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Landscape and Urban Planning xxx (2006) xxx–xxx
LANDSCAPE AND URBAN PLANNING
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Landscape level planning in alluvial riparian floodplain ecosystems: Using geomorphic modeling to avoid conflicts between human infrastructure and habitat conservation

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Received 30 March 2006; accepted 21 April 2006

Abstract

River channel movement processes necessary to maintain the natural heterogeneity in wildlife-dependent riparian ecosystems often conflict with the need to protect adjacent human infrastructure (e.g. towns, bridges, water pumps). This conflict can be avoided through long-term planning efforts which use process-based geomorphic simulation modeling to forecast potential long-term (>50 years) landscape-level effects of water management decisions on river meander migration. We describe two management conflicts from the Sacramento River, California, USA, and analyze alternative management scenarios using results from a meander migration and cutoff simulation model. The first example shows that the existing rock revetment upstream from Woodson Bridge State Recreation Area alters the river meandering and causes erosion problems. Removing the revetment would relocate the channel and create a natural meander-neck chute cutoff, reducing erosion at the park while providing ecosystem benefits. The second example suggests that although a bank revetment is needed to prevent the river from moving away from a major water pump, removing an upstream bank revetment would provide habitat benefits without causing pump facility problems. These examples demonstrate the benefits of taking a long-term, landscape-level view when implementing infrastructure projects in dynamic landscapes.

Keywords: Bank erosion; Riparian vegetation; River channel meander migration; River bend cutoff; Environmental planning

1. Introduction

Large alluvial rivers provide vital functions to natural ecosystems and human societies (Constanza et al., 1997). Riparian systems are some of the most diverse and productive ecosystems in the world and some of the most highly impacted by humans (NRC, 2002; Tockner and Stanford, 2002). Humans have often lived along alluvial rivers because food, water, transportation, and fertile soil is readily available; likewise, aquatic and riparian ecosystems are richly biodiverse (Ward et al., 2002). However, river channel migration results in erosion which can cause problems for adjacent towns, farms, water pumping facilities, and transportation infrastructure. Efforts to protect against erosion often involve lining the river bank with riprap, or large rocks. Riprap has virtually halted natural river processes such as river channel meander migration and meander cutoffs that create and maintain a complex landscape habitat mosaic in riparian ecosystems (Naiman et al., 1993; Lytle and Poff, 2004). Recently, there has been a nationwide focus on river restoration (Bernhardt et al., 2005) including the use of natural fluvial processes such as river migration and environmental flow prescriptions to maintain and restore riparian landscapes (Poff et al., 1997; CALFED, 2000; Richter and Richter, 2000; USDA, 2001; Rood et al., 2005).

One of the primary processes driving riparian ecosystem function on large, single-channel alluvial rivers (as opposed to braided rivers) is meander migration (Hughes, 1997). When not constrained by natural or man-made erosion-resistant banks, large alluvial meandering rivers have a tendency to migrate laterally (Johannesson and Parker, 1989). For example, in bank erosion studies conducted on the Sacramento River annual migration rates have been observed to vary between 0 and 39 m/year (Larsen et al., in press). Channel migration of meandering rivers has been shown to be necessary to establish and

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doi:10.1016/j.landurbplan.2006.04.003

maintain riparian, oxbow lake, and river bank ecosystems (Hupp and Osterkamp, 1996; Scott et al., 1996; Ward et al., 2002).

River meandering creates a heterogeneous landscape mosaic of uneven aged vegetation patches, including dense riparian habitat often associated with oxbow lakes that provide critical wildlife habitat and support high levels of biodiversity (Ward et al., 2002). For example, many bird species including the yellow warbler, yellow-breasted chat, blue grosbeak, and western yellow-billed cuckoo prefer early seral stages of riparian habitat subject to regular disturbance (from high water events, meander migration, and channel abandonment) for foraging and nesting (RHJV, 2004). Bank swallows in particular are dependent on eroding banks for nesting substrate (Morken and Kondolf, 2003; RHJV, 2004). Bats preferentially forage near oxbow lakes along the Sacramento River (Rainey et al., 2003). The riparian and oxbow areas are a complex habitat mosaic that supports high species richness within a relatively confined area. In fact, in the western United States, riparian vegetation occurs on less than 1% of the landscape yet provides habitat for more bird species than all other vegetation types combined (Knopf et al., 1988).

A management conflict can arise between promoting natural river process and protecting human interests (Golet et al., 2006). This conflict can be avoided by using environmental planning that includes analytical and process-based hydraulic and ecological models. Such models can both forecast the long-term landscape-level effects of management decisions and provide alternatives which promote natural processes, while at the same time avoiding stakeholder losses (Richter et al., 2003). Computer modeling of channel migration in alluvial rivers can deal objectively with these conflicts and provide alternative management scenarios (Richter and Richter, 2000; Larsen and Greco, 2002).

Long-term, landscape-scale planning is rarely used during the planning and implementation of human infrastructure along the corridors of large rivers, yet has many benefits to offer. "Landscape-scale" in the context of river meandering means considering a certain reach of river and its surrounding riparian corridor rather than a series of isolated sites with problems at single river bends (e.g. a pump or a bridge). Site-by-site planning solutions often lead to more problems in the near to long-term, especially in dynamic landscapes such as riparian corridors. For example, changing bank erosion rates at one site, either by removing vegetation or hardening the banks, can alter the migration pattern as far as three or four bends downstream. These channel alterations can occur over relatively short periods of time (less than 5 years), and may affect the timing and location of avulsion events. Clearly, planning and management of infrastructure at a site should consider long-term consequences (e.g. periods >50 years). These may include how infrastructure may be impacted by upstream conditions, as well as effects on river channel and adjacent floodplain conditions downstream.

