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A GRAVEL BUDGET FOR THE LOWER AMERICAN RIVER

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A GRAVEL BUDGET FOR THE LOWER AMERICAN RIVER

A Thesis

by

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Dr. Timothy C. Horner, Graduate Coordinator Date

Department of Geology

ABSTRACT

of

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The gravels of the Lower American River (LAR) provide spawning habitat for Chinook Salmon and Steelhead Trout. To sustain or enhance populations of these fish, gravel of appropriate quantity and quality needs to be maintained. Historic perturbations – including mining, levees, and dams – have changed the sediment loads and transport conditions of the river; and the volume of gravel has declined since the construction of Folsom and Nimbus Dams in the 1950's. This study examines geomorphic changes to the river since dam construction, the effects of discharge on gravel depletion, the depths of gravel on the LAR, and uses this information to construct a gravel budget to assess the rates and significance of gravel losses.

Photos and maps indicate that the overall planform of the LAR has changed little since 1865. At Goethe Park, one of the few locations that have shown significant planform change, the channel has straightened and become more braided. Longitudinal profiles indicate a steep gradient (knickpoint) which may be responsible for these planform changes. In the upper 17km, where most natural spawning takes place, some gravel bars have shown downstream migration between 1957 and 2002. At Sailor Bar, a gravel bar with an estimated volume of more than 20,000m^3 moved 650m downstream, while at Lower Sunrise, a 10,700m^3 gravel bar moved 115m downstream.

Periodic movement of bed material may provide benefits to spawning habitat (Horner 2005), but bed mobility on the LAR is generally limited to large flood events. A tracer rock study showed movement of grains as large as 8.9 – 10.8cm after flows of 26,500cfs. Ayres Associates (2001) produced a two-dimensional hydraulic model indicating that bed material is generally immobile below 50,000cfs and that the extent of mobility increases at higher flows. To distinguish between flows that barely exceed the incipient motion of the bed and those resulting in loss of large volumes of gravel, yearly cross-sections were plotted from records at the Fair Oaks Gauge. Significant channel widening or deepening (volume loss) occurred after all flood events greater than 100,000cfs with little volume loss occurring below 100,000cfs. This indicates that flows between 50,000 and 100,000cfs may mobilize (and enhance) bed material without significant volume loss.

Using historic photos, cross-sections, and longitudinal profiles, gravel inputs and net gravel loss from the channel were estimated, and gravel output by downstream transport was calculated from the two. With supply from upstream cut off by Nimbus Dam and no tributaries of consequence on the LAR, gravel inputs are limited to bank erosion. An estimated 440,000m^3 of gravel has been eroded from banks in the upper 17km of the LAR between 1957 and 2002. Net gravel loss from the channel is estimated at 1,600,000m^3 between 1962 and 1998. It is estimated that 2,000,000m^3 of gravel has been transported out of the upper 17km of the LAR between about 1960 and 2000.

Gravel thickness and the extent of bedrock control of the river were evaluated by mapping bedrock outcrops in the channel and estimating gravel thickness using seismic refraction. More than ten bedrock outcrops were identified on the active channel bottom in the upper 17km of the LAR, but these outcrops represent less than 1% of the channel bottom. Seismic surveys of four gravel bars indicate thicknesses greater than 7m. The variability of depths suggests that the bedrock surface varies and leaves the extent of bedrock control as a largely unanswered question.

Horner (2005) has determined that factors such as grain-size distributions and subsurface flow due to geomorphic features (such as riffles) may be limiting the available spawning habitat. The lack of gravel supply from upstream has likely impacted these variables by coarsening of the bed below Nimbus Dam and reducing the complexity of channel features such as gravel bars and riffle-pool sequences. Future attempts to enhance spawning gravels on the LAR need to consider the quality of the gravel and complexity of geomorphic features, as well as gravel quantity.

_______________________________, Committee Chair
Dr. Timothy C. Horner

DEDICATION

This thesis is dedicated to my mother, Marjorie Miller, and in loving memory of my father, Jerome Fairman.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

1.1 Purpose

Folsom and Nimbus Dams (completed in 1955) have blocked access by anadromous fish to large amounts of spawning habitat in the upper reaches of the American River watershed. In addition, these dams have cut off the supply of gravel to the lower reaches that are still accessible for spawning. Despite these constraints, the Lower American River (LAR) has supported large populations of naturally spawned salmon (Hannon and Deason 2005). Efforts are being made by river managers to ensure that this section of river continues to provide habitat of suitable quantity and quality.

