Evolution Assessment and Conservation Strategies for Sacramento River Oxbow Habitats
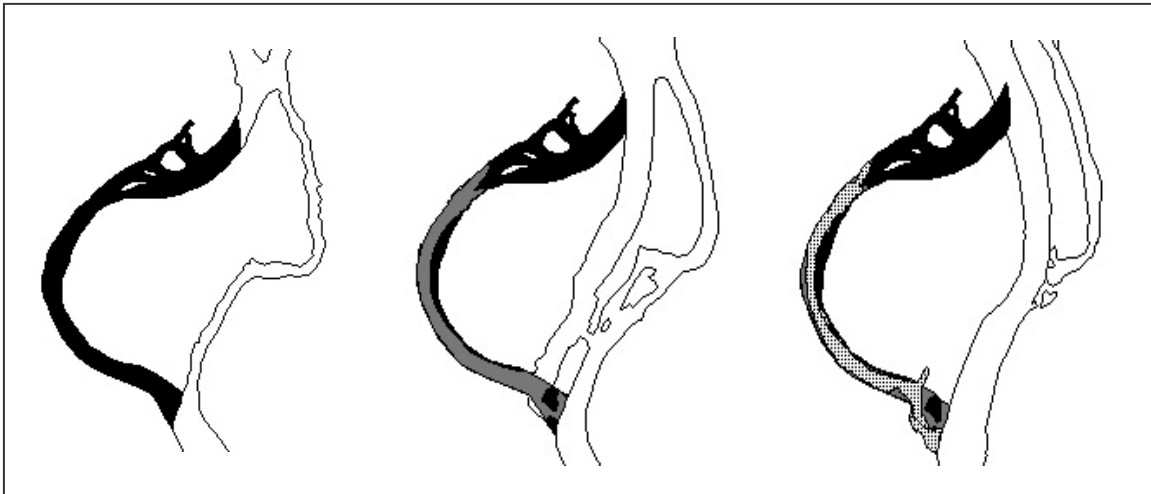
A Report to The Nature Conservancy, Sacramento River Project

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June 2003

STUDY SUMMARY

Oxbow lakes provide critical wildlife habitat and support rich biodiversity in the Sacramento River system, making them priority candidates for research and conservation. As floodplain water bodies that gradually terrestrialize, oxbow lakes are dynamic elements of the river system, providing different types of habitat as they evolve. Little is known about the silting-in dynamics of Sacramento River oxbow lakes, however, although such information is necessary to assess and conserve these important ecosystems. In this study, we address critical gaps of knowledge in oxbow lake ecology and evolution, particularly the silting in dynamics, and provide information necessary for conservation decisions specific to the Sacramento River. We include not only oxbow lakes, or abandoned channels isolated from the river, but all types of cut-off channels, including those still connected to the river. We accomplish this by drawing upon studies from other river systems, the expertise of researchers active on the Sacramento, and field and aerial photograph data collected for selected oxbows lakes in the system.

OBJECTIVES

➢ Determine sedimentation rates and evolution scenarios for three oxbow lakes by taking sediment cores and analyzing aerial photos from the time of cut-off to the present.

➢ Survey the longitudinal profile of one oxbow, including the upstream alluvial plug, to ascertain the amount of sediment accumulated in the plug and the aquatic area.

➢ Assess the ecological implications of aquatic plant distributions from surveys of sixteen cut-off channels.

➢ Make initial water chemistry measurements for comparison among sites.

➢ Consult experts of various ecological and biological sciences on the habitat value of oxbow lakes and the processes that influence their evolution.

➢ Identify conservation measures and future research needs for Sacramento River oxbow lakes.

BACKGROUND

Ecological Importance and Context of Sacramento River Oxbow Lakes

Oxbow lakes are ecological "hot spots," providing habitat for numerous plant and wildlife species (Ward and Stanford 1995, Bornette et al. 1998, Greco 1999, Piégay et al. 2001). In fact, the contribution to regional biodiversity is the most widely valued ecological function of riverine wetlands such as oxbows (Henry and Amoros 1995). In the Sacramento River, oxbow lakes and backwaters create habitat for many different types of wildlife, such as herons, salmon, pond turtles, and beavers (California Resources Agency 2000). Oxbow lakes also provide important hydrologic functions, such as floodwater retention and groundwater recharge. As oxbows terrestrialize, riparian forests replace the once wetland areas. Large areas of exposed soil substrate along the banks of the abandoned channels allow riparian tree species to colonize rapidly (Greco 1999), and overbank floods that deposit silt and contribute nutrients to the floodplain soils nourish and sustain nascent riparian forests.

While oxbow lakes and adjacent riparian forests host a high level of biodiversity within the Sacramento River system and provide valuable hydrologic functions, their existence is threatened by human alterations to the river and the surrounding landscape. Beginning in the mid-nineteenth century, European settlers altered the river system dramatically. Many oxbow lakes and other cut-off channels were filled in and transformed to agriculture fields. Riparian forests were cut down to produce fuel wood for steamboats (Greco 1999). Levees built along the river isolated the active channel from its floodplain. Large dams on the river and its tributaries reduced the area of floodplain that was frequently inundated and decreased river flows driving channel migration. Bank stabilization projects hardened many of the banks of the river, further reducing lateral channel migration needed to create meander bends and cut-offs. As the number of oxbow lakes and their rate of formation decline, the presence of the remaining ones at various transitional stages gain in ecological importance and value. Most of the oxbow lakes along the Sacramento River today occur between the towns of Red Bluff and Colusa, in a reach flanked by floodplains where the river can still migrate.

Oxbow Lakes as Critical Habitat

Oxbows provide habitat different from the active channel. Compared to the active channel, oxbows usually have little to no water current, large areas of shallow water, and relatively warm water temperatures. Many species of birds, fish, reptiles, and amphibians seek such habitat characteristics for survival. As they evolve, oxbows provide different types of habitat for different types of species. For example, when an oxbow has an open connection to the main channel, fish can swim into the oxbow and seek refuge. Oxbows completely isolated from the main channel, however, typically provide better habitat for amphibians since fish are not as prevalent (Ward et al. 1999). Ensuring the existence of oxbows at different evolutionary stages is necessary to protect the diversity of species reliant on different types of oxbow habitats.

Fish

In order for fish to access floodplain water bodies such as cut-off channels, the water body must be connected to the main channel, at least intermittently. Studies done on the Yolo Bypass, a floodplain on the lower Sacramento River, indicate that floodplain

water bodies provide better rearing and migration habitat for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) than adjacent river channels (Sommer et al. 2001a). Several habitat characteristics of floodplains could account for the faster growth. These include a warmer water temperature in the floodplain water bodies, a more abundant population of dipterans (a food for the fish), and a slower water velocity (Sommer et al. 2001b). Initial results from a similar study on the Cosumnes River also show faster growth for juvenile Chinook salmon that rear on the floodplain rather than in adjacent river channels (Sommer et al. 2001a).

The floodplain also appears to be particularly good habitat for the federally listed splittail (*Pogonichthys macrolepidotus*). Splittail depend on floodplain waters for survival; adults move on to the floodplain in the winter and early spring to find food and spawn on inundated vegetation (Sommer et al. 2001a). As the floodwaters recede, the splittail then emigrate to river channels. Cut-off channels with a connection to the river farther upstream in Sacramento River likely provide similar, beneficial habitat for Chinook salmon and other fish that were found in the Yolo Bypass. Other native fish that use the relatively warm, calm water may include blackfish (*Orthodon microlepidotus*), California roach (*Hesperoleucus symmetricus*), hardhead (*Mylopharodon conocephalus*), hitch (*Lavinia exilicauda*), Sacramento squawfish (*Ptychocheilus grandis*), speckled dace (*Rhinichthys osculus*), Sacramento sucker (*Castostomus occidentalis*), threespine stickleback (*Gasterosteus aculeatus*), pumpkinseed (*Lepomis gibbosus*), redear sunfish (*Lepomis microlophusl*), Sacramento perch (*Archoplites interruptus*), and, prickly, riffle and Staghorn sculpins (*Cottus asper*, *Cottus gulosus*, and *Leptocottus armatus*) (J. Silveira, U.S. Fish and Wildlife Service, pers. communication 2003).

The relatively warm water of oxbows also attracts non-native fish, however. Fish such as bass species prey on ducklings as well as on native fish (J. Silveira, U.S. Fish and Wildlife Service (USFWS), pers. communication 2003).

Reptiles and Amphibians

A wide variety of reptiles and amphibians utilize oxbows and side channels for habitat. The western pond turtle (*Clemmys marmorata*), a Federal species of concern and a California species of special concern, favors aquatic habitats with access to deep, slow water, underwater refugia, and emergent basking sites (Holland 1994). Juvenile turtles, as poorer swimmers than adults, especially seek areas with slow, shallow, warmer water, often with emergent vegetation (Reese 1996). Side channels, especially sloughs with an open connection to the river, provide key habitat for the western pond turtle due to the relatively slower current and warmer temperature of the water (D. Wilson, California State University – Chico, pers. communication 2002).

The giant garter snake (*Thamnophis couchi gigas*) is listed as a federally and state threatened species, and inhabits marshes, sloughs, ponds, including cut-off channels (U.S. Fish and Wildlife Service 2002).

Amphibian populations tend to thrive better in aquatic habitats farther from the main channel, at least in part because fish predation on amphibians is lower in floodplain water bodies isolated from the river (Ward et al. 1999). A study done on the Danube River in the Alluvial Zone National Park demonstrated that the highest species richness

of amphibians occurred in isolated cut-off channels with no surface water connection to the main channel except during large floods (Tockner et al. 1999).

Several amphibian species, which could potentially utilize oxbow habitat, require Federal protection for their survival. One amphibian, the red-legged frog (*Rana aurora*), is a Federally threatened species, another species, the tiger salamander (*Ambystoma tigrinum*) is a Federal candidate, and two others, the foothill yellow-legged frog (*Rana boylei*) and the western spadefoot (*Scaphiopus hammondi*), are species of Federal concern (California Resources Agency 2000). The distribution and abundance of these species is drastically reduced compared to historical levels. Studies are necessary to monitor how and to what extent amphibians use oxbows as habitat and how other factors such as oxbow lake water quality affect them.

Birds

Many water and land birds benefit from the calm water, available prey, and habitat structure of oxbow lakes. Water birds, such as cormorants (*Phalacrocorax auritus*), herons (*Ardea herodias*), egrets (*Casmerodius albus*), and grebes (*Podilymbus podiceps*), are adapted to feed in this type of wetland environment, preying on fish and other aquatic animals. Likewise, heron, egret, and cormorant rookeries are often located near oxbows (J. Silveira, USFWS, pers. communication 2003).