Managers and decision makers rarely consider a natural process-based approach to minimize costs and unwanted effects. For example, a question rarely asked is "can our management goals be met through the natural processes of river meander migration?" The initial financial burden can prevent decision makers from incorporating long-term thinking into the planning process. Planning is often only considered in time scales as short as 10 years, or may only consider a limited scope of potential impacts (e.g. impacts on local velocities but not surrounding areas). In the short-term, the benefits of allowing meander migration may not outweigh the costs. Over longer time scales, which take into account repair and replacement costs, a solution that incorporates or accommodates natural river migration may reveal long-term cost savings. In short, the broader economic benefits (e.g. ecosystem services, Tockner and Stanford, 2002) of long range planning tend to come to fruition with time and generally outweigh the initial costs of project implementation.

In this paper we describe two management conflicts involving human resource use (infrastructure) and biological impacts, and present alternative measures using results from a meander migration model (Larsen and Greco, 2002; Golet et al., 2006) on the Sacramento River, California, USA. Alternative scenarios offer concrete and realistic examples of how managers can incorporate landscape level conservation planning in alluvial riparian ecosystems. By considering landscape level changes in river meander migration, demands to protect infrastructure and limit erosion through private lands can be balanced with the need to conserve and promote ecological functions.

2. Methods and materials

2.1. Study area

The Sacramento River in north-central California, USA, flows south through the Sacramento Valley (Fig. 1) over sedimentary rocks and recent alluvium. The Sacramento Valley is 96 km wide and 418 km long and is a structurally controlled basin between the Cascade and Sierra Nevada Mountains to the east and the Coast Ranges of California to the west (Harwood and Helley, 1987). The total drainage area of the river is 6.8×10^4 km^2, more than half of the total drainage area of the San Francisco Bay, which is located on the western coast of California. The160 km sector of the Sacramento River between Red Bluff and Colusa (Fig. 1) is primarily a single-thread sinuous actively migrating channel (Brice, 1977).

The hydrology of the Sacramento River is controlled by northern California's semi-arid climate. The river receives most of its water during the winter and early spring months in the form of rain (predominately from January to March) and snow melt. Historically, the Sacramento River maintained a low flow of about 85 cubic meters per second (cms) during the summer and fall. Due to the nature of California's geography, Sacramento River hydrology is highly variable. Winter flooding is common; the valley floor reflects this high frequency flooding in the form of flood basins and peripheral channels. Large areas of wetlands and riparian vegetation once spanned the valley floor, especially in the lower delta region (Thompson, 1961). The 1943 construction of Shasta Dam on the Sacramento River, about 200 miles north of San Francisco Bay, as well as hundreds of other dams, weirs, diversion canals, have allowed people to cultivate the rich, loamy soils adjacent to the river channel.

To protect agricultural lands and infrastructure from flooding and channel migration, the river has been restrained in many areas by riprap and levees. Not all of the riprap installed is

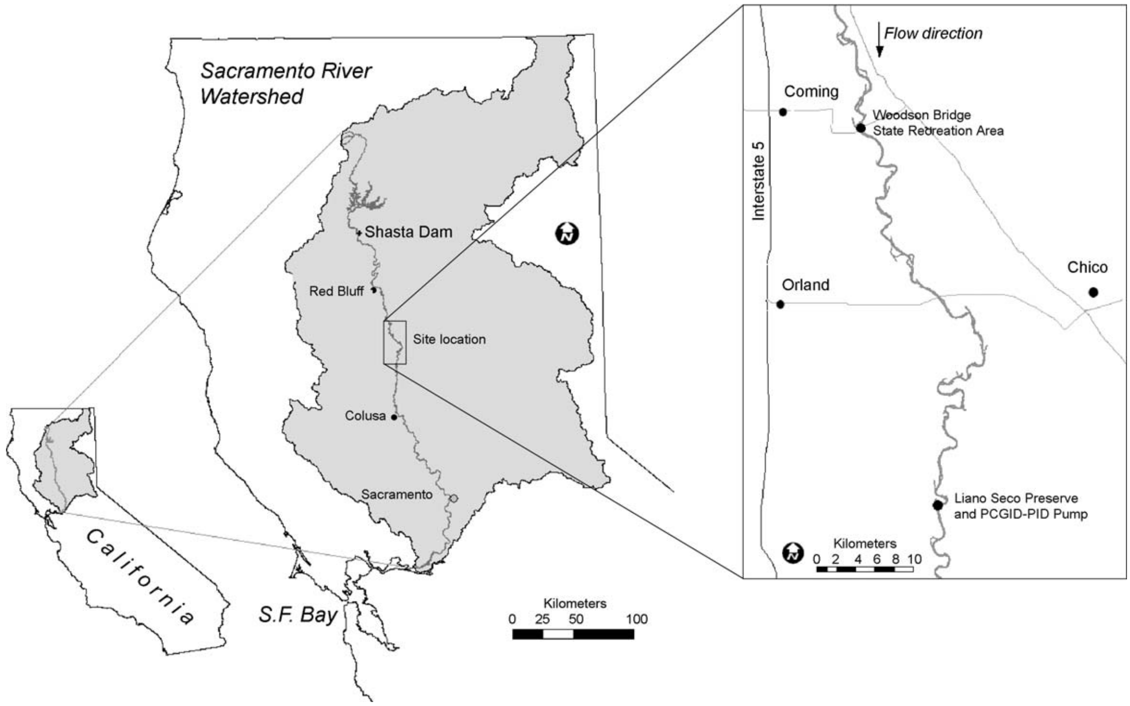

Fig. 1. Location of study area within California. The currently actively meandering sector of the Sacramento River is located between Colusa and Red Bluff.