Attempts have been made to improve habitat, including a gravel enhancement experiment completed in the fall of 1999 (Vyverberg, et al. 1997). This work involved ripping and gravel addition at three sites. Horner (2005) has spent the last four years evaluating the quality of gravels at these and other locations. However, the quantity of natural gravel supply and the rate of depletion of this supply on the LAR remain largely unknown. These values will become increasingly important as managers develop practices that will sustain natural spawning on this important stretch of river.

The purpose of this study is to assess the nature of gravel supply on the LAR by constructing a gravel budget, or accounting for addition and removal of spawning gravel. The gravel budget will quantify the volume of gravel inputs, outputs, and net change within the river channel over the last fifty years. This study will address the following questions:

- How has channel morphology changed since the onset of detailed mapping and record-keeping?
- Is spawning gravel being lost from the LAR? If so, how fast?
- Where are the gravel sources on the LAR? How successful is gravel recruitment?
- Are there areas of gravel deficit on the LAR?
- Should gravel be added to the LAR, and if so, where?

In addition, some related issues are addressed. First, the data collected for the quantitative assessment of the gravel budget will be examined qualitatively to describe the nature of historic changes to the LAR. Geomorphic changes and trends are described in light of the human-induced changes to the channel over the last 150 years. Second, gravel mobility is examined. Existing data on the incipient motion of bed material is described, and a different approach to mobility and channel scour is employed which looks at the change to yearly cross-sections at the Fair Oaks stream gauging station. Finally, the depth of gravel on the LAR is investigated using seismic refraction.

1.2 Definition of a gravel budget

A gravel budget differs from a sediment budget only by the constraint on sediment size. Following the Unified Soil Classification (USC) system, gravel is defined as sediment with a diameter between 4.75 and 75mm, cobbles between 75 and 300mm, and boulders greater than 300mm. Bed material in the LAR is not always well sorted and often ranges from fine silts and clays to boulders. The median grain diameter (D_{50}) is important, and Chinook Salmon tend to select gravel with a D_{50} between 7mm and 100mm (Platts et al. 1979; Reiser and Bjornn 1979; Kondolf 1988). Some locations on the LAR contain excess coarse material (armored beds that can't be excavated by salmonids) or excess fine material (which inhibits delivery of oxygen to embryos) despite the fact that the majority of the material would otherwise be suitable for spawning (Vyverberg et al. 1994; Horner 2005). Because of this variability in bedload and grain size, it is important to distinguish between primarily coarse (gravel, cobbles, and boulders) and primarily fine (sands, silts, and clays) bed material. This distinction is made easier by the fact that rivers with D_{50} values between 1mm and 10mm are rare (Parker 1980). Therefore, gravel in this study is considered any material with a median diameter (D_{50}) greater than 7mm.

Reid and Dunne (1996) give detailed descriptions of how to quantify sediment production and transport for traditional sediment budgets. Limiting the budget to gravel eliminates the need to evaluate many of these processes because gravel can only be transported as bedload. Gravel input is therefore limited to areas near the channel and transport conditions above a certain threshold (usually only exceeded during rare, large flow events). In addition, there are no tributaries that are capable of transporting gravel into the LAR, further limiting potential locations of gravel supply.

Figure 1-1 is a conceptual diagram showing the relationship between gravel inputs, outputs, and storage within a stream. The volume of storage will change over time if there is a difference between inputs and outputs. Therefore, the change in storage (ΔS) over a time period (Δt) is calculated by the formula $\Delta S/\Delta t$ = gravel input – gravel output, where gravel input and output are the volumes of gravel transported into and out of the reach for the specified time period. The two components that are the most practical and important to measure for this study are gravel inputs and ΔS, and therefore the budget will be completed by measuring these two components and calculating gravel output by the difference (gravel output = ΔS/Δt – gravel input). Gravel output is difficult to measure, and will not be addressed directly in this study.

Total gravel storage volume could be estimated with accurate information about the depth to bedrock throughout the LAR. However, seismic refraction was used to measure gravel thickness at four localities on the LAR, and the bedrock surface appears to be quite inconsistent, making an accurate determination of gravel storage volume difficult to make. As a result this study does not attempt to measure gravel storage directly, but uses stream cross-sections and profiles to estimate the change in storage (ΔS).

