processes to reach particular states, such as invasion history and invasion resistance (Robinson and Edgemon, 1988).

We believe the empirical approach presented in this paper to map and detect relevant ecological patterns using the floodplain age gradient of an alluvial river will contribute towards development of a robust predictive modeling environment of riparian systems on the Sacramento River (see Fremier, 2003; Williams, 2006) and elsewhere (Richter and Richter, 2000; Richards et al., 2002). The results from this study could assist wildlife and flood control managers in forecasting future structural states of restored forest sites given different planting design scenarios.

Modeling potential future states of riparian ecosystems is an important tool for scientists and land managers to effectively design and recommend restoration and enhancement measures of degraded systems (Richter and Richter, 2000; Golet et al., 2003). Intentional (i.e. active) process management to allow river meander dynamics in appropriate areas of a floodplain is essential to the maintenance of landscape heterogeneity and the sustainability of riparian plant and animal habitats over time. Natural process restoration can be a complex task to implement because many terrestrial and aquatic ecosystems are structured and regenerated by natural disturbance regimes, such as flooding and fire, and this is complicated by proximity to human land uses. The timing and magnitude of flows needed for geomorphic effects to benefit riparian conservation and restoration are also often challenging to implement. Thus, managers may have to maximize, to the best extent possible, the limited ecosystem dynamics that remain functioning (e.g. maintain meandering channel bends), or negotiate a set of prescriptions for riverine dynamics under various inter-annual climatic scenarios. Given the reality of "scaled-down" ecological systems (see McBain and Trush, 2000), modeling becomes a valuable tool to assist in the maximization of conservation benefits from those limited ecosystem dynamics.

Acknowledgements

This paper was greatly improved by the suggestions of two anonymous reviewers. The funding for this research was provided by the California Department of Water Resources (CDWR), Northern District, Red Bluff, California and the CDWR Planning and Local Assistance Office, Sacramento, California under Interagency Agreements #B-81714, #4600001950, and #4600000736. The authors express a special thanks to S.A. Cepello and A. Henderson and the staff at Department of Water Resources, Northern District Office; and S. Roberts, J. Wieking, and S. Sou from the Offstream Storage Investigation and North-of-the-Delta Offstream Storage Program. The data used in this study were the product of the dedicated efforts of many individuals working in the Landscape Analysis and Systems Research Laboratory in the Department of Environmental Design at the University of California, Davis. We acknowledge the following current and former staff members: E.H. Girvetz, L. Griffith, J.L. Tuil, J.P. Mann, T. Perry, S. Stekoll, A. Wheaton, C.A. Alford, P. McEnany, M.G. Vaghti, and A. Young for their valuable work and contributions.

Appendix A. Surficial floodplain age calculation process

A.1. 'Land year' map preparation

Each discrete channel-edge time slice must be prepared prior to being input into the automated model to calculate cumulative floodplain age. We term the product of this preprocessing stage a 'land year' map. The preprocessing for each channel-edge map (and buffered centerline channel-edge maps) in the series began with clipping each channel map to a shared common boundary such that each channel map shared an identical extent and area. This shared common boundary ensured spatial continuity and forms the basis for comparison of the time slices for all subsequent analyses. The channel water was assigned an attribute value of 0 and land was coded with the value of 1 (Eq. (A.1)).

The next step was to create river bank topology for each channel map by assigning (i.e. coding) lands on the left bank as negative land year values and lands on the right bank as positive. (At the end of the floodplain age modeling process all negative land years are converted to their absolute values.) Establishing bank topology using positive/negative orientation is an important step because it permits tracking the age of lands that are reworked by the channel between the time periods. These lands are the result of the channel migrating greater than a single channel width between the two respective time slices. We term these land areas "inside effects" (see Fig. A.1) and they must be accounted for and properly coded prior to automated processing to avoid generating error in the land age map.

The first step in creating left/right river bank topology requires that each channel map centerline be used to split the common boundary polygon of the study reach for each time period. The resultant river-right polygon was coded with a positive value of the channel year (e.g. '1870,' '1887,' '1904,' etc.) and the river-left polygon was coded negative (e.g. '−1870,' '−1887,' '−1904,' etc.) (Eq. (A.2)). The actual bank topology was created by overlaying the original channel-edge map and the positive/negative centerline polygon map layers using a union function (Eq. (A.3)); Fig. A.2). The final coding of the first interim 'land year' map from that step is shown in Eq. (A.3a).