still needed. One bank restraint was installed and maintained due to fears that its removal would significantly alter the flood capacity of the river. Recently, a hydraulic flow model showed this belief to be incorrect (USACE, 1997). On the other hand, bridge placements seem to fit the river well. Engineers typically selected geologically constrained areas where little river migration occurs. However, some current conflicts have arisen with natural meander migration, largely because the long-term patterns of change were not anticipated. The CALFED Bay Delta program has stressed the need to consider natural meander migration dynamics when any management action is planned (CALFED, 1997, 1999). Other sources of conflict are agricultural pumping facilities placed without fluvial dynamism in mind. Pumps require a stable river channel and are placed along the river to provide water to surrounding agricultural land. When they are located where the river is actively migrating, pump sites require an engineering solution to attempt to halt local migration.

2.2. Meander migration modeling

Computer simulation modeling programs based on mathematical-physical algorithms of water flow and sediment transport have been used to predict future river channel meander patterns (e.g. Larsen, 1995; Darby et al., 2002). Our paper discusses a simulation model of river meander migration that uses a geographic surface of erosion potential to incorporate effects due to infrastructure such as bridges, pumps, and bank erosion control projects such as riprap and levees (Johanesson and Parker, 1985; Larsen and Greco, 2002; Larsen et al., 2006). Because the model is a process-based simulation model, it is calibrated based on observed historical channel locations. As such, it should help predict the future location of the river channel. The model accommodates changes in input variables and projects the consequences of conditions that have not existed in the past, such as the addition or removal of a bank erosion control project. Understanding the dynamics of the river given different management scenarios will provide important information to inform planning decisions.

To illustrate how meander migration modeling can both suggest alternative management scenarios and analyze their benefits and disadvantages, we discuss two conflicts between infrastructure projects and riparian habitat management occurring along the actively meandering sector of the Sacramento River. We first describe an example of a potential problem with bank erosion near a bridge in a state park. This example illustrates how understanding patterns of meander migration in the context of bridge placement can reduce potential conflicts while creating habitat. We then describe how meander migration modeling could have avoided a conflict between pump placement and a nature reserve. Our results suggest that future pumping plants consider pumping with off-stream collectors to reduce or eliminate the source of conflict. In both examples we use meander migration tools to quantitatively measure the ecosystem costs and benefits related to river migration.

3. Results

3.1. Case study 1: Woodson Bridge State Recreation Area

Woodson Bridge State Recreation Area, on the northern Sacramento River (Figs. 1 and 2), consists of 108 acres of ripar-

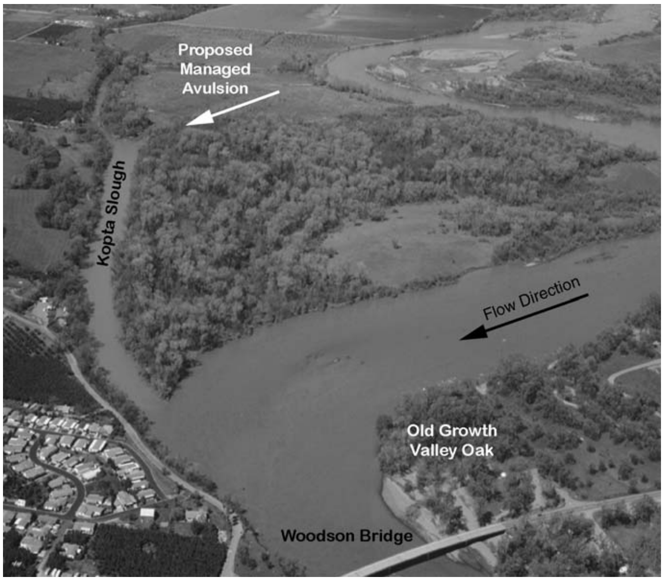

Fig. 2. Aerial photo of the Woodson Bridge area of the Sacramento River. The river flows from top to bottom.

ian forest, valley oak woodland, and grassland. This area has experienced significant river migration over the past 100 years. River managers are concerned that bank erosion threatens one of the largest remaining stands of late-seral (old growth) valley oak (*Quercus lobata*), a once-common Sacramento River vegetation community type (Thompson, 1961). Channel migration along this reach may also harm the recreational facilities and the Woodson Bridge structure itself.