1.3 Background

1.3.1 Hydraulic mining sediment in the Sierra Nevada

Gilbert (1917) produced the first comprehensive study of mining debris in the Sierra Nevada. By measuring the volume of sediment missing from mining sites, he estimated that 1,189 million cubic meters (1,555 million cubic yards) of sediment were produced by mining throughout California. Of this, 196 million m^3 (257 million yd^3) were produced in the American River Basin.

Gilbert predicted that some material would be deposited in overbank areas and permanently stored, but much of the debris was contained within the channel. He documented 3m (10ft) of channel aggradation in the Sacramento River at Sacramento, but predicted a return to pre-mining levels with time (Figure 1-2). His model described a sediment wave moving through the river system, growing longer and flatter as it progressed. He observed that the apex of the wave appeared to have passed the mouth of the American River by about 1896 (Figure 1-2). Therefore, return to pre-mining bed elevations would be expected by the mid-twentieth century as this symmetrical wave of sediment passed (Figure 1-3). This timeframe was based on observations in the lowlands and was probably limited to fine sediment. Coarse sediment had a different fate.

The sediment produced as mining debris was segregated, with the fine clay, silt, and sand quickly transported to the lowlands and bay by streamflow. Coarse sediment lagged behind and was only transported by large flows. Gilbert observed that many of the mining dumps lie directly on hillsides and "…are washed only by rain, and no important fraction of it [is] removed." (Gilbert 1917, p. 27) The coarse sediment that is accessible to streams for transport is only moved by large flows and is deposited either in upland creeks and valleys or at the foot of the mountains where the gradient decreases and the river releases onto its alluvial plain. Gilbert calls these piedmont deposits. When this coarse sediment was deposited, Gilbert observed the tendency of the river to incise into the coarser material producing terraces. He postulated that when these terraces were formed and the bed of the main channel returned to pre-mining elevation, the terraces would be permanently emplaced and cease to be mobilized.

More recent work by James (1993) has shown that current sediment loads are still greater than pre-mining levels. Rivers have continued to rework the terrace deposits through the twentieth century. James documented erosion of several meters of mining sediment on the Bear River during the large flood event of 1986, an event that not only increased coarse sediment loads, but delivered and deposited fine sediment to the bypass system in the valley (Springborn et al. 2005). This sustained reworking of mining sediment caused James to postulate that Gilbert's sediment wave model should not be symmetrical but right-skewed with respect to time.

1.3.2 Downstream effects of dams

Dams have a variety of downstream effects on rivers. These effects can be physical (e.g. water temperature and changes in discharge and sediment supply), chemical (e.g. nutrient abundances and contaminants), and biological (e.g. changes to in-stream and riparian habitat). All three of these effects interact with one another and should not be studied in isolation. With that said, this study will focus on the physical responses of the downstream channel, with emphasis on sediment transport and geomorphology.

The geomorphic response of rivers downstream of dams can vary widely. Channels can degrade or aggrade, widen or narrow, coarsen or fine, become more braided or more meandering, and may change their response over the time and space of adjustment. This precludes sweeping generalizations of how rivers respond, and perhaps the only generalization that can be made is that changes will be varied (Phillips 2003). The thrust of this section will be to point out some of the important factors to stream adjustment and describe some "typical" adjustment scenarios with particular emphasis on gravel bed rivers that are similar to the LAR.

Causes

How do dams cause changes in sediment regimes downstream? The answer to this question is refreshingly simple: they change flow and trap sediment. The ways in which streams respond downstream depend to a large extent on the nature of these two changes.

Flow

For the most part, dams reduce high flows and increase low flows. They also change the timing of flows throughout the day or year. Specifics of changes to flow regime depend on the size and purpose of the dam. Flood control, water storage, hydropower, sediment control, and recreation are just some of the reasons dams are built. Most, however, have multiple purposes, and this precludes all but the broadest generalizations about the changes to flow.

Sediment

Dams trap sediment. With very few exceptions this statement is true, especially with large dams that commonly have trapping efficiencies greater than 99% (Williams and Wolman 1984). Brune (1953) developed a model for trapping efficiency based on the ratio of reservoir capacity to mean annual inflow or C/I (Figure 1-4) (Grant 2003; USACE 1989). Dams that have a capacity equal or greater than the mean annual inflow will trap virtually all sediment. Only extremely small dams ($C/I < 0.004$) have efficiencies that approach zero, and at low efficiencies small dams that have not filled with sediment are likely to preferentially trap coarse sediment (fine sediment takes more time to drop from suspension) producing an impact on downstream sediment distribution.