Other types of birds, such as the common yellowthroat (*Geothlypis trichas*), the marsh wren (*Cistothorus palustris*) and blackbirds (*Agelaius phoeniceus*), often nest in cattails that grow in still water. Osprey (*Pandion haliaetus*) nest in snags close to the water where they prey on fish species. The red-shouldered hawk (*Buteo lineatus*) nests in wooded habitats, and oxbows provide edges to many terrestrial habitats that attract these and other raptorial predators (J. Silveira, USFWS, pers. communication 2003).

Oxbows also benefit a great variety of riparian birds. For example, the spotted towhee (*Pipilo maculates*), California towhee (*Pipilo crissalis*), and California quail (*Callipepla californica*) seek cover in the dense blackberry thickets that often grow along the edges of oxbows. Other riparian bird species that may nest in trees associated with oxbows include hummingbirds, woodpeckers, flycatchers, the oak titmouse, the bushtit, nuthatches, kinglets, bluebirds, thrushes, vireos, warblers, grosbeaks, and finches (J. Silveira, USFWS, pers. communication 2003). Further research is necessary to assess how birds such as these use different types of cut-off channels as habitat and the extent of their populations.

Mammals

Many terrestrial mammals use oxbows for food, water, and cover, including beavers (*Castor canadensis*), which often build dams in oxbows, river otters (*Lutra canadensis*), mink (*Mustela vison*), and ringtail cats (*Bassariscus astutus*) (J. Silveira, USFWS, pers. communication 2003). Several types of bats also use oxbow habitats. In a recent study done in the Sacramento River system, bat activity was monitored at several sites along the active channel and backwaters to assess the importance of these areas as bat foraging habitat (Rainey et al. 2003). Compared to the active channel, backwaters are more sheltered with little water surface turbulence. The highest bat activity measured in the study occurred at a sampling location at an open-water backwater site near the Koehnan Orchard.   Backwater sites covered with macrophytes did not have as much bat

activity as the open-water site, however. Another result of the study demonstrated that the *Myotis* group of bats, especially *Myotis yumanensis*, has a "bimodal pattern" of foraging, focusing on backwater sites early in the evening and the main stem later in the night. This pattern suggests that backwaters and the river provide different types of foraging resources for bats (Rainey et al. 2003). The results of this study indicate that oxbows and other backwaters provide important, unique bat habitat, another reason to ensure oxbow conservation and protection.

Oxbow Lake Evolution

Oxbow lakes form either by the gradual narrowing and eventual breaching of the meander bend, or by chute cut off during floods (Brice 1977). Sacramento River oxbow lakes form most often by chute cutoff. These cut off channels fill in with sediment brought in by overbank flows and with organic matter produced by aquatic plants, and over time they evolve from aquatic to terrestrial habitats (Piégay et al. 2001). However, as the river migrates across the floodplain, it can reoccupy cut-off channels.

During and after the cut off event, the abandoned channel transforms as it undergoes a series of transitional stages with varying degrees of connection to the main channel (Ward and Stanford 1995). The conceptual model of oxbow lake evolution (Figure 1) illustrates the typical intermediate transitional stages of Sacramento River cut-off channels and provides a basis for studying the processes driving their transformation.
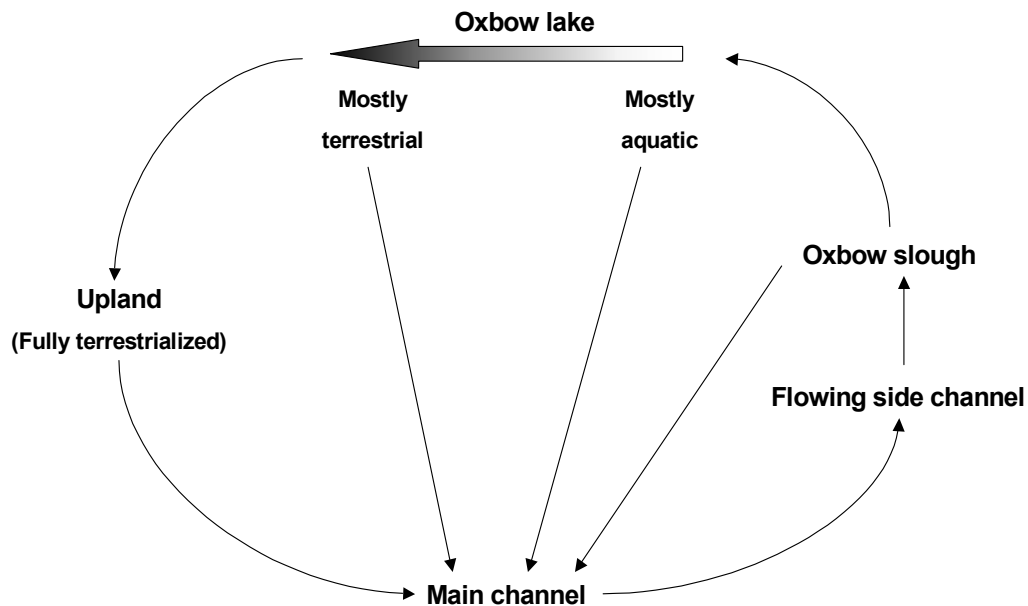

Figure 1: Conceptual model of oxbow lake evolution.

Prior to the cut-off event, a flowing side channel usually exists that is separate but connected to the main channel. We observed the formation of such side channels in time series of Sacramento River aerial photographs, and Gagliano and Howard (1983) also observed this pattern in the Mississippi River system. The main channel, usually during a high flow, eventually shifts to the side channel, shortening its route and abandoning a bend. Typically, the main channel then deposits sediment in the upstream end of the abandoned channel, creating an alluvial plug between the main and former channels. The downstream end of the former channel most often remains connected to the main channel for a longer period of time; during this time the cut-off channel is considered an oxbow slough. When alluvial plugs form at both the upstream and downstream ends of the abandoned channel, an isolated water body, designated as an oxbow lake, remains (Gagliano and Howard 1983). Eventually the oxbow lake fills in completely with sediment and organic matter and becomes terrestrialized upland.

Physical Processes Driving Oxbow Lake Terrestrialization

Geomorphic and hydrological processes determine oxbow lake evolution and define the vegetation communities in and adjacent to the water bodies. The hydrologic and geomorphic factors are complex, causing each oxbow lake to undergo a somewhat unique evolution scenario (Citterio and Piégay 2000).

The hydrologic connectivity between the former and main channels is one of the most important factors affecting sedimentation rates of an oxbow lake (Citterio and Piégay 2000). Overbank floods are the primary in-filling events that bring in sediment to former channels. Thus, flood frequency and sediment load concentration have a substantial effect on oxbow lake sedimentation rates (Gagliano and Howard 1983). Oxbow lakes that are rarely flooded or flooded only by well-filtered waters may have relatively longer life spans than those more often flooded (Piégay et al. 2001). While floods most often deposit sediment in former channels, they can also scour and remove fine sediment from former channels under certain conditions (Bornette et al. 1994a).

The "flood pulse" concept used by Junk et al. (1989) emphasizes the importance of alternating dry and wet periods to enhance biodiversity and productivity within the "aquatic/terrestrial transition zone" on the floodplain. Intermittent wet and dry periods in oxbow lakes and the floodplain increase organic matter, decomposition, and nutrient cycling, which enhance biodiversity and productivity within the system (Ward and Stanford 1995). When productivity increases, the amount of decaying organic matter in oxbow lakes also increases, accelerating the sedimentation process (Piégay et al. 2001).

Groundwater also can influence the ecological succession of oxbow lakes. Floods and groundwater can work synergistically in oxbow sedimentation rates. Floods scour out fine sediments and facilitate groundwater flow, and groundwater flows can destabilize coarse substrate and allow abrasion by floods (Bornette et al. 1994a). In such cases, the oxbow lake is usually nutrient poor and the water is oligotrophic (Piégay et al. 2001). The lack of nutrients prohibits the eutrophication of the cut-off channel, and relatively little organic matter contributes to the in-filling of the basin. Likewise, when the groundwater supply of an oxbow lake is blocked by fine sediment accumulation, the eutrophication and subsequent terrestrialization of the oxbow can occur at a faster rate (Bornette et al. 1994b).

Alluvial Plug Attributes

The alluvial plug characteristics of abandoned channels can influence rates of sedimentation. The sedimentation rate is controlled in part by the differential connectivity of the upstream and downstream ends of a former channel. When overbank flows inundate both the upstream and downstream ends of a former channel, the flows can retain a velocity high enough to scour fine sediment in the aquatic zone. When only the downstream end is inundated, the relatively slow backflows deposit greater amounts of sediment in the former channel (Piégay et al. 2001).

The length and geometry of the upstream plug can indicate former channel sedimentation rates as well. Longer upstream plugs are associated with greater backflow influences and faster sedimentation rates (Piégay et al. 1999). The angle between the plug and main channel axes can also influence the former channel sedimentation rate. For example, cut-off braided channels are more likely to be axially aligned with the main channel than a cut-off meander bend and experience more direct flows and flooding from the main channel. Cut-off meander bends may potentially have longer lifespans than cut-off braided channels since they tend to be more isolated from the main channel and experience less flooding (Piégay et al. 2001).

A relatively long, forested upstream alluvial plug slows the velocity of overbank flows and reduces the scouring effects of floods on a former channel (Piégay et al. 2001). A shorter, less forested plug allows more floodwater to enter and scour out accumulated fine sediment in the former channel (Bornette et al. 1994). Thus alluvial plugs can function as a buffer between the main and former channels and trap sediment before the floodwaters reach the former channel aquatic zone (Piégay et al. 2001).

Channel Migration

Another important factor affecting hydrologic connectivity between the former and main channels, and thus former channel lifespan, is the direction of main channel migration. If the river laterally migrates away from the former channel, floodwater must travel a greater distance before entering the former channel, and in these situations, infill generally occurs at a slower rate (Gagliano and Howard 1983). Main channel incision also affects former channel sedimentation, because the cut-off channel will be higher relative to the main channel and thus less frequently inundated and experience less overbank sedimentation. Incision can also lower the floodplain water table and cause former channel water bodies fed primarily by river seepage to dry up and terrestrialize at a more rapid rate (Piégay et al. 2001). Assessing both the lateral and vertical movement of the main channel over time can help determine the sedimentation rates and lifespans of former channels.