Near the recreation area, the erosion-resistant terrace deposits of the Riverbank Formation crop out along the western edge of Kopta Slough (Figs. 2 and 3A) and act as a geologic constraint, limiting channel migration along the southern portion of the reach. In 1963, the US Army Corps of Engineers installed riprap on the outside cut-bank of Copeland Bar and the bend immediately downstream, preventing bank erosion along the riprapped area of the state park (Fig. 3A and B). The effect of this riprap can be seen by comparing simulations with and without the riprap (Fig. 3A and B). Under current conditions (Fig. 3B), the simulation predicts river migration into the old-growth valley oak trees located in the state park (this pattern of erosion is also the observed current tendency). The old growth stand and bridge could be protected by extending local bank protection (e.g. riprap, Fig. 3C). However, this would further lock the river into place, halting fluvial dynamism and preventing the creation of new riparian habitat. To investigate potential alternatives, we modeled how a physical realignment of the channel from its present location would direct the river away from the oak trees and bridge, where erosion is a concern. This managed avulsion would create a bend cutoff that recaptures the river's historical (pre-1930s) channel, an area now known as Kopta Slough, while allowing more opportunities for floodplain reworking and oxbow lake creation (Fig. 3D).

Our channel migration simulations suggest that: (1) channel stabilization alters the future channel planform locally and downstream from the stabilization; (2) rock revetment currently on the bank upstream from the Woodson Bridge recreation area causes more erosion of the channel bank at the recreation area than if the revetment were not present; (3) relocating the channel to the west and allowing subsequent unconstrained river migration relieves the erosion pressure in the Woodson Bridge area (Fig. 3D); (4) the subsequent migration will rework (erode along one river bank and replace new floodplain along the other) 26.5 ha of land; (5) the river will rework between 8.5 and 48.5 ha of land in the study reach over the course of 50 years, depending on the bank stabilization plan used (Fig. 4).

To our knowledge, this study, described in Larsen and Greco (2002), was the first time a numerical meander migration model has been applied to evaluate river channel stabilization plans. Modeling benefits include the ability to quantitatively assess downstream impacts of bank stabilization and to quantitatively assess the rates of land reworked (a process roughly corresponding to floodplain creation). In the case of the Woodson Bridge study reach, our simulations suggest that a management strategy that permits channel migration will lead to reworking of significant floodplain area, will help to maintain riparian ecosystem heterogeneity, and will reduce bank erosion near critical portions of the Woodson Bridge recreation area.

3.2. Case study 2: conflicts between riparian preserve and water pump placement

A consortium of water-users – the Princeton, Cordora, and Glenn Irrigation District and the Provident Irrigation District (PCGID-PID on Fig. 1) – recently built a large ($11 million) pump along the Sacramento River adjacent to a riparian habitat preserve (Figs. 1 and 5). The pumping plant consolidated three previous plants and includes a fish screen. For purposes of analysis, the riparian preserve is split by the river into two sections, one upstream of the pump, and the other downstream (Fig. 5). The channel in the vicinity of the pump has evolved in shape through natural processes, resulting in lateral and downstream meander migration through the riparian preserve area over the last century (Fig. 5). Channel migration away from the pumping facility in recent years has concerned pump managers. The current concern is that meander migration would direct the flow of the river more toward the pumping plant, reducing the "sweeping" velocity (parallel to the fish screens) and would potentially impinge young fish on the screen. The immediate concern is that the plant would be shut down because of fisheries issues, not because the water would not be available to the pump. Historic maps show that the Sacramento River near the pumping plant has experienced typical downstream patterns of meander bend migration. As the river meander bends continue to move downstream, the near-bank flow of water and eventually the river itself will tend to move away from the pump location. The owners of the preserve would like to restore their land by removing the riprap and allowing a natural river cutoff to form. However, the pump managers worry that removing riprap upstream from the pump might hasten the river's movement away from the pump.

We used the meander migration model to predict the impact of different management scenarios aimed at keeping the river