River bed type

River bed type is one of the key variables that will determine geomorphic response. Bedrock, gravel-bed, and sand-bed rivers behave very differently and therefore will respond very differently when disturbed. Distinguishing among these types is straight forward. Bedrock rivers are easily recognized, and very little overlap exists between gravel and sand-bed rivers because beds with median grain sizes of 1-10mm are rare (Parker 1980).

Bedrock rivers typically occur in low-order mountain watersheds and may have limited sediment supply. Very coarse sediment due to mass wasting events may constitute significant proportions of sediment input. These large boulders are typically only moved by extremely large events. The degree to which a dam limits these large flows will determine how well these large boulders are moved through the channel. Graf (1980) found that dam construction results in an increase in the number and severity of downstream rapids due to reduced large flows and unchanged inputs of large boulders from tributaries. Whether this idea can be extrapolated to all bedrock streams is doubtful, but the idea of dams limiting "flushing flows" is important. Regardless, bedrock streams have unique characteristics and will probably not have responses typical of alluvial streams such as scour and bank erosion immediately downstream of the dam.

Phillips (2003) studied the Sabine River, a sand-bed river on the Texas-Louisiana border. Despite the fact that Toledo Bend Reservoir impounds 74% of the basin, he found little downstream impact except immediately downstream of the dam. He contends that rivers that are transport-limited before impoundment may have limited impact due to sediment trapping effects of dam construction. It would be logical that changes to flow regimes would dictate effects of these types of streams. The fact that impacts due to dam construction on the Sabine River are limited illustrates an important distinction of sand-bed rivers. Normal transport conditions can be maintained even after dam construction because sand-bed rivers transport bedload sediment over a wide range of discharges (Grant 2003) and are therefore mobile most of the time (Parker 1980).

Gravel-bed rivers only transport bedload sediment above a threshold flow (Grant 2003). Because many dams suppress the large magnitude (i.e. above threshold) events, gravel-bed systems respond quite differently to impoundment. Even unaltered gravel-bed systems develop a "pavement" layer with median grain sizes 2-3 times larger than the sediment below (Parker 1980). The size of the pavement grains dictates the threshold flow needed for bed movement. However, these grains are naturally moved on a "statistically regular basis" (Parker 1980). With suppressed large flows and gravel supply limited from upstream, the pavement can gradually coarsen to an armor and essentially become immobile (Galay 1983). The development of armor depends on the supply of gravel available from tributaries and bank erosion to replenish gravel transported downstream and the abundance of grains too large to be moved by the post-dam flow regime (Parker, 1980).

Immediately downstream of the dam

Degradation (lowering of bed elevation) virtually always occurs directly downstream from large dams, unless constrained by coarse sediment or bedrock (Williams and Wolman, 1984). Williams and Wolman (1984) were able to show how degradation progressed over time by using repeated cross-sections from gauge stations below 114 dams. Despite the fact that the modal time to reach 95% of maximum degradation is slightly more than 100 years (although many reach it in 10-100 years), the modal time for half of the degradation to occur is 7 years, with many reaching this milestone in 0.6-3 years. Stated differently, 75% of the adjustment happens in the first 13% of the adjustment period. The bottom line is that rivers degrade quickly immediately below the dam, until they are constrained by bedrock, armoring, or reduced gradient (Williams and Wolman, 1984).

How the degraded zone changes spatially is much more complex than the temporal (at-a-site) relationships discussed above. The propagation of the degraded zone downstream varies among rivers. Rivers can degrade for long distances (the Colorado River has degraded over 120 km below Hoover Dam) and the zone of degradation can continue to lengthen for 30 years or more. In most of the cases studied by Williams and Wolman (1984), there was no evidence that the zone of degradation had stopped lengthening. The ultimate length of the degraded zone will depend on flow, bed material, and topography. Probably the most important factors limiting this, however, are the sources of sediment downstream of the dam.

Tributaries

Tributary inputs of sediment can act to buffer the sediment-starved main channel. These inputs are often coarser than the main channel if the tributaries are lower order or have a steeper gradient (Galay 1983). The main channel will get progressively finer downstream from the confluence (Galay 1983). Degradation may still occur after the river is supplied with tributary sediment, but there is usually no coarsening or formation of an armor (Parker 1980).