Physical Processes Influencing Vegetation Succession in Cut-off Channels

In addition to controlling the in-filling rate of oxbow lakes, hydrologic and geomorphic processes affect the variety and abundance of plant species. Former channels provide a rich breeding ground for nascent and developing riparian plants and forests. Due to the dynamic nature of the floodplain ecosystem, riparian forests can be considered to be in a state of "perpetual succession" (Campbell and Green 1968). Within this system, the most extensive riparian forests occur on landforms such as islands, along bends in the river, and, significantly, adjacent to oxbow lakes (Strahan 1984). Due to their close proximity to the water table, cutoff

channels provide an ideal location in the floodplain for vegetation to establish and flourish (Greco 1999).

The hydrologic regime influencing an oxbow lake affects the composition, density, and succession of floodplain forests adjacent to the oxbow lake as well as aquatic and wetland plant communities within the aquatic and buffer areas. Flooding can provide both beneficial and adverse consequences to plants depending on the frequency, duration, and depth of inundation (Teskey and Hinckley 1978). Flooding affects abandoned channel vegetation in two major ways, including the deposition of a large amount of suspended material within the channel and the reduction of light penetration for several days after the event (van der Valk and Bliss 1971). Although sediment deposition and reduction in light penetration can damage aquatic plants, flooding can also benefit plant communities in and adjacent to former channels by providing nutrients and sustaining the water supply of the aquatic area (van der Valk and Bliss 1971).

Both the low flow regime and the flood frequency are also important in the distribution and establishment of riparian tree species along cut-off channels. The low flow regime occurring in the summer months provides freshly exposed surfaces for seedlings to establish. Flooding, however, may remove young seedlings as well as scour new surfaces for seedling establishment (Strahan 1984, Bornette et al. 1998). In the process, floods temporarily reverse successional trends and result in plant succession occurring "not linearly, but rhythmically, with four steps forward followed by three steps backward" (van der Valk and Bliss 1971).

Riparian landscape change and diversity also rely on the meandering nature of the Sacramento River; without lateral migration, oxbow lakes do not form and riparian forest regeneration and primary succession essentially come to a halt. The fluvial processes of erosion and deposition function to create new topographic surfaces such as point bars on which species such as willows (*Salix* spp.) and cottonwood (*Populus fremontii*) colonize, form forested backwaters still connected the main channel, and initiate channel abandonment (Greco 1999).

Human Impacts on Sacramento River Oxbow Lakes

As in many alluvial river systems, humans have drastically altered the physical processes and landscape that compose the Sacramento River watershed, affecting both the creation and evolution of oxbow lakes (Buer et al. 1988). In comparing recent aerial photographs of the Sacramento River with those from the late 1930s, a decrease in the number of oxbow lakes is readily visible. The interplay of both natural processes and human actions dictate the rate of oxbow lake terrestrialization in highly managed systems. While terrestrialization is a natural process, human activity has undermined the processes that create oxbow lakes and in some cases directly destroyed them. Some of the most significant human impacts to oxbow lakes in the Sacramento River system are artificial in-filling, dams, bank protection, levees, and the removal of riparian forests.

One of the most severe threats to the existence of oxbow lakes is the direct in-filling of them for farmland (B. Bundy, Sacramento River Conservation Area, pers. communication 2002). When oxbow lakes are artificially filled, any habitat they provided is lost. The terrestrialization process, which would have lasted for hundreds of years, is abruptly concluded.

A fundamental influence on the hydrologic processes responsible for the creation of Sacramento River oxbow lakes is the existence of dams and upstream reservoirs. Since the building of Shasta Dam in 1945, floods have been reduced, and therefore rates of erosion,

deposition, and meander migration have declined (Buer et al. 1988). Neck cut-offs require active channel migration, and chute cut-offs require high flows to instigate erosion of a channel across the bed. Reduced high flows in the river imply a reduced rate of cut-off activity (Shields and Abt 1989, Ward and Stanford 1995).

Most river banks along the Sacramento River have been hardened by riprap to reduce erosion and avoid the loss of adjacent land, effectively "channelizing" the river and reducing lateral migration (Henry and Amoros 1995). Bank protection undermines the erosion processes that produce cut-off channels and is likely another cause of the reduced numbers of Sacramento River oxbow lakes.

Levees reduce floodplain area and artificially isolate former channels from the main channel (Ward and Stanford 1995). In acting as a topographical barrier between the main and former channels, levees can prevent floodwaters from entering the cut-off channel and potentially reduce the rate of sedimentation.

Decreased water quality due to run-off from surrounding agriculture fields can also adversely affect oxbow lake habitat. Toxic chemicals can poison wildlife and limit species diversity within an abandoned channel aquatic area. Water quality can also have a direct impact on sedimentation rates since more or less aquatic plants grow in a cut-off channel based on the water chemistry and therefore affect the amount of accumulating organic matter.

Extensive loss of riparian forests, with only about five per cent of the original riparian forests in the Sacramento River system remaining, is another impact to the system (Buer et al. 1988). The reduction of riparian forests adjacent to oxbow lakes can reduce "roughness" and increase the rate of siltation since trees can act to block and capture sediment (Piégay et al. 2001).

STUDY SITES

The oxbow lake study sites occur within the reach between Colusa and Red Bluff (RM 143 – 244), which has most of the extant oxbow lakes. The site selection criteria were known year of cut-off event (established using historical aerial photos and maps), public ownership or landowner permission to access, and variations in size and age. We selected three cut-off channels for sediment core collection: "La Barranca" (RM 237), Merrills Landing (RM 213-214), and Jenny Lind Bend (RM 195) (Table 1). We sampled aquatic plants in sixteen different cut-off channels, from RM 168 to RM 237 (Table 1). We labeled the sites "R" or "L" according to each site's location on the right or left bank and numbered the sites sequentially beginning from the site farthest downstream.

Sediment Core Study Sites
La Barranca, so-called after an adjacent U.S. Fish and Wildlife Service unit, is one of several abandoned channels between river miles 235 and 237. Within this reach, the length of the water-land interface along the main channel is twice as high as elsewhere along the river due to the presence of side channels, sloughs, and oxbow lakes (California Resources Agency 2000). The youngest of the study sites, La Barranca cut off between 1982 and 1983. La Barranca is actually an oxbow slough since its downstream end remains connected to the main channel at low flows. The surrounding landscape includes orchards, riparian forests, and open grassy fields (Figure 2).

Merrills Landing, which cut off between 1976 and 1979, is the longest of the three study sites (about 6.5 km). The surrounding landscape includes open grassy fields and riparian forests. Little agricultural land surrounds the oxbow, making it the least impacted of the study sites (Figure 3).

The third site, Jenny Lind Bend, cut off sometime between 1945 and 1947. The surrounding land uses include agriculture, riparian forests, and grassland. Of the three study sites, Jenny Lind Bend is the most impacted by anthropogenic alterations to the land, most notably by the razing of the riparian forests in its upstream and downstream plugs (Figure 4).

Aquatic Vegetation Survey Sites

We surveyed aquatic vegetation in sixteen different cut-off channels (see Figures 5 to 13), ranging in identifiable age from 20 years old (site R11) to at least 850 years old (site R2) (Sullivan 1982). Seven of the cut-off channels have a mostly linear form while nine of them have a relatively sinuous form (Table 1). The sites also vary in hydrological connectivity with the main channel. Five of the sites (R6, R7, L6, R9, R11) have a downstream connection to the main channel while the rest of the sites are isolated from the main channel except during high flow events. All of these factors can influence the type of aquatic plant species existing in each cut-off channel.

METHODS

Assessing Oxbow Lake Evolution

A number of factors, both natural and human-influenced, determine oxbow lake evolution. After reviewing scientific literature on oxbow lake dynamics and terrestrialization within various river systems, we developed a set of parameters to measure in the field and with aerial photographs.

Sediment Accumulation

At each of the three sedimentation study sites, including La Barranca, Merrills Landing, and Jenny Lind Bend, we took sediment cores to measure depth of fine sediment deposited in the former channel since it was cut off from the main channel. First, we determined the approximate length of the former channel aquatic zone through global positioning system (GPS) analysis and established four to six points equidistant along the length. The upstream end of alluvial plugs themselves may comprise cobble and gravel, which are difficult to core. We took sediment cores within the aquatic zone of each site (except for two cores which were taken in dry areas at Jenny Lind Bend) where the substrate was small and wet enough to remove with a hand auger. We made GPS point markers for each sediment core location.

At each point, we took a sediment core with a 3 meter (10 foot) hand auger as close to the center of the cut-off channel as possible, noting composition of the sediment using the soil science standard texture by feel method (e.g. fine silts, sand, or organic matter) and depth of sediment to gravel, assumed to represent the former channel bed. Based on the sediment core information, we calculated an annual average sedimentation rate for each site. This method assumes the former channel bed was gravel, which would

probably be true for these reaches of the Sacramento, with the exception that the inside of these bends would likely have point bars, which could be composed principally of sand.

At some core locations, the fine sediment was deeper than our 3-m auger or too compacted to remove, so we recorded only minimum depths to gravel (designated as "min." in the tables). To calculate the annual sedimentation rate for each cut-off channel, we divided the mean depth to gravel (excluding the minimum values) by the mean of the range of years during which the oxbow potentially cut off from the main channel.

Water chemistry

Identifying groundwater sources in oxbow lakes is important in assessing rates of sedimentation. Oxbow lakes with a regular groundwater supply tend in fill in at relatively slower rates than those without a supply (Piégay et al. 2001). By comparing specific conductivity measurements in each oxbow lake and the adjacent main channel, we evaluated the potential groundwater influences in the oxbows. At locations where the conductivity measurements in the former channel varied significantly from the measurement in the main channel, we inferred that groundwater contributed to the oxbow lake water composition at a relatively high rate. Since we measured conductivity on only one day, the measurements provide only initial data on cut-off channel nutrient levels. Regular measurements taken over a period of several months to a year is necessary to determine if the water chemistry of cut-off channels is consistent.

At three to four points along the aquatic zone of each cut-off channel and in the adjacent main channel, we measured specific conductivity using a handheld Hydrolab® Surveyor 4a instrument. Differences in specific conductivity between the main and former channels provided information on possible groundwater influences in the former channel.

Water Surface Elevation Measurements and Observations

We measured water surface elevation at La Barranca on March 5 and August 16, 2001, when mean daily flows were 26,780 and 11,300 cfs respectively and at Merrills Landing and Jenny Lind Bend on March 5 and April 6, 2001 when mean daily flows were 26,780 and 7,296 cfs respectively. All flow measurements in this study come from the U.S. Geological Survey gauge "Sacramento River at Bend Bridge" near Red Bluff (Station ID: 11377100).