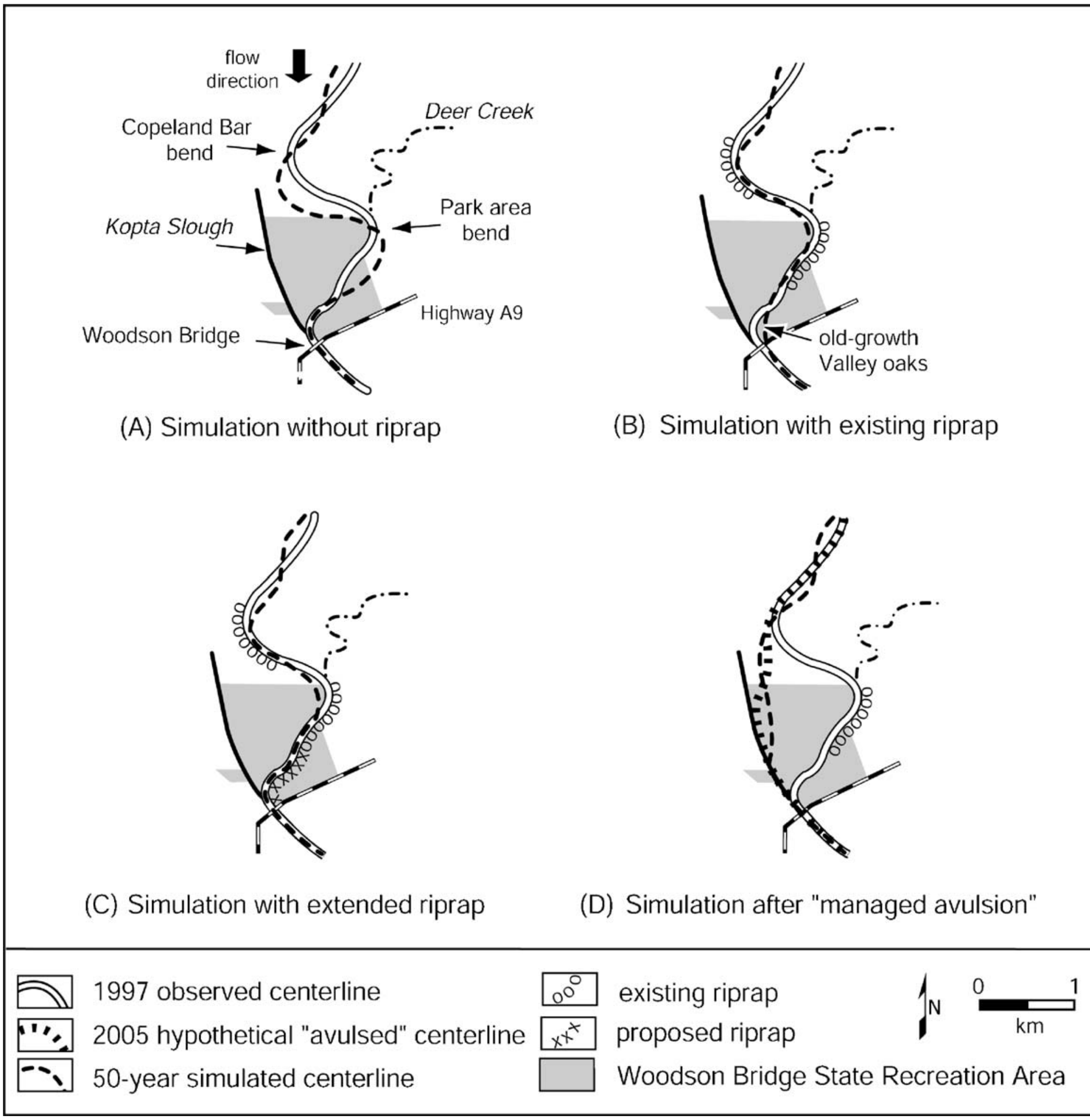

Fig. 3. Channel centerline locations showing 50 years of simulated migration assuming that: (A) the channel is unconstrained by riprap, (B) riprap is maintained in its 1997 location, (C) riprap near the state recreation area is extended, and (D) the channel is relocated to Kopta Slough (figure from Larsen and Greco, 2002).

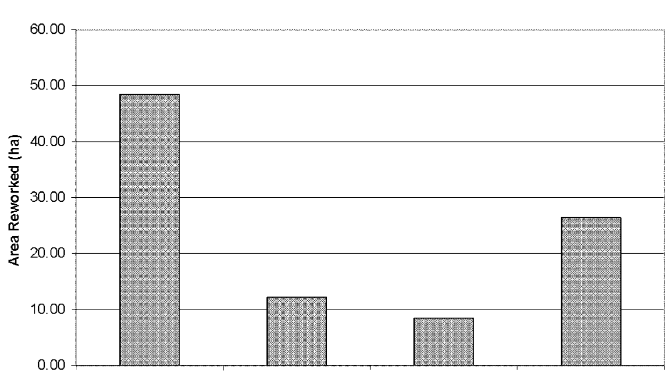

Fig. 4. Area of land reworked by river at Woodson Bridge State Recreation Area for each scenario. This figure is based on results from Larsen and Greco (2002).

near the pump for a period of 50 years. The area of floodplain reworked, which plays an important ecological role in the colonization of riparian vegetation, was calculated from the simulations for each channel migration scenario. The five scenarios show two major areas where the floodplain can be reworked: the riparian preserve upstream from the pump and another riparian preserve downstream (Fig. 5).

In the first two scenarios (Fig. 6A and B) existing bank restraints were left in place, thereby limiting the formation of an upstream bend cutoff. In both of these scenarios, a total of less than 10 acres of land was reworked over 50 years in the upstream and downstream areas (Fig. 7A and B). In addition, the migration rate over time was fairly constant during the entire analysis period (Fig. 8A and B). The first scenario – which models future migration given current conditions of bank restraint – showed that the river bend near the pump site tended to move downstream and pull away from the pump location (Fig. 6A). In the second