Aggradation or degradation

Despite the common notion of dams ubiquitously causing downstream erosion, aggradation is at least as common as degradation as you progress downstream (Grant 2003). Predicting which will occur is a complex issue which depends on factors such as sediment loads, sediment size, discharge, and channel slope. Lane (1955) came up with a simple model that does a great deal to help us understand how disturbing these aspects of the river system may interact (Figure 1-5). He showed that sediment load times sediment size is proportional to discharge times slope (Grant 2003). Brandt (2003) describes it more simply, stating that degradation will occur when sediment load is less than transport capacity and aggradation when sediment load exceeds transport capacity. This shows that despite the logical notion that reduced sediment loads cause erosion, decreased transport capacities act as a counterbalance, making aggradation as common as erosion.

Bank erosion and channel width

Williams and Wolman (1984) looked at 231 cross-sections below dams and found few generalizations about bank erosion (channel widening). 22% kept a constant width, 46% widened, 26% narrowed, 5% widened initially then narrowed, and 2% narrowed then widened. Clearly there are a variety of channel responses that probably depend on the stability of the bank and channel material as well as the nature of flow regulation. Collier et al. (1996) observed that bank erosion may have a delayed response after dam closure, suggesting that the river must degrade its bed before significant bank erosion can begin. Xu (1990) goes further to postulate a three-stage response: 1. clear-water scour resulting in reduced gradient and width/depth ratio, 2. slowed gradient decrease and increased width/depth ratios, and 3. establishment of new equilibrium.

Channel narrowing likely results from reduced discharges, confining the effective flows to a smaller portion of the channel. Vegetation plays a significant role here. Riparian flora stabilizes sediment as it becomes established on abandoned portions of the channel. Without large flows regularly wiping out this vegetation, the sediment is rendered immobile (Williams and Wolman 1984). This phenomenon likely occurs on bars and other exposed bedforms as well.

Planform changes

Braiding increases as coarse sediment load, discharge, and slope increase (Brandt 2003). Because all three of these factors typically decrease on impounded rivers, the tendency is for braiding to decrease after dam construction. On meandering, sand-bed rivers, decreased sediment loads from upstream may result in more bank erosion and an increased tendency to meander.

1.4 Study area and geologic/hydrologic setting

The American River Watershed (Figure 1-6) has an area of over 5000 square kilometers (about 2000 square miles) and is located on the western slope of the Sierra Nevada mountains east of Sacramento. The elevation of the watershed ranges from 3000m (10,000ft) peaks at the crest of the Sierra near Lake Tahoe to near sea level at the confluence with the Sacramento River. The lowest reaches of the river even experience some tidal influence (Dillinger et al. 1991).

The climate is Mediterranean with hot, dry summers and cool, wet winters. Precipitation varies greatly spatially and temporally. Average rainfall ranges from 46cm/yr (18in/yr) in Sacramento to 178cm/yr (70in/yr) on the slopes of the upper basin (NRC 1995). Yearly peak flows at Fair Oaks have ranged from 9,900 to 180,000cfs before construction of Folsom Dam and 1,920 to 134,000cfs after dam completion (Figure 1-7). The dam has greatly reduced peak flows in years with moderate to low peak flows, but has only reduced peak flows to a small degree in years with large peak flows (Figure 1-8). Folsom Dam is operated for both flood control and water supply, but it "…has a low volume-to-runoff ratio, and given its current design and operations it is incapable of storing and then releasing the bulk of a major flood on the river (NRC 1995, p. 15)." Minimum yearly flows have been greatly altered by dam operations (Figure 1-9). Average flows in August through October have increased from 350 to 2300cfs.

The watershed above Folsom Dam has three major forks that primarily consist of bedrock-dominated channels in steep-walled canyons. Fourteen percent of the upper basin (above Folsom) is controlled by five reservoirs. Below Folsom, the terrain is much gentler as the river releases onto an alluvial plain. The most striking topography of the LAR is the tall (up to 50m) bluff of Miocene-Pliocene sandstone and siltstones on the north side of the river (Shlemon 1967). The terrain on the south side of the river is gently terraced with more recent (Plio-Pleistocene to modern) alluvium. The bed of the LAR is dominated by coarse-grained material (gravel), but gets progressively finer (sands and silts) as it approaches the confluence with the Sacramento River (Vyverberg et al. 1997).