Topography and Vegetation of La Barranca

In addition to the sediment cores and water quality measurements, at the La Barranca site, we sampled vegetation and surveyed a longitudinal profile. Beginning with the upstream alluvial plug and proceeding downstream along a depression to the aquatic zone of the former channel at La Barranca, we surveyed the lowest points of the former channel where possible (Figure 21). In one area, dense riparian vegetation prohibited surveying elevation along the low points, but we continued to measure distance. With the topographical information provided by the longitudinal profile, we can better define the hydrologic connectivity of the entire former channel from both its upstream and downstream ends.

We also documented the different species of riparian trees existing within the former channel, including the upstream alluvial plug. As our interest was riparian forest regeneration in cut-off channels, we did not identify non-woody terrestrial wetland plants.

Flow Record to Estimate Cut-Off Date at La Barranca

To estimate when the La Barranca former channel most likely cut off, we examined flow records. For water years 1981 to 1984, we counted the number of days with flow exceeding 55, 70, 85, and 100 thousand cfs as a basis for comparing the relative stream energy in each year.

Aerial Photograph and GIS Analysis

To evaluate the spatial evolution of a Sacramento River cut-off channel, we analyzed a time series of aerial photographs of the La Barranca, Merrills Landing, and Jenny Lind Bend sites. These included: 1947 (U.S. Dept. of Agriculture 1947), 1980 (U.S. Army Corps of Engineers 1980), 1984 (U.S. Army Corps of Engineers 1984), and 1999 (Cal. Dept. of Water Resources 1999) aerial photographs at 1:12,000 scale.

For the La Barranca site, we traced the boundaries between land and water of the main and former channels from the aerial photographs on acetate overlays. We scanned the traced drawings and digitized them in a geographic information system (ArcView 3.2). The images were then orthorectified using fixed locations on the landscape. The images were transformed into real-world coordinates, using ArcInfo version 8.02. We used these "control points" in such a way as to minimize distortion, by locating them near the exterior boundaries of the mapped areas. By subtracting the aquatic areas of the former channel and main channel for each year, we calculated the changes in area of the former channel and aquatic zone for the three time steps of 1980, 1984, and 1997.

For all three sites, we measured the length, width, distance of plugs, and area of the cut-off channels using ArcView 3.2 on rectified aerial photographs. We measured these variables on aerial photographs taken within one to six years after the cut-off event for each site as well as on 1999 photos.

Land Use Change Assessment

Using available aerial photography, we also evaluated land use changes over time for the area surrounding our three sites. We noted landscape features in the areas upstream and downstream of the aquatic area, the aquatic area itself, the island, and the adjacent land outside of the oxbow lake.

Aquatic Plant Survey

Aquatic macrophytes can indicate the ecological state of oxbow lakes (Amoros et al., 2000). Plant communities are relatively easy to survey and can provide information about the origin of water supply in an oxbow, the water nutrient content, the effects of flood disturbances, and terrestrialization processes (Amoros et al., 2000). Different species of aquatic plants grow under different conditions and reflect different physical processes occurring in a given cutoff channel. With our collaborator Gudrun Bornette, a specialist in aquatic vegetation from the University of Lyon 3, we surveyed the aquatic vegetation at twelve different cut-off channels. In each cut-off channel, Bornette identified the dominant vegetation types. Within each vegetation type, she identified and recorded the percent area of each aquatic plant species found within fifteen 2 m^2 quadrats along a transect or randomly when the accessibility was poor. With this information, we

made assessments on aquatic plant species richness, hydrologic and geomorphic activity, and water quality of the cut-off channels.

RESULTS

Oxbow Lake Sedimentation
The depth of fine sediment to gravel varied in and among each oxbow lake (Tables 2,3, and 4). The composition of the core material at each site included fine silt and clay particles, some sand, and a substantial amount of organic matter, identified by its dark brown and black color. The varying composition usually occurred in layers with the uppermost layer containing mostly organic matter. This pattern suggests that both the deposition of fine sediment from the main channel during floods and decaying vegetation within the cut-off channel contribute to the infilling. Sullivan (1982) observed this infilling pattern at "Little Packer Lake," an oxbow lake also located along the Sacramento River.

At the La Barranca site, the depth of fine sediment to gravel ranged from 30 to 131 cm and averaged 90 cm (Figure 14, Table 2) for an average annual sedimentation rate of 4.5 cm. Merrills Landing had greater depths of fine sediment, ranging from 169 to 300 cm, for an average sedimentation rate of 7.3 cm/y (Figure 15, Table 3). Jenny Lind Bend had 129 to 218 cm, averaging 3.9 cm/y (Figure 16, Table 4). However, we reached channel gravel at only one point, so the Jenny Lind Bend the sedimentation rate is based mostly on minimum values.

We took initial sediment cores at two other cut-off channels: one core at RM 169 and one core at RM 203. At RM 169, the annual sedimentation rate was 4.3 cm/y, at RM 203 4.6 cm/y, similar to the sedimentation rate observed at La Barranca (4.5 cm/y), and perhaps a more typical sedimentation rate within the Sacramento River system than those measured at Merrills Landing or Jenny Lind Bend.

The rates calculated for Sacramento River oxbow lakes are about six to ten times higher compared to the average sedimentation rates calculated for the Ain (~0.6 cm / year), Doubs (~0.7 cm / year), and Rhône (0.5 cm / year) Rivers in France where similar research has been done (Citterio and Piégay 2000). The higher sedimentation rates presumably reflect higher sediment loads from the catchment, despite sediment trapping by Shasta, Whiskeytown, and Black Butte dams.

Water Chemistry
Conductivity measurements varied, with greater differences between former and main channels at Merrills Landing (Table 5). While we were not able to measure conductivity of the main channel adjacent to Jenny Lind Bend, we assumed the conductivity would be similar to that of the main channel adjacent to the other two study sites. At La Barranca, a gradient in specific conductivity was evident, with higher values occurring closer to the downstream end of the former channel. Values closer to that of the main channel occurred farther up the aquatic zone. This is opposite of what we would expect but could be explained by variations in nutrient levels in the aquatic zone. Conductivity can reflect the floodplain waterbody's nutrient content. The nutrient content of floodplain waterbodies tends to increase with greater hydrologic connectivity to the main channel since the river inputs nutrient-rich water and sediment (Amoros 2001). We observed this pattern among the study

sites. Jenny Lind Bend, the most hydrologically isolated of the sites, had the lowest average conductivity measurement (120.1 æS/cm).

Water Surface Elevation Measurements and Observations

At La Barranca, the water surface was 2.23 m higher on March 5, 2001 (26,780 cfs) than August 16, 2001 11,300 cfs), and the downstream connection with the mainstem was open during both flows (Figures 17,18, Table 6).   At Merrills Landing, the water surface was 2.56 m higher in March than August, and in August the water surface was obscured by a cover of aquatic plants, especially Montevideo waterweed (*Ludwigia peploides* ssp. *montevidensis*) (Figures 19, 20, Table 6). At Jenny Lind Bend, the water surface was 2.46 m higher in March than August, despite its greater distance and apparent isolation from the main channel. These observations, supplanted by further observations in the future, can be used to develop stage-discharge relations, which can be used with the historical flow record to estimate frequency and duration of hydrological connection with the main channel and inundation of various surfaces adjacent to the oxbow.

Topographic Surveys of La Barranca

The upstream plug extends approximately 374 m and was approximately 2.4 m higher than the Sacramento River water surface at flow of approximately 6300 cfs (Figure 21). Substrate size decreased from cobbles near the river to sand downstream, a pattern consistent with those observed in other oxbow plugs (Piégay et al. 2001) reflecting decreased competence with distance downstream from the main channel. At a river flow of 10,000 cfs, the aquatic zone is approximately 1314 m long. Because the downstream end of the former channel was connected to the main channel at the range of flows observed, this could result in more rapid sedimentation compared to a more isolated oxbow (Citterio and Piégay 2000). This connection can also allow aquatic organisms to move between the river and the former channel with ease, enhancing its habitat value for certain species (Shields and Abt 1989).

Riparian Vegetation at La Barranca

The vegetation we observed (listed in Table 7) corresponded to the vegetation characterization of Sacramento River oxbow lakes described by Strahan (1984) and Greco (1999).

Aerial Photograph Measurements

The La Barranca oxbow cut off date between the air photos of 1980 to 1984, probably during the wet years of 1982 or 1983 (Table 8). Most of the upstream alluvial plug sedimentation, covering an area of 90,000 m^2, had occurred by the 1984 air photo, i.e., within one to two years of the cutoff. From 1984 to 1999, the area of the former aquatic zone diminished by only about 30%, from 6.5 to 4.6 ha (Table 9, Figure 22). These results demonstrate that oxbow lakes evolve not only on an annual, incremental basis, but also in pulses, responding to high flows, especially within the first years after cut-off when higher magnitude flows occurred with greater frequency and/or longer duration.

While the mean width of the aquatic zone of La Barranca decreased between 1984 and 1999, its length increased, because the main channel migrated away from the cut-off channel, forming a backwater between the main and former channels. Thus, La Barranca has two parts: a meander-shaped bend and a more linear backwater. The Merrills Landing cut-off channel decreased by the greatest percentage of the study sites. Between 1984 and 1999, its

aquatic zone area diminished to less than one third of its original area and about two thirds of its original length (Table 10), consistent with the relatively high sedimentation rate here.

Between 1947 and 1999, the length of the Jenny Lind Bend aquatic zone decreased by over 100 m, mean width decreased by about 3 m, and area of the aquatic zone decreased from 2.2 to 1.8 ha. The relatively little change in area may be due to Jenny Lind Bend being the most isolated from the main channel. The upstream and downstream plugs are by far the longest of the cut-off channel study sites (Table 10).

Landscape and Land Use Changes

Our assessment of land use change adjacent to the three oxbows from historical aerial photography showed land use essentially unchanged adjacent to the La Barranca and Merrills Landing oxbows from 1980 to 1999 (Tables 11, 12). However, at Merrills Landing, the aquatic zone grew narrower, and as visible on the 1999 air photos, the upstream end was no longer connected to the main channel, the downstream end only minimally. With better topographic information and stage discharge relation for this site, it should be possible to state the flows at which the downstream and then upstream ends become hydrologically connected to the river.

Land uses adjacent to Jenny Lind Bend changed the most over time. Jenny Lind Bend is also the oldest of the cut-off channels, however. In 1947, the land around the aquatic area of Jenny Lind Bend was relatively natural, composed of a mix of forest and open field patches. By 1984, almost all of the forests patches were gone and the land just outside of the aquatic area was converted to orchards (Table 13). By 1999, more forest patches developed in the downstream plug of Jenny Lind Bend, but most of the land surrounding the aquatic area was devoid of forests and transformed to orchards or open fields.