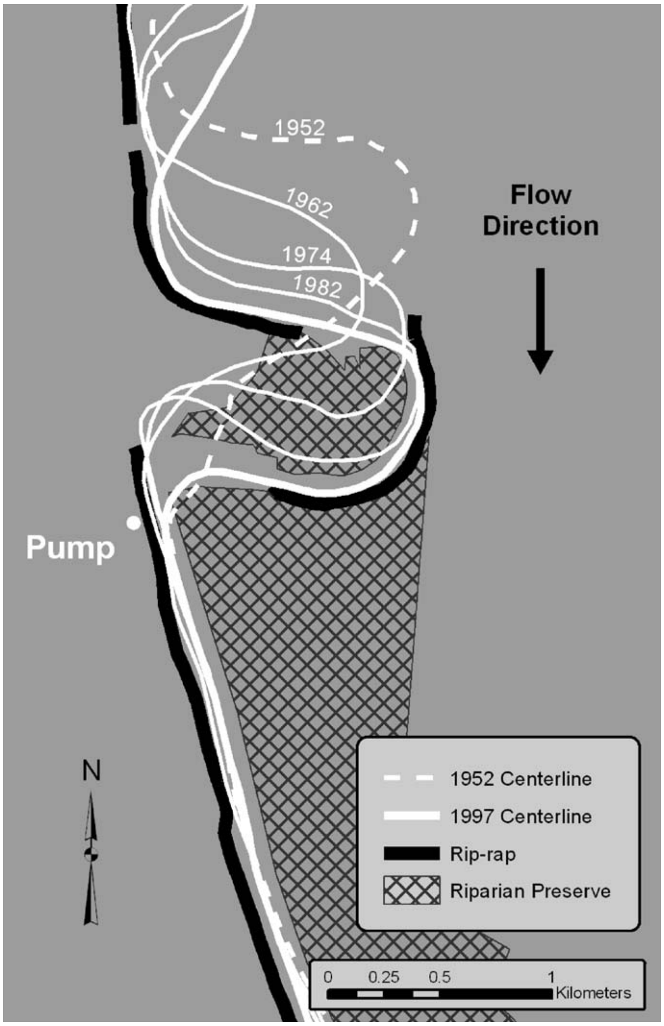

Fig. 5. Context map showing location of Llano Seco water pump, adjacent riparian reserve, and location of upstream bank revetment (i.e. riprap) removed in simulation modeling. River channels are shown for the years 1952, 1962, 1974, 1982, and 1997.

scenario – which extends the riprap immediately upstream of the pump site (on the opposite bank) – the river maintained contact with the pump site (Fig. 6B).

In the three other future migration scenarios, upstream riprap was removed. This resulted in the formation of a bend cutoff and increased channel migration within the riparian reserve area (Fig. 6C–E). In the upstream area, all three scenarios reworked about 30–35 ha of land in 50 years (Fig. 7A), with rates of land reworking declining from about 2 ha/year immediately following the cutoff, to a fairly constant 0.5 ha/year 30 years after the cutoff (Fig. 8A). What differs in these scenarios is the area reworked downstream. Removing or not extending the downstream riprap resulted in about 34 ha of floodplain reworked downstream (Fig. 7B). However, when the riprap was extended at the pump site, the area reworked in the downstream area shrinks to less than 4 ha, a difference of about 30 ha when the riprap was not extended.

These modeling results suggest that if the pump remains in its current location, the riprap near the pump must be extended (Fig. 6A, D and E) to keep the river near the pump. However, our results also suggest that if the riprap were extended to stabilize the channel bank across from the pump site, the bend upstream could be allowed to form a cutoff and provide natural regeneration of the upstream floodplain area and associated abandoned channel communities, all without causing migration at the pump site. This scenario can be seen as a compromise protecting the water pump operations while allowing natural, passive river processes to create and maintain riparian and wetland habitat – including an oxbow lake – in the upstream area designated as a nature preserve.

4. Discussion

The inherently dynamic nature of alluvial river systems, including channel migration and cutoff processes, is the major factor maintaining the natural heterogeneous landscape mosaic of associated riparian habitat. The reworking of floodplain lands and associated bend cutoffs are important riparian ecosystem functions that maintain habitat heterogeneity. Heterogeneity is an essential factor for the long-term survival of many species, including several of management and regulatory concern in the Sacramento River area. However, channel migration and cutoff processes that drive habitat heterogeneity have caused problems for human societies that desire river stasis and plan for short-term goals. To control the dynamics of river meandering, many river bank erosion control projects have been installed on the Sacramento River over the past century. It is not uncommon for people to believe that rip-rap is a permanent solution. The rip-rap on the upstream portion of the Llano Seco site was placed after 1986 and is already on the verge of failure. A number of these projects no longer have a function, and many were installed for no practical reason other than the prevailing belief that a moving river is not desirable for human society. However, a renewed interest protecting riparian ecosystems – 95% of which have been lost in California – has shifted management focus away from restraining the Sacramento River and toward solutions that allow natural river processes (e.g. meander migration) to occur in conjunction with water and flood control management efforts. In many cases however, this has created conflicts between riparian habitat management and the management of infrastructure within the meander zone of the river.

In recent years, there has been increased interest and activity in large-scale river restoration on the Sacramento and other northern California rivers. In 1986, California State Senate Bill 1086 initiated the *Upper Sacramento River Fisheries and Riparian Habitat Management Plan* (Advisory Council and Action Team, 1989) which called for native salmon habitat restoration and the preservation and restoration of riparian ecosystems along the river. In addition, the CALFED Bay Delta program has spotlighted the preservation and restoration of natural river meander processes and riparian ecosystem health along the Sacramento River and its tributaries (CALFED, 1997, 1999). Additional studies related to flow diversions have stressed the importance of understanding the natural dynamics of the fluvial geomorphology and riparian ecosystems (CALFED, 2000). The restoration programs described in these and other documents have been sup-