The 37 kilometers (23 miles) of the LAR below Nimbus Dam is divided into four reaches (Figure 1-6). Reach 1 is the 8.9km (5.5mi) from the confluence with the Sacramento River to Paradise Beach. The river is low gradient in this reach with depth and velocities controlled more by the stage of the Sacramento River than by discharge upstream (Snider et al. 1992). There is some tidal influence in this reach. The river is leveed on both sides and the bed material is primarily sand.

Reach 2 is 13.2km (8.2mi) long and extends from Paradise Beach to the Jedediah Smith bike bridge near Goethe Park at river kilometer 22.0 (mile 13.7). The gradient is also low in this reach except for the two kilometers near Goethe Park where the reach extends into the high-gradient knickpoint that divides reach 2 from reach 3. Reach 2 has a mostly sand bed with frequent gravel bars, especially in the upstream portions. The banks have levees, but many are set back from the channel (Figure 1-10).

Reach 3 is 6.9km (4.3mi) long and covers the area from Goethe Park to San Juan Rapid at river kilometer 29.0 (mile 18.0). The gradient in this reach is higher and the bed is primarily gravel with some sand beds in areas of slack water. There are few formal levees in this reach, but many of the banks are reinforced with riprap or other erosion control measures.

Reach 4 includes the 8.2km (5.1mi) from San Juan Rapid to Nimbus Dam at river km 37.2 (river mile 23.1). This reach has the highest gradient, coarsest bed material, no sand bars, and few bank stabilization features. It also supports most of the spawning on the LAR (Hannon and Deason 2005). Some spawning also occurs in reach 3, so for the purposes of this study, most analysis included reaches 3 and 4 only.

1.5 Human history

Another mining practice that had significant impact on the LAR was the use of gold dredges near and within the channel of the LAR (Figure 1-12). This practice started in 1899 and continued until the 1960s, with most operations stopping during World War II and never restarting. Although this mining practice generally did not result in a net extraction or introduction of sediment to the LAR, it did disturb the channel a great deal and the tailings piles are still easily visible in aerial photographs.

The first diversion dam was built on the American River in 1852 and many other small structures have been built over the years. The predecessor to the modern Folsom Dam was completed in 1891, was 30m (98ft) high, 119m (389ft) wide, and had sluice gates for passage of debris (CSMB 1890). Modern Folsom Dam was built between 1948 and 1956 (closed in 1955), is 104m (340ft) high, 427m (1400ft) wide, and has a reservoir capacity of nearly 1,000,000 acre-feet. In conjunction with Folsom Dam, Nimbus Dam (Figure 1-13) was built 11km (7mi) downstream in order to diminish the daily fluctuations in flow required for hydropower generation at Folsom. These two dams have eliminated sediment supply from the upper watershed to the LAR.

To mitigate the reduction of available spawning habitat caused by the construction of Nimbus and Folsom Dams, the Nimbus Fish Hatchery (Figure 1-13) was built in the years following dam completion. As part of its structure, there is a removable screen that is used to divert fish into the hatchery during spawning season. This structure is frequently damaged by large flow events, and has often been reinforced with boulders at the site, although the volume of sediment added is likely not a significant source to the LAR (Figure 1-14).