Aquatic Plant Analysis

While twenty-seven different aquatic plant species were observed in the cut-off channel sites (Table 14), the species richness was relatively low for most cut-off channels, ranging from 0 to 12 species, and averaging 3.9 (Table 15, Figure 23). The highest species richness occurred at sites with a perennial hydrologic connection to the main channel (at sites R6 (12 species), R11 (10), and R9 (8)). This result is consistent with the findings of Bornette et al. (1998) who found, in a study performed on the Rhone River in France, that the highest species richness of aquatic plants occurred in the most frequently flooded cut-off channels.

One species, the non-native Montevideo waterweed (*Ludwigia peploides* ssp. *montevidensis*), occurred in all but two of the study sites and comprised at least 90% of the emergent aquatic vegetation at ten of the sixteen sites (Table 15). This invasive plant likely negatively influences the diversity of aquatic plants in Sacramento River cut-off channels, and its proliferation could also affect infilling rates of the cut-off channels as an input of organic matter.

Our initial water quality measurements indicated that linear cut-off channels with a high connectivity to the river are the least anoxic, and have the most diverse aquatic flora (Table 16). Although we did not test for chemical contaminants (e.g., herbicides, pesticides, heavy metals) or nutrients (e.g., nitrates, phosphates), the level of these is probably lower in the channels that are still connected to the main channel.

DISCUSSION AND CONCLUSIONS

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The results of this study provide some initial information on sedimentation processes, temporal and spatial landscape changes, and aquatic plants of Sacramento River cut-off channels:

1. The sediment core data suggest that cut-off channels of the Sacramento River are filling in faster than comparable French sites (Citterio and Piegay 2000), and thus the aquatic zones are disappearing. Meantime, the processes of meander migration needed to produce new cut-off channels are inhibited by dam-reduced flood magnitudes, extensive riprap, and other human alterations, resulting in a net decrease of oxbow lakes.

2.   Oxbow lakes fill in not only incrementally, but in pulses during high flows, as demonstrated at La Barranca.   Oxbow lakes both decrease in depth as they fill in with sediment, and decrease in surface area as sediment accumulates on the former channel banks and riparian vegetation encroaches.

3. Aquatic plant species diversity was higher in cut-off channels hydrologically connected to the river than in older, more isolated oxbows, suggesting that both hydrological connectivity and water quality influence aquatic plant composition of Sacramento River oxbows.

4. The dissolved oxygen content of several of the cut-off channels was low; in five of the sixteen study sites, the content was less than 15% (Table 16). No aquatic plants occurred at two oxbows (R2 and R3), probably due to poor water quality. Further water quality sampling will be needed to better understand water quality influences on these aquatic ecosystems.

CONSERVATION STRATEGIES

The disappearance of Sacramento River oxbow lakes calls for conservation and management strategies to protect and restore them. Management of cut-off channels should be based on increasing habitat diversity and be oriented to restore processes rather than individual species, for a more sustainable restoration of the ecosystem. Amoros (2001) suggested that restoring cut-off channels to maximize habitat diversity must take into account (1) flow velocity and flood disturbances, (2) hydrological connectivity, and (3) water supply. On the scale of individual cut-off channels, habitat diversity can be achieved by varying water depth, width, and velocity and the bed substrate (Amoros 2001). Since restoration activities can be costly in time and resources, existing oxbows should be protected and then prioritized for possible restoration actions. Engineering solutions, however, do not provide feasible long-term fixes.

Monitoring water quality of oxbow lakes is an important first step in conservation. Orchards and croplands surround many Sacramento River oxbow lakes, and the run-off from these agricultural fields can contain fertilizers and pesticides. The high nutrient content of the fertilizers can accelerate the eutrophication of cut-off channels. Pesticides can have a toxic effect on organisms within the oxbow lake aquatic area. Staff of The Nature Conservancy, for example, observed a fish kill at a backwater near the Kaiser Unit shortly after a pesticide application followed by irrigation, which

produced run-off into the slough.   Water quality should be monitored to detect possible contaminants from agricultural runoff or from culvert effluents emptying into the aquatic zone. Aerial application of pesticides should avoid spraying oxbow lakes adjacent to orchard and croplands.

Restoring riparian forests adjacent to oxbow lakes, especially in the upstream plugs, can increase habitat diversity and act to decrease oxbow lake sedimentation rates. These forests filter flood water and run-off from surrounding land, stabilize the banks, and can increase shade in the aquatic area, decreasing the proliferation of aquatic plants (Henry and Amoros 1995). The proximity to the water table of former channels facilitates riparian forest growth and development also.

Along the Rhône River, a cut-off channel was successfully restored by dredging a layer of fine, nutrient-rich sediment (0.15-1.00 m thick) to expose the underlying gravel substrate to increase the supply of nutrient-poor groundwater to the oxbow and thereby impede ecological succession toward eutrophication and terrestrialization (Henry et al. 2002). This project demonstrated increasing groundwater supply and effectively diluting nutrient concentrations could initiate regression from a highly eutrophic state to a mesotrophic. This approach may be applicable to some cut-off channels along the Sacramento River where these conditions are met (Amoros 2001): (1) an aquifer (alluvial or hillslope) must exist with a sufficient discharge potential, (2) the slope within the waterbody must be steep enough to drain groundwater out from the aquifer and release it downstream, and (3) the impact of the expected groundwater drainage on the surrounding water tables must be assessed and found to be acceptable. Sinuous waterbodies have lower slopes and may be less appropriate for groundwater restoration than the more linear cut-off channels.

Another potential short-term action to increase the ecological function of existing oxbows may be to open the upstream or downstream plugs to that fish can access the cut-off channels from the main river. Oxbow lakes with relatively short plugs may be candidates for plug removal. However, improving only the downstream connection may actually accelerate the rate of sedimentation within the oxbow, leading Amoros (2001) to propose construction of sediment traps at the connecting ends to reduce sediment inputs. In any event, an approach like this does not address the underlying, long-term problem of reduced creation of new oxbow lakes; it would only slow the transition from aquatic to terrestrial.

The only documented created oxbow lake along the Sacramento River is the Kachituli Oxbow constructed in 1991 outside the flood control levee as a new, excavated oxbow lake (not restoration of an existing feature) to mitigate the loss of nearby wetlands (as mandated by Section 404 of the Clean Water Act) (Hey and Philippi 1999). A fourth-year monitoring report indicated that planted vegetation was growing as anticipated (Jones & Stokes Associates Inc. 1995). While no doubt providing some habitat value, such a static feature is very different from a natural oxbow lake, in that it is disconnected from the main channel and does not evolve over time, as do natural oxbows. No studies directly comparing this restored habitat with natural oxbows have been conducted, but it is likely that this habitat is less ecologically valuable than natural oxbow lakes, and certainly artificial construction of such features is expensive. While a poor substitute for naturally evolving oxbow lakes, such restoration projects may be needed to avoid loss of

such habitats. In any event, long-term monitoring will be needed to gauge its success or failure.

FUTURE RESEARCH NEEDS

Further sediment coring of Sacramento River cut-off channels is required to assess sedimentation rates in a more comprehensive manner. Assessing the core sample substrate for information on organic matter content, sediment stratification, and seed propagules would provide further information on the temporal dynamics of cut-off channels.

Our discovery of anoxic water and low aquatic plant diversity in many oxbows suggests that adverse water quality limits these ecosystems. Further sampling and analysis of water quality in these cut-off channels is needed to pinpoint problems from nutrients such as nitrates and phosphate, agriculture chemicals such as herbicides and pesticides, and heavy metals. Sustainable restoration of these features will probably require understanding the pathways of agricultural runoff and interception, diversion, or treatment of agricultural runoff to prevent the pollution of these water bodies.

The role of groundwater in these oxbow lakes needs to be better understood. Groundwater pumping for irrigation of adjacent lands may lower water tables and reduce groundwater inflow, concentrating nutrients and other constituents in surface runoff, and increasing sedimentation rates. Installing observation wells or piezometers around oxbows and monitoring groundwater levels in relation to river levels can provide basic information on surface-groundwater interactions.

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TABLES

Table 1: Location, form, and age characteristics and methods applied for Sacramento River cut-off channels study sites.

Site Number / Common Name	River Mile - Bank	Form	Cut-off Date	Age (y)	Methods Applied		
					Sediment Cores	Water Chemistry	Aquatic Plants
● **R1** Packer Lake	168 – R	crescent, isolated	1867 - 1874	< 136			
R2 Little Packer Lake	168 – R	crescent, isolated	1100 - 1200	< 900			
● **R3** Rasor Slough	169 – R	crescent, isolated	?	?			
R4 N/A	169 – R	linear, connected	1973 - 1976	< 29			
● **R5** Beehive Bend	170 – R	crescent, isolated	?	?			
L1 N/A	177 – L	crescent, isolated	?	?			
● **L2** N/A	177 – L	linear, isolated	?	?			
L3 N/A	177 – L	linear	?	?			
● **R6** N/A	178 – R	linear, connected	1980-1991	< 22			
R7 N/A	179 – R	linear	?	?			
● **L4** Indian Fishery	194-195 – L	crescent, isolated	1945 -1947	< 29			
R8 Jenny Lind Bend	195 – R	crescent, isolated	1945-1947	< 29			
● **L5** Wilson's Landing	203-205 – L	crescent, isolated	1970 - 1973	< 32			
L6 Merrills Landing	213-214 – L	crescent, isolated	1976 - 1979	< 25			
◐ **R9** Kopta Slough	219 – R	linear, connected	?	?			
R10 N/A	235 – R	linear, isolated	1939-1950	< 60			
● **R11** La Barranca	237 – R	upper part crescent, lower part linear, connected	1982 - 1983	< 21			

●

●

Table 2: The location, water depth, and sediment depth to gravel for each sediment core site at La Barranca.

Location	Distance from upstream alluvial plug intersection with main channel (m)	Water depth (cm)	Fine sediment depth to gravel (cm)
LB 1	1506	100	≥ 131 (min.)
LB 2	1300	78	77
LB 3	1069	20	74
LB 4 C	887	273	≥ 68 (min.)
LB 4 L	887	22	119.5
LB 5	860	0	102
LB 6	389	0	121
LB 7	370	0	30
Average annual sedimentation rate: 4.5 cm / year			

Table 3: The water depth, and sediment depth to gravel for each sediment core site Merrills Landing.

Location	Water depth (cm)	Fine sediment depth to gravel (cm)
ML 1	29	169
ML 2	70	≥ 300 (min.)
ML 3	85.3	≥ 168 (min.)
ML 4	56	211
Average annual sedimentation rate: 7.3 cm / year		

Table 4: The water depth, and sediment depth to gravel for each sediment core site at Jenny Lind Bend.