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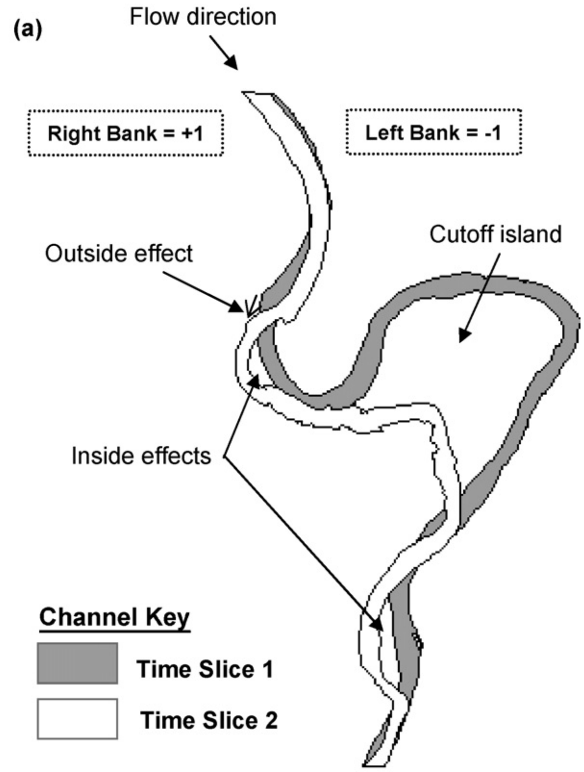

Fig. A.1. Low-flow channel data were coded with +1 for lands on the right bank and −1 for lands on the left bank. If channel movement between a sequential pair of channels is greater than the width of the low-flow channel then an "inside effect" is generated and is accounted for with the river bank topology. The channel time sequence is indicated by the channel key.

To briefly summarize, each channel map for each time slice year is clipped to a common boundary and then coded with the appropriate values (listed below in Eqs. (A.1)–(A.3a)) to create the first interim 'land year' map for all channel year time slices as follows:

$$[\text{prep\_channel}_n] = \begin{cases} 0: \text{open water} \\ 1: \text{land} \end{cases} \tag{A.1}$$

$$[\text{prep\_center}_n] = \begin{cases} -\{\text{channel year}\}: \text{left bank} \\ +\{\text{channel year}\}: \text{right bank} \end{cases} \tag{A.2}$$

$$[\text{land year}'_n] = \text{union}([\text{prep\_channel}_n], [\text{prep\_center}_n]) \tag{A.3}$$

$$[\text{land year}'_n] = \begin{cases} 0: \text{water} \\ -\{\text{channel year}\}: \text{left bank} \\ +\{\text{channel year}\}: \text{right bank} \end{cases} \tag{A.3a}$$

where n equals the channel time slice year and the bracketed spatial datasets are vector-based map layers. Eq. (A.3) uses modified ArcInfo Workstation (version 8, ESRI, 2003b) syntax and Eq. (A.3a) shows the resultant coding for the first interim 'land year' map.

Using the first interim 'land year' maps created for each time slice (i.e. $[\text{land year}'_n]$), a second analytical preprocessing step was required to identify the land areas (e.g. islands) where bend cutoff events did *not* rework the land area between 'land year$_n$' and 'land year$_{n+1}$' (i.e. between each sequential pair of time periods). The cutoff polygons are in contrast to the "inside effects" polygons previously discussed. The inside effects polygons are lands known to have been reworked by the channel whereas the cutoff polygons are not reworked. To create the cutoff polygons each sequential pair of channel time slices (channels at t_n and t_{n+1}) were overlayed using a vector-based union function (Eq. (A.4)) in ArcGIS (ESRI, 2003b) (see Fig. A.2). The model uses river bank topology to identify all polygons that change signs (positive/negative) from one time period to the next. The model assumes progressive channel migration (i.e. the land is reworked) unless a known cutoff (i.e. channel avulsion) event occurred. For this reason, the AML program prompts the user to identify any cutoff islands that may have occurred between the two time slices. Areas that flip from left to right bank or vise versa, are displayed to the user who then determines if they are to be reset to progressive migration (i.e. reworked land), or abandoned land (i.e. not reworked because of a cutoff event) with the value of its formative 'land year.' The formative land year is the first year that it is recorded in the map record as land. To determine the timing and location of bend cutoff events, several sources of historical data were reviewed (e.g. CDWR, 1978, 1984; Greco and Alford, 2003a,b and Greco et al., 2003). It is important to identify cutoff locations because they can have a significant effect on erosion rate calculations and floodplain age modeling results.