1.6 Figures and Tables

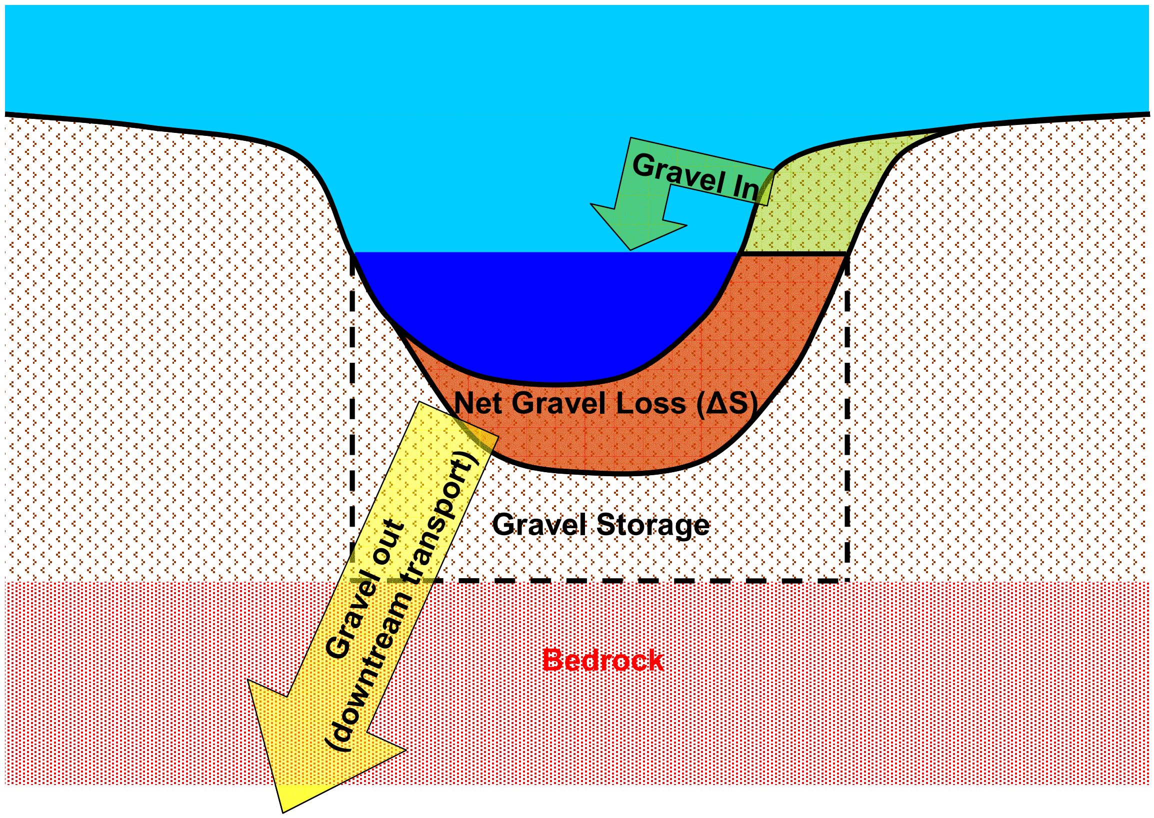


Figure 1-1 Conceptual diagram of gravel budget components.