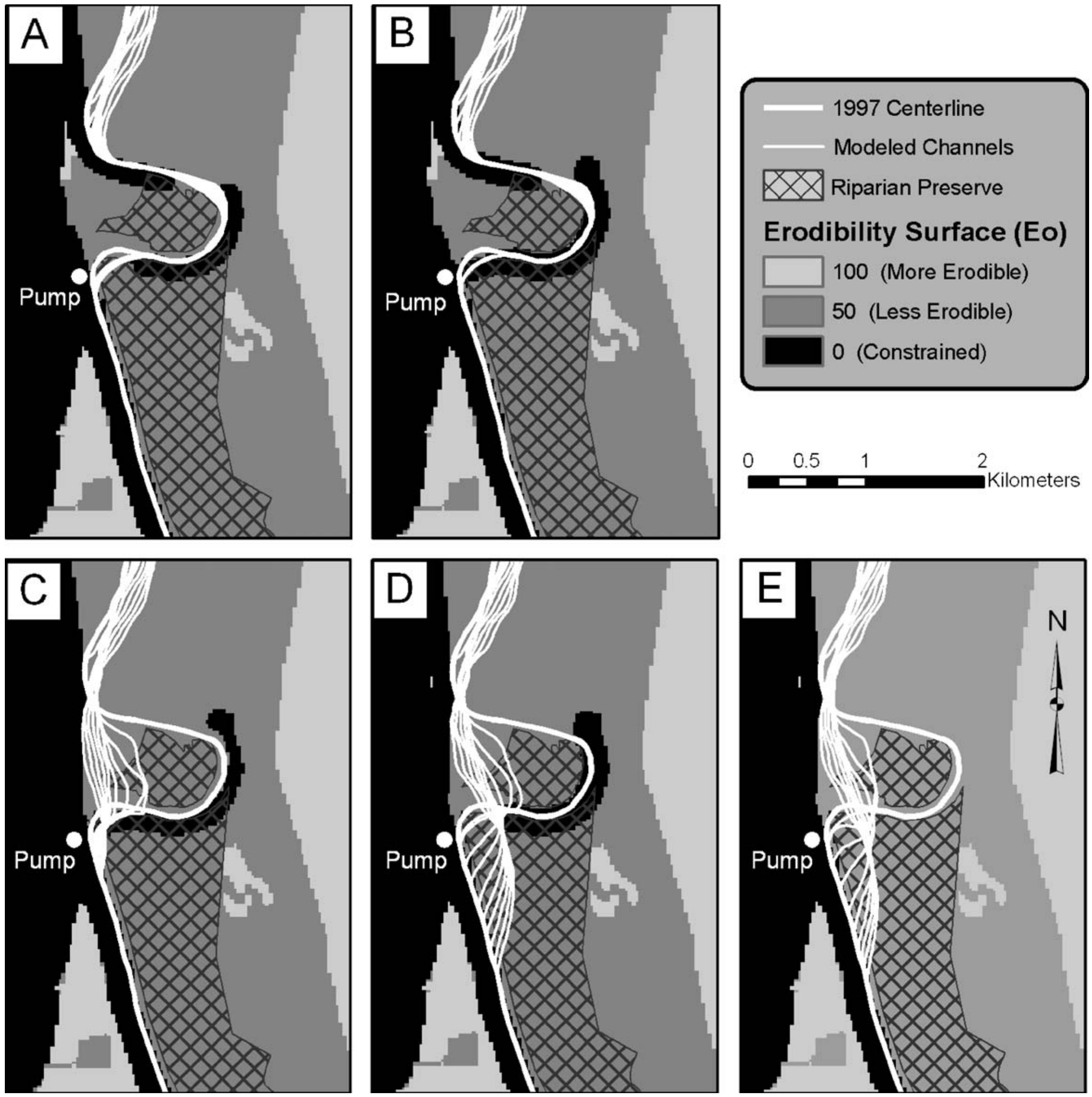

Fig. 6. Meander migration modeled 50 years into the future for different bank revetment management scenarios: (A) current conditions, (B) additional bank restraint for the area around pump, (C) additional bank revetment near pump with upstream revetment removed, (D) current conditions with upstream revetment removed, and (E) all revetment removed. Note that a bend cutoff event creating oxbow lake habitat occurred in scenarios (C)–(E).

ported by substantial federal and state funds. In the light of this immense restoration effort, it is not only relevant but urgent to employ large-scale planning to avoid conflicts between habitat restoration and human infrastructure.

This paper presented two examples to show how planning with meander migration simulation modeling can reduce human/habitat conflicts by considering management scenarios that work with natural river movements rather than constraining them. In the Woodson Bridge case study, a solution arises out of natural river meander processes that both benefits erosion control efforts and ecosystem habitat management. The model shows that initiating a managed avulsion event through Kopta Slough, would create riparian habitat – including an oxbow lake community – and the river would no longer threaten the auto bridge and old-growth oak trees.

In the water pump placement case study, natural river meander processes alone could not prevent the river from leaving the water pump. Yet the impacts of installing more bank protection at the pump can be mitigated by removing bank protection upstream—likely resulting in the river channel cutting off and creating an oxbow lake community. The conflict between pump placement and river meandering could have been avoided by considering long-term impacts of natural river processes using meander migration modeling prior to pump construction.