Once the user selects the cutoff areas (polygons) between each sequential pair of channels, the program automatically codes them a separate value (see Eq. (A.5)) so they are not reworked, i.e. land age is not reset during the automated floodplain age modeling process. The cutoff polygons retain their formative 'land year' value and are embedded back into the 'land year' map layer using a union overlay function (Eq. (A.6); shown in modified ArcInfo Workstation syntax).

$$[\text{land year}''_n] = \text{union}([\text{land year}_n], [\text{land year}_{n+1}]) \tag{A.4}$$

$$[\text{isl\_land year}_n] = \begin{cases} -9999 - \{\text{Year}_n\}: \text{left bank cutoff island} \\ 9999 + \{\text{Year}_n\}: \text{right bank cutoff island} \\ +\{\text{Year}_n\}: \text{right bank reworked land} \\ -\{\text{Year}_n\}: \text{left bank reworked land} \end{cases} \tag{A.5}$$

$$[\text{land year}_n] = \text{union}([\text{isl\_land year}_n],][\text{land year}'_n]) \tag{A.6}$$

$$[\text{land year}_n] = \begin{cases} 0: \text{open water} \\ +\text{Year}_n: \text{right bank} \\ -\text{Year}_n: \text{left bank} \\ 9999 + \{\text{Year}_n\}: \text{right bank cutoff island} \\ -9999 - \{\text{Year}_n\}: \text{left bank cutoff island} \end{cases} \tag{A.6a}$$

At this point in the data preparation process the 'land year' maps are ready as input to create a cumulative floodplain age

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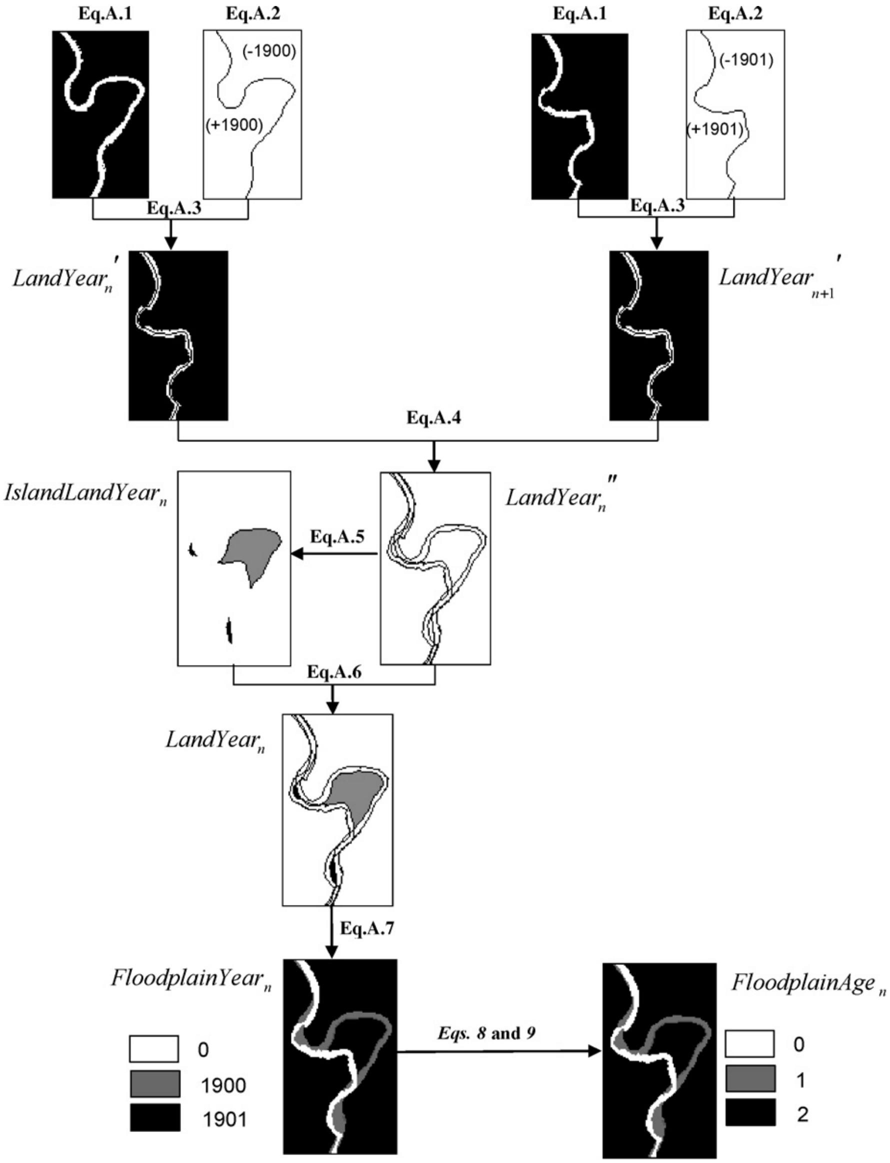