Location	Water depth (cm)	Fine sediment depth to gravel (cm)
JL 1	113	≥ 134.5 (min.)
JL 2	131	≥ 129 (min.)
JL 3	0	≥ 218 (min.)
JL 4	0	203.2
Average annual sedimentation rate: 3.9 cm / year		

Table 5: Comparison of specific conductivity measurements within cut-off channel sites and main channel.

Site	Average specific conductivity (æS/cm)
La Barranca	173.8
Main channel near La Barranca	130.8
Merrills Landing	477.2
Main channel near Merrills Landing	138.2
Jenny Lind Bend	120.1

Table 6: Water surface elevation measurements of sediment core study sites at two different flows. Water surface elevation measurements are relative to an arbitrary datum.

Site	Date	Flow (cfs)	Water surface elevation (m)
La Barranca	3/5/2001	26,780	26.44
	8/16/2001	11,300	24.21
			Difference: 2.23 m
Merrills Landing	3/5/2001	26,780	26.59
	4/6/2001	7,296	24.03
			Difference: 2.56 m
Jenny Lind Bend	3/5/2001	26,780	27.38
	4/6/2001	7,296	25.72
			Difference: 2.46 m

Table 7: Observed tree species within La Barranca upstream alluvial plug, August 2001.

Scientific name	Common name
Acer negundo	Box elder
Alnus sp.	Alder
Fraxinus latifolia	Oregon ash
Juglans nigra	Black walnut
Platanus racemosa	California sycamore
Populus fremontii	Cottonwood
Quercus lobata	Valley oak
Salix exigua	Narrow leaf willow
Salix lasiolepis	Arroyo willow

Table 8: Number of high flow days, Sacramento River, water years 1981-1984.

Hydrologic Year	Number of days above given discharge			
	55,000 cfs	70,000 cfs	85,000 cfs	100,000 cfs
1981	0	0	0	0
1982	18	1	0	0
1983	67	26	7	2
1984	6	1	1	0

Table 9: A comparison of the La Barranca aquatic zone area and accompanying river discharge in 1980, 1984, and 1997.

Date of photo	Aquatic zone area (ha)	Ave. Daily Flow (cfs)
29 Sept. 1980	15.209	6,440
19 March 1984	6.528	16,200
18 May 1999	4.648	11,047

Table 10: Aerial photograph measurements for La Barranca, Merrills Landing, and Jenny Lind Bend, taken from Sacramento River photos shortly after cut-off and in 1999.

	La Barranca		Merrills Landing		Jenny Lind Bend	
Date of Photo	3/19/1984	5/18/1999	3/19/1984	5/21/1999	6/13/1947	6/14/1999
Ave. Daily Flow (cfs)	16,200	11,047	16,200	11,461	6,800	11,823
Aquatic zone area (ha)	6.528	4.648	26.54	8.064	2.195	1.775
Aquatic zone mean width (m)	59	43	80	32	43	40
Aquatic zone min. width (m)	47	28	38	16	32	36
Aquatic zone max. width (m)	74	71	140	49	50	46
Aquatic zone length (m)	1094	1249	3628	2497	557	427
Upstream plug length (m)	552	451	0	953	1645	1473
Downstream plug length (m)	0	0	0	0	626	725

Table 11: Qualitative assessment of landscape change over time for La Barranca (RM 237) using aerial photographs from 1980, 1984, 1991, and 1999.

	19 March 1984	15 July 1991	18 May 1999
Ave. daily flow (cfs)	16,200	9,340	11,047
Upstream	Large gravel alluvial upstream plug exists.	Open gravel plug; a few small linear forest patches exist.	Riparian forest filling in plug; it's about half forest and half open gravel.
Downstream	Strong downstream connection exists.	Downstream end narrower but still connected to main channel.	Linear backwater exists, connecting cut-off and main channels.
Aquatic area	Little to no riparian vegetation exists around aquatic area.	Narrow riparian fringe exits around aquatic area.	Narrow riparian fringe exists around aquatic area.
Island	Island is about half forest patches and half gravel and open fields.	Island is about half forest patches and half open gravel and fields.	About half forest patches and half open gravel and fields.
Adjacent land	Orchards surround outside of aquatic area except area of upstream plug.	Orchards surround outside of aquatic area except area of upstream plug.	Orchards surround outside of aquatic area except area of upstream plug.

Table 12: Qualitative assessment of landscape change over time for Merrills Landing (RM 213-214) using aerial photographs from 1980, 1984, 1991, and 1999.

	29 Sept. 1980	19 March 1984	15 July 1991	21 May 1999
Ave. daily flow (cfs)	6,400	16,200	9,340	11,461
Upstream	Upstream end of waterbody connected to main channel.	Upstream end of waterbody connected to main channel.	Minimal connection to main channel; surrounding area natural, gravel and forest.	Plug almost formed at upstream end; riparian forest surrounds upstream area.
Downstream	Strong downstream connection to main channel.	Downstream end narrower but still connected to main channel.	Downstream end of waterbody connected to main channel.	Downstream end plug formed; riparian forest filling in plug.
Aquatic area	Aquatic area wider at downstream end becomes narrower towards the upstream end.	Riparian fringe surrounds most of aquatic area.	Riparian fringe exists around aquatic area.	Riparian fringe surrounds aquatic area.
Island	About 2/3 of island open fields and 1/3 forest patches. Largest forest patch near downstream end.	About 2/3 of island open fields and 1/3 forest patches.	About 2/3 of island open fields and 1/3 forest patches.	About 2/3 of island open fields and 1/3 forest patches.
Adjacent land	About ¾ agriculture and open fields and ¼ natural.	About 2/3 open fields and agriculture and 1/3 natural.	About 2/3 open fields and agriculture and 1/3 natural.	About 2/3 open fields and agriculture and 1/3 natural.

Table 13: Qualitative assessment of landscape change over time for Jenny Lind Bend (RM 195) using aerial photographs from 1947, 1962, 1984, and 1999.

	13 June 1947	25 June 1962	3 March 1984	14 June 1999
Ave. Daily Flow (cfs)	6,800	9,920	8,380	11,823
Upstream	Linear forested patch with large patches of open fields.	Only remnants of linear forested patch remain, replaced by open fields.	No forest exists; land appears leveled and open.	No forest exists; land appears leveled and open.
Downstream	Large forested patch within plug; appears mostly natural.	Forest reduced to linear strip along length of plug, replaced by open fields.	No forest exists; land appears leveled and open.	Narrow linear forest patch exists along plug with larger forest patch adjacent to river.
Aquatic area	Riparian vegetation fringes aquatic area.	Riparian vegetation fringes aquatic area, wider fringe in upstream section.	A narrow fringe of riparian vegetation surrounds area with wider band upstream.	A narrow fringe of riparian vegetation surrounds area with wider band upstream.
Island	Open fields and grasslands with small patches of trees.	Open fields and grasslands with fewer small patches of trees than in 1947.	No trees visible; land appears leveled and open.	Small patches of trees exist among open fields.
Adjacent land	Patchy forests and open fields.	Patchy forests and open fields.	Orchards exist, replacing any natural forest patches or open fields.	Orchards exist, replacing any natural forest patches or open fields.

Table 14: Scientific and common names of aquatic plant species observed at cut-off channel study sites.
*Identity uncertain

Scientific name	Common Name
Azolla mexicana	Mosquito fern
Ceratophyllum demersum	Coon's tail
Echinochloa muricata	Rough barnyardgrass
Egeria densa	Water hyacinth
Elodea nuttallii	Western waterweed
*Hibiscus californicus**	California hibiscus
Juncus effusus	Common rush
Leersia oryzoides	Rice cutgrass
*Lemna minor**	Duckweed
Ludwigia peploides ssp. *montevidensis*	Water primrose
Myriophyllum spicatum	Spike watermilfoil
*Myriophyllum aquaticus (brasiliense)**	Parrotfeather watermilfoil
Nymphea odorata	White water lily
Phalaris sp.	Canarygrass
*Polygonum hydropiperoides**	Swamp smartweed
Polygonum punctatum	Dotted smartweed
Potamogeton crispus	Curly pondweed
Potamogeton pectinatus	Fennel-leaf pondweed
Potamogeton pusillus or *foliosus*	
*Sagittaria latifolia**	Common arrowhead
Scirpus acutus ssp. occidentalis	Bulrush
Sparganium angustifolium	Narrowleaf bur-reed
Typha latifolia	Common cattail
Utricularia gibba	Humped bladderwort
Veronica anagallis-aquatica	
Wolffia sp.	Watermeal
Zannichellia palustris	Horned pondweed

Table 15: Aquatic vegetation data collected in late June and early July, 2002, in cut-off channel study sites. The mean per cent area of each species is shown for the dominant vegetation type within each cut-off channel (Vegetation type key: E = floating, emergent plants, F = floating, unrooted plants without stems, S = floating, unrooted plants with stems and leaves, and O = open water). *Identity uncertain.

Cut-off channel	Vegetation type	Ludwigia peploides ssp. montevidensis	Phalaris *	Ceratophyllum demersum	Lemna minor *	Potamogeton pusillus or foliosus	Wollfia sp.	Azolla mexicana *	Sagittaria latifolia *	Potamogeton pectinatus	Potamogeton crispus	Typha latifola	Leersia oryzoides	Echinochloa muricata	Polygonum hydropiperoides *	Polygonum punctatum *	Juncus effusus	Hibiscus californicus *	Myriophyllum aquaticus	Scirpus acutus ssp. occidentalis	Myriophyllum spicatum	Sparganium angustifolium	Elodea nuttallii	Veronica anagallis-aquatica	Zannichellia palustris	Egeria densa	Nymphea odorata	Utricularia gibba
R2	O																											
R3	O																											
R1	S			100			100																					
R1	E	100				0.3																						
R4	E	95.5	2.0	2.0																								
R4	S	1.5	0.0	98.5		0.1																						
R4	O	NO vegetation																										
R5	E	100																										
R5	O	NO vegetation																										
L1	M	54.7		0.8																							42.7	
L1	O	NO vegetation																										
L2	M	22.3																		0.7							78.3	
L3	S	39.3		68.7																							19.3	1.1
L3	O	NO vegetation																										
R6	E	100							7.2			3.3	6.9	2.1	1.9	3.2	1.3	0.1										
R6	O	1.3		2.8					3.7	0.5																		
R7	E	99.3		2.0	0.3																							
R7	O	0.7		7.4	0.5																							
L4	S			1.0			17.7																					
L4	E	99.3		34.0			5.7																					
L5	E	100																										
L5	O	NO vegetation																										
L6	E	90.7										16.0								0.7	18.0							
R9	S	3.0	3.0		97.3	10.7	0.3													1.3				0.1			0.1	
R9	O	NO vegetation																										
R10	F	4.6		74.3	8.6		92.9	1.9																				
R10	E	90.0		5.0	3.6		11.0																					
R11u	E	92.0													2.1	2.1												
R11u	O	NO vegetation																										
R11l	O	1.3		11.9						1.6	6.6									11.3		28.4	0.7	8.8	0.1	0.3		

Table 16: Sinuosity and water chemistry measurements for aquatic plant study cut-off channel sites.