Modeling future meander migration patterns could have forewarned that placing the pump at its present location would incur future management costs as the river migrated away from the pump (as is currently occurring). Modeling could also have forecast the effects of alternative water pump placement and/or technologies. A feasible alternative to more traditional on-channel pumps is off-stream pumping. These off-stream water pumps collect water from beneath the river (using devices such as Ranney collectors) through a series of subsurface and sub-riverbed lateral infiltration collectors. Their operation does not require the

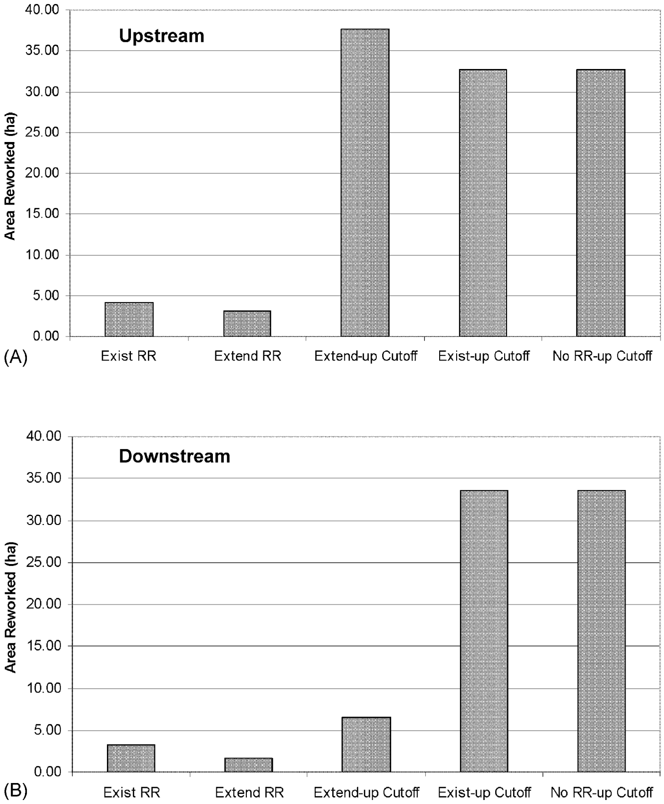

Fig. 7. Area of land reworked for the different bank revetment management scenarios: (A) upstream and (B) downstream of the Llano Seco water pumping plant. "RR" on the graphs stands for "rip-rap".

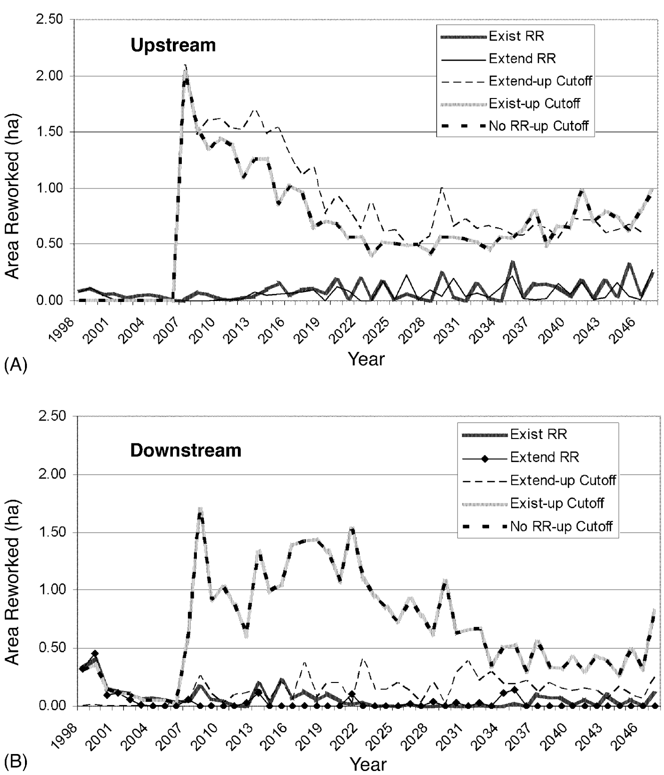

Fig. 8. Temporal patterns of land reworked for the different bank revetment management scenarios: (A) upstream and (B) downstream of the Llano Seco water pumping plant.

installation of fish screens. Although on-channel pumps may initially be cheaper to install than off-channel pumps, the long-term maintenance and management costs of having to install a fish screen (which can lead to costs of millions of US dollars) and extend the riprap on the bank across from the pump will likely outweigh the costs and maintenance of off-stream collectors.

5. Conclusion

Understanding channel migration rates and spatial patterns of both erosion and deposition are critical to environmental planners, river and wildlife managers, and restoration practitioners. Long-term environmental planning in large alluvial basins will become increasingly important as increased human population demands for fresh water clash with basic riverine and riparian habitat management requirements. As managers and planners are faced with site-specific projects that directly affect adjacent land owners and businesses, they need quantitative and comprehensible tools with which to accurately balance ecological and economic objectives. Likewise, impacts on larger areas, such as functionally similar reaches of rivers and adjacent riparian lands, should be integrated into regional planning efforts (Bernhardt et al., 2005). This type of long-term and large-scale environmental planning in lowland river floodplains has become particularly important as traditional approaches (such as riprap and near-bank levees) are recognized to conflict with riparian habitat conservation efforts and greater value is placed on ecosystem services.

Acknowledgements

The Woodson Bridge study was partially supported by the California Department of Water Resources, Northern District. Research related to the Llano Seco Project was partially supported by River Partners, Chico California. The authors thank Stacy Cepello, Koll Buer, Adam Henderson, Dan Efseaff, and Steve Greco for valuable input for this paper.

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