Fig. A.2. A concept diagram illustrating the floodplain age surface calculation process for one pair of low-flow river channel time slices. The final space–time composites are shown as the floodplain year map and the floodplain age map.

map. The final coding for each ‘land year’ map is shown in Eq. (A.6a). In summary, each channel map is coded with river bank topology (positive and negative); land has a value of the channel year; water is coded zero; “inside effects” polygons are automatically coded to reset the formative land year; and cutoff areas not reworked are uniquely coded to retain their formative land year.

A.2. *Automated floodplain age modeling*

The respective ‘land year’ maps were converted to raster format (20 m cell size or 0.04 ha cell resolution) to facilitate cartographic modeling of a floodplain age surface using a set of algorithms described below. The algorithms use the previously identified areas that are eroded, newly deposited, or abandoned (i.e. not reworked) between t_n to t_{n+1}. The logic assumes only what is defensible about what is known of channel location and movement through historical information about channel dynamics.

Eq. (A.7) shows the conditional logic statement that sequentially combined the rasters starting with the initial ‘land year’ raster, $[\text{landyear}_{n-1}]$, and the succeeding ‘land year’ raster, $[\text{landyear}_n]$, to produce a ‘floodplain year’ raster $[\text{FPY}_n]$.

$$[\text{FPY}_n] = \begin{cases} [\text{landyear}_{n-1}] - 9999 : [\text{landyear}_n] > 9999 \\ [\text{landyear}_{n-1}] + 9999 : [\text{landyear}_n] < 9999 \\ 0 : [\text{landyear}_n] = 0 \\ \text{if}[\text{landyear}_n] \text{ and } [\text{landyear}_{n-1}] \text{ have same signs} : [\text{landyear}_{n-1}] \\ \text{if}[\text{landyear}_n] \text{ and } [\text{landyear}_{n-1}] \text{ have opposite signs} : [\text{landyear}_n] \end{cases} \tag{A.7}$$

where $[\text{FPY}_n]$ is a cumulative ‘floodplain year’ raster as n proceeds from 1 to p, and p equals the number of time slices. Every subsequent combination joins the previous interim FPY_{n-1} raster with the succeeding 'land year' raster, [land year_n] in an iterative fashion.