Cut-off channel site (River Mile)	Date of measure-ment	Sinuosity	Conductivity (µS/cm)	Tempera-ture (°C)	pH	Dissolved Oxygen (%)	Salinity (ppt)	Total Dissolved Solids (g/l)
R1 (168)	6/25/02	26.88	259.6	30.03	7.36	85.3	0.12	0.1655
R2 (168)	6/25/02	19.77	159.4	22.73	7.33	23.3	0.07	0.1022
R3 (169)	6/25/02	1.62	339.9	29.08	7.11	66.5	0.17	0.2237
R4 (169)	6/24/02	1.47	188	30.06	9.32	177	0.09	0.1208
R5 (170)	6/24/02	2.66	375	22.9	6.68	13.2	0.19	0.241
L1 (177)	7/1/02	2.5	107.8	28.97	8.03	113.2	0.04	0.0715
L2 (177)	7/1/02	1.5	148	24.3	6.8	13.4	0.06	0.094
L3 (177)	7/1/02	1.5	112	28.7	7	30	0.04	0.0719
R6 (178)	6/25/02	1.21	288.4	26.64	6.86	10.3	0.14	0.1849
R7 (179)	6/26/02	1.07	376.6	20.76	7.13	6.2	0.19	0.241
L4 (194-195)	6/30/02	2.17	359.4	32.8	10.1	191.5	0.17	0.2268
L5 (203-205)	6/30/02	2.26	600.3	28.96	6.96	123.1	0.31	0.3913
L6 (213-214)	6/26/02	2.76	767.5	21.78	7.04	7	0.48	0.4931
R9 (219)	6/30/02	1.29	116.9	20.18	6.97	117.5	0.05	0.0749
R10 (235)	6/27/02	1.45	425.2	30.6	7.69	94.6	0.21	0.2721
R11 (237)	6/26/02	1.66	218.4	26.06	6.83	13.1	0.1	0.1401

FIGURES

Figure 2: Aerial photograph of La Barranca sediment core study site. (California Dept. of Water Resources (DWR) 1999)
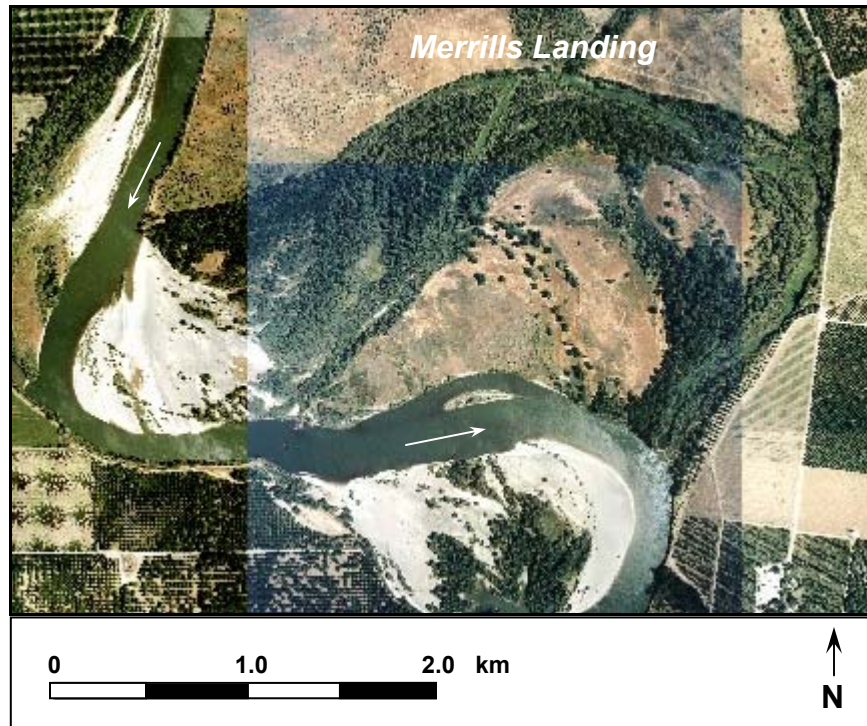
Figure 3: Aerial photograph of sediment core study site Merrills Landing (DWR 1999).

Figure 4: Aerial photograph of sediment core study site Jenny Lind Bend (DWR 1999).

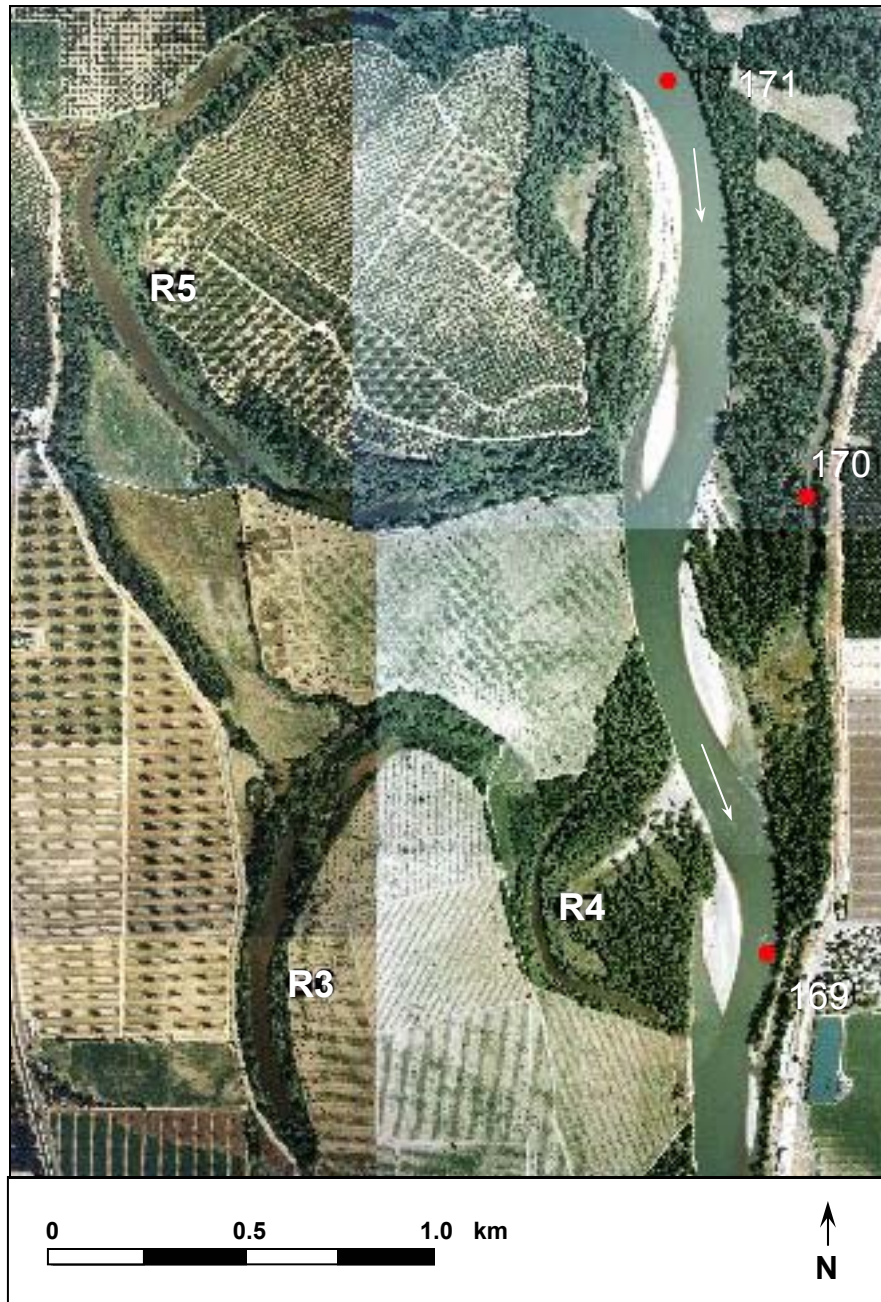**Figure 5**: Aerial photograph of study sites R1 and R2 between river miles 167 and 169 (DWR 1999).

Figure 6: Aerial photograph of study sites R3, R4, and R5 between river miles 169 and 171 (DWR 1999).

Figure 7: Aerial photograph of study sites L1 and L2 near river mile 176 (DWR 1999).

Figure 8: Aerial photograph of study sites R6 and R7 (partial) between river miles 178 and 179 (DWR 1999).

Figure 9: Study site L4, on the left bank between river miles 195 and 196 (DWR 1999).

Figure 10: Study site L5, on the left bank between river miles 203 and 205 (DWR 1999).
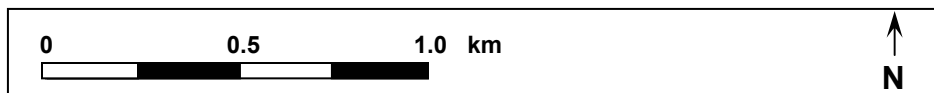
Figure 11: Study site L6, on the left bank between river miles 212 and 215 (DWR 1999).

Figure 12: Aerial photograph of aquatic plant study site R9 (DWR 1999).

Figure 13: Aerial photograph of aquatic plant study sites R10 and R11 between river miles 235 and 237 (DWR 1999)
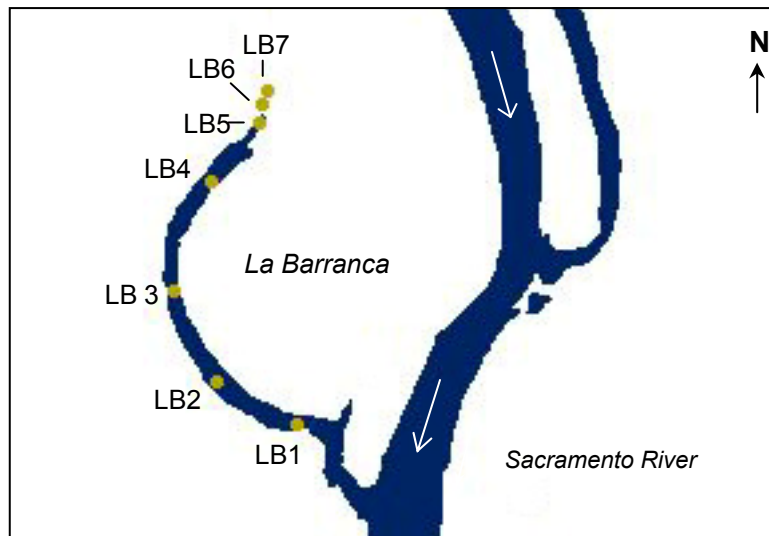
Figure 14: Map of La Barranca sediment core locations. Scale = 1:36,000.

Figure 15: Map of Merrills Landing sediment core locations. Scale = 1:36,000.
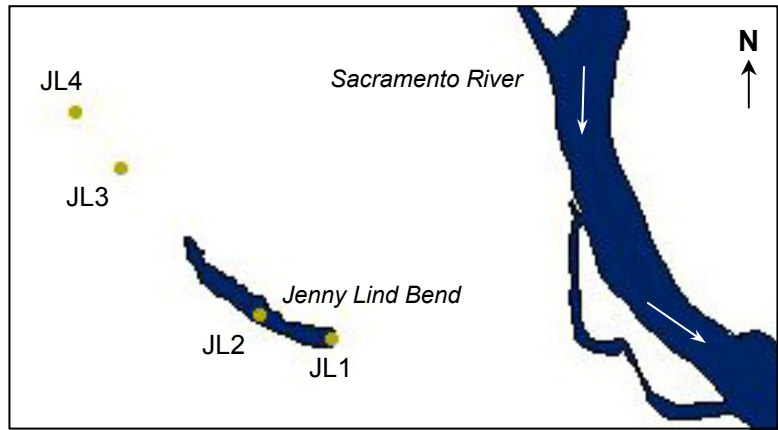
Figure 16: Map of Jenny Lind Bend sediment core locations.
Scale = 1:36,000.

Figure 17: Photograph of La Barranca downstream end entering the main channel, August 16, 2001. Main channel discharge = 11,300 cfs.

Figure 18: Photograph of La Barranca downstream end entering the main channel at same point as in Figure 17, March 5, 2001. Main channel discharge = 26,780 cfs.

Figure 19: Photograph of Merrills Landing, August 16, 2001.
Main channel discharge = 11,300 cfs.

Figure 20: Photograph of Merrills Landing from same point as in Figure 19, March 5, 2001. Main channel discharge = 26,780 cfs.
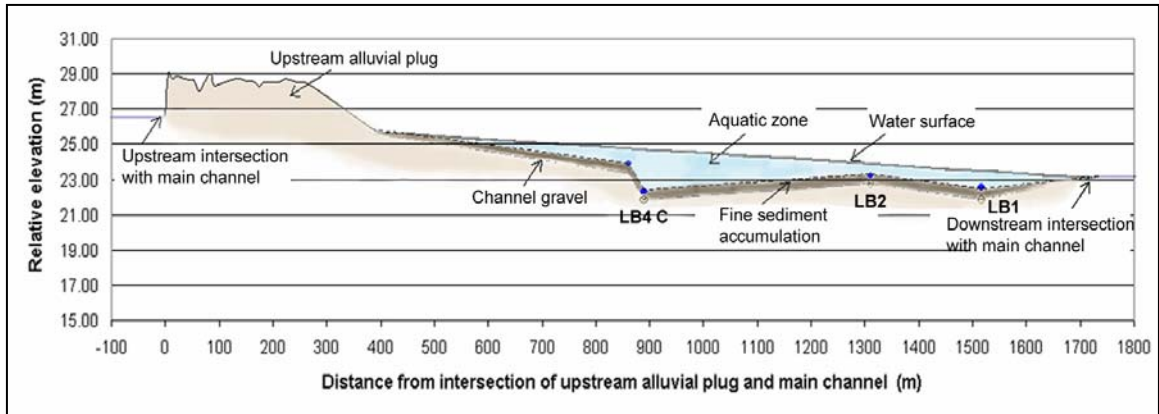
Figure 21: Longitudinal profile of La Barranca cut-off channel between the upstream intersection with the main channel to the downstream intersection with the main channel. The upstream alluvial plug, channel gravel surface, fine sediment accumulation since the time of cut off (in dark brown), three of the sediment core locations, and the aquatic zone are noted.
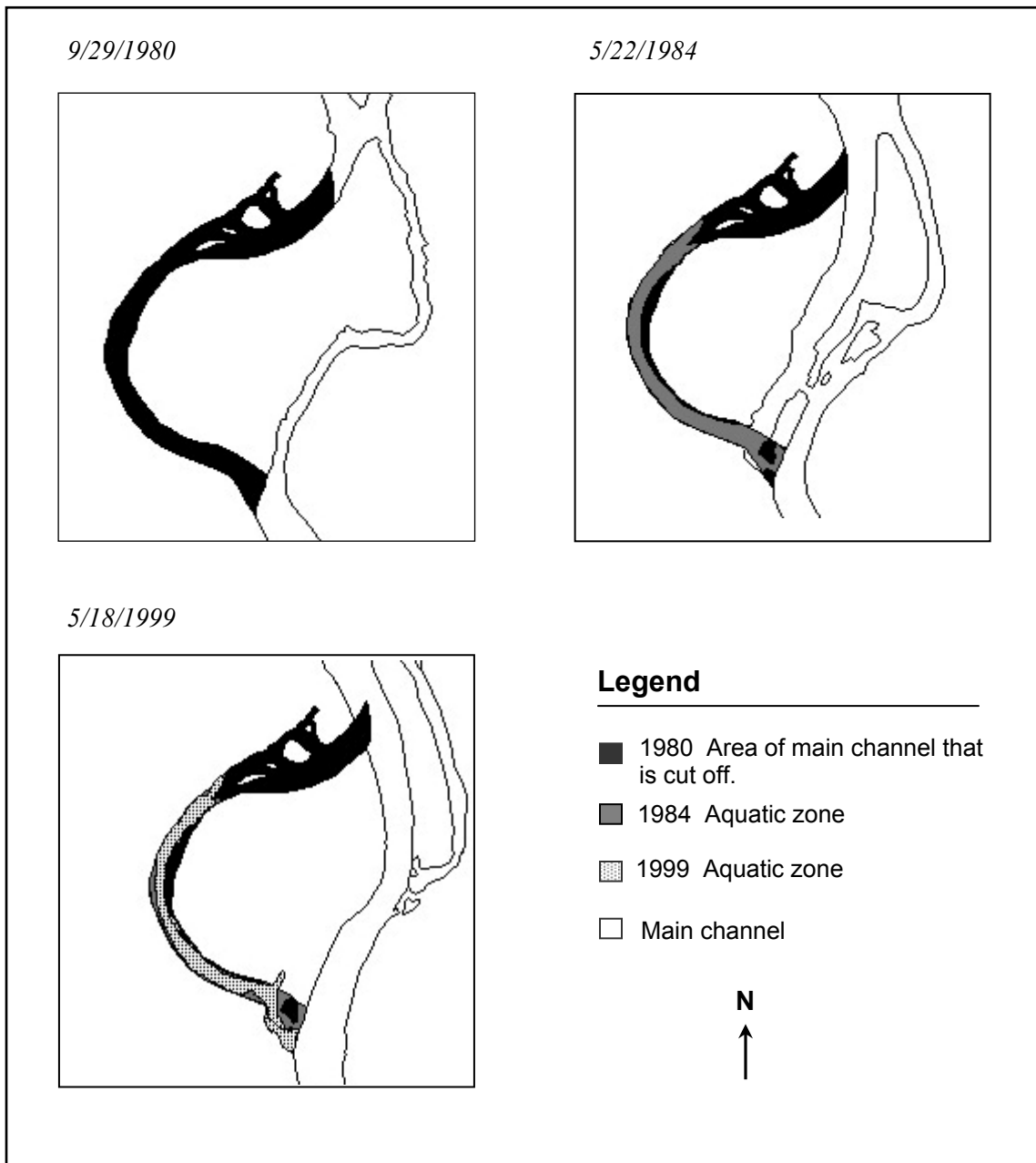
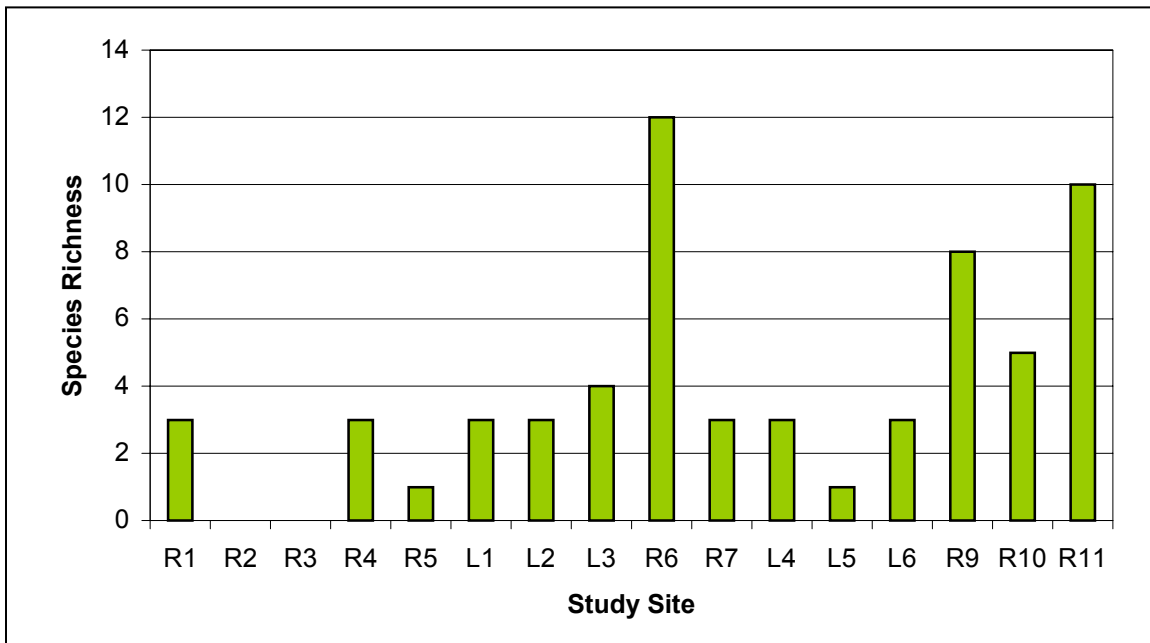**Figure 22:** Spatial analysis of La Barranca in 1980, 1984, and 1999, 1:36,000 scale.

Figure 23: Aquatic plant species richness at cut-off channel study sites of the Sacramento River.