Each 'floodplain year' raster ($[\mathrm{FPY}_n]$) contains cell values that denote the year of the 'land year_n' map that last reset those cells to a land state. In essence, this equation recodes all combinations of the precoded 'land year' attributes into the appropriate floodplain year classes according to channel migration within that time period. It is worth noting that within the logical statements and loop protocol, the left bank remains negative. This is used to determine topological changes within the logic processing. Consequently, the absolute value of the interim raster ($[\mathrm{FPY}'_n]$) becomes the floodplain year at time n. This is shown in Eq. (A.8):

$$[\mathrm{FPY}'_n] = \text{if cell} < 0, \text{then}|[\mathrm{FPY}_n]| \quad (\mathrm{A.8})$$

$$[\mathrm{FPA}_n] = \text{if cell} > 0, \text{then}(\{\text{final year in series}\} - [\mathrm{FPY}'_n]) \quad (\mathrm{A.9})$$

In the final step, a 'floodplain age' raster was calculated by subtracting the last time period year value in the time series from the cumulative 'floodplain year' raster values (in $[\mathrm{FPY}'_n]$) (see Fig. A.2). For example, a floodplain last reworked in 1974 has a 'floodplain year' (FPY) value of 1974 and a 'floodplain age' (FPA) value of 23 years in the year 1997.

A.3. Sources of error in floodplain age calculations

There are several potential sources of error in calculating the floodplain age surfaces since they are composites of a variety of data sources. In the following we discuss our solutions to six potential sources of error: (1) variation in natural low-flow channel width was minimized by using aerial photographic dates that corresponded with flows between 83 and 351 $\mathrm{m}^3\,\mathrm{s}^{-1}$ (2940–12,400 $\mathrm{ft}^3\,\mathrm{s}^{-1}$) resulting in less than a half-channel's width in variation at low-flow in reaches where the river channel did not change between the respective time periods. For the historical maps (1870, 1887, 1896, and 1904) there were no records available of the flow or precise calendar date and thus it was assumed the channel widths represented a base-flow consistent with observed summer flows at the respective time period. To minimize the effect of potentially arbitrary historical map channel widths we used the buffered centerline approach to minimize this error source in the geomorphic analysis of new land production. (2) The 1904 channel map was derived from historical U.S. Geological Survey quadrangles and was the first fully geodetically controlled map; channels derived from historic maps prior to 1904 had some minor but obvious geodetic control problems and were georeferenced and adjusted relative to the 1904 channel to correct for the localized distortions (see Greco and Alford, 2003a). (3) The historical low-flow channel data derived from aerial photography in two cases, the 1938 and 1966 channels, consisted of temporal composites to achieve full coverage of the study area (see Table 2); this was due to a lack of availability of full photographic coverage in those respective years. However, it should be noted that some large flows did occur in those 1–2 year periods potentially contributing to error. (4) Distinguishing between channel "inside effects" and cutoff islands as discussed previously, is a step that requires the AML user to identify them respectively and, therefore, the determination is only as accurate as ancillary historical data makes it interpretable. We had excellent resources to distinguish between progressive bend migration and bend cutoff events. (5) Another phenomena of channel movement over decadal time scales is the potential production of "outside effect" errors. This spatial effect occurs on the outside of channel bends as a result of channel movement being captured in discrete rather than continuous time intervals. Small areas of reworked land at these bend margins are potentially unaccounted for and therefore represent a potential source of error (see Fig. A.1). Again, we felt the area represented by this potential source of error was small relative to the area of main effects as measured by the observed channel movement between the mapped time periods. (6) We developed two types of floodplain age models and each has its own strengths and weaknesses. For the analysis of new land production we implemented a floodplain age calculation method that used buffered channel centerlines (a subset of lotic features from the channel mapping) that minimized the error associated with variation of channel widths (discussed above) and excluded oxbow lake dynamics. For the vegetation analysis we implemented a floodplain age calculation method that used natural channel-edges (all lotic water features) and tracked all oxbow lake dynamics (all lentic water features) because vegetation patterns correspond to natural channel-edges and respond to a variety of dynamic processes in the floodplain. One inherent source of error associated with oxbow lakes is inter- and intra-annual water level variation associated with those systems, for example some oxbow lakes are used as irrigation tailwater ponds by farmers and others are affected by climatic or seasonal effects.

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Please cite this article in press as: Greco, S.E. et al., A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design, Landscape Urban Planning (2007), doi:10.1016/j.landurbplan.2007.01.002

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