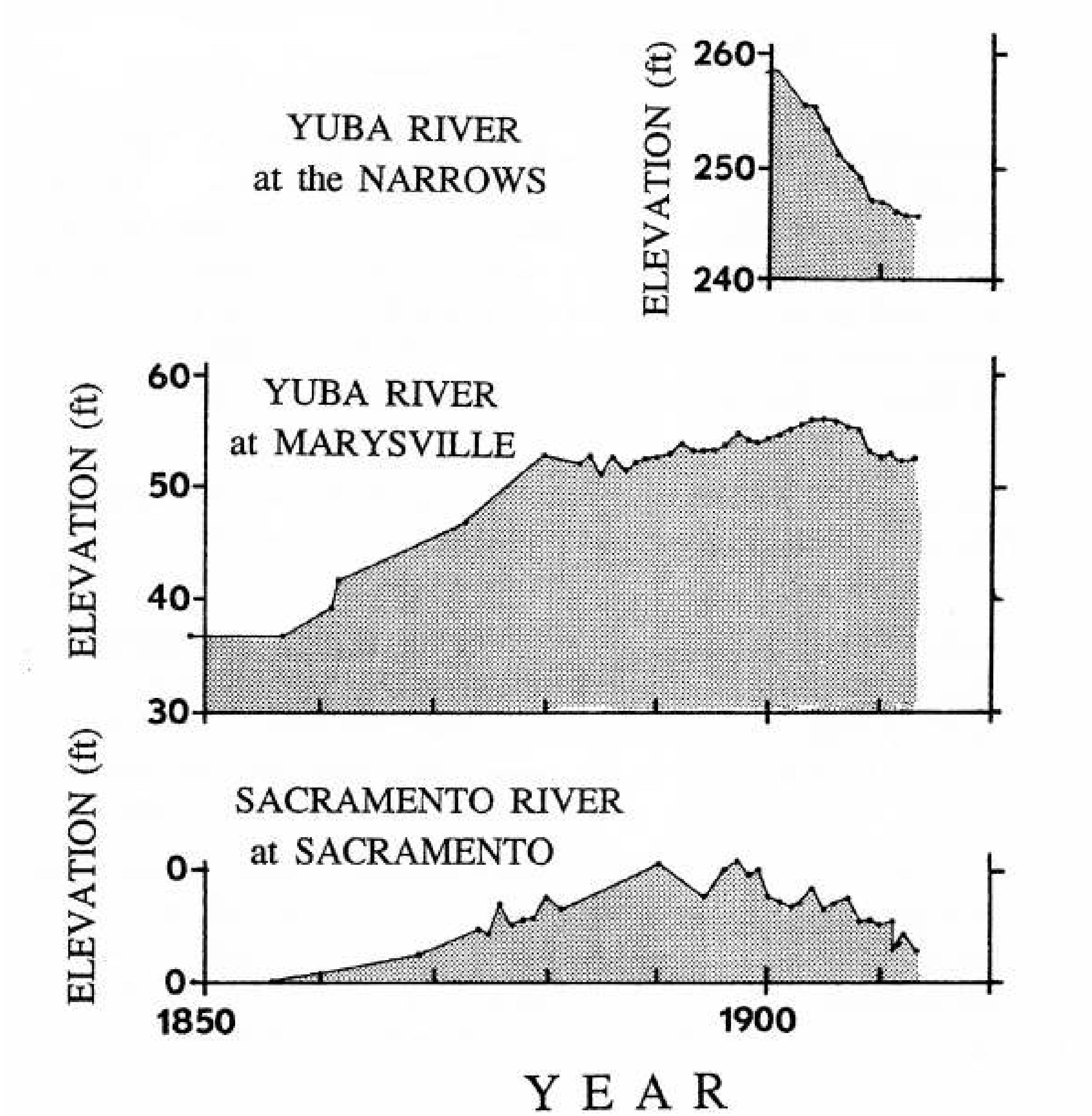


Figure 1-2 Low water elevations documenting channel aggradation and used as the basis for Gilbert's (1917) sediment wave model. (from James 1993)

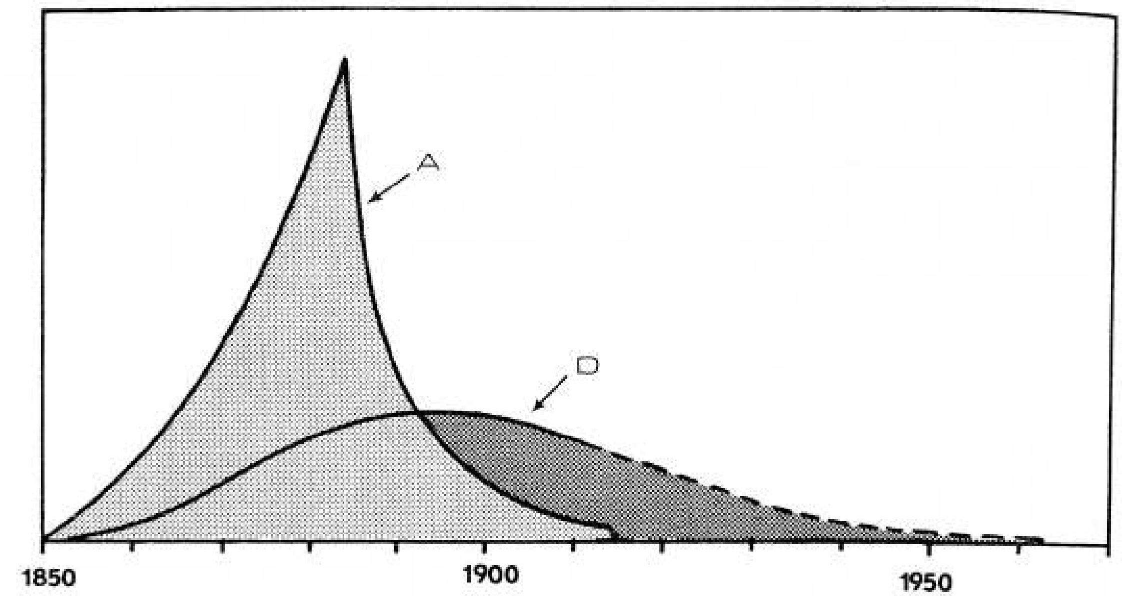


Figure 1-3 Gilbert's (1917) model predicting the return of channels to pre-mining elevations. (A) represents sediment production and (D) represents sediment delivery (from James 1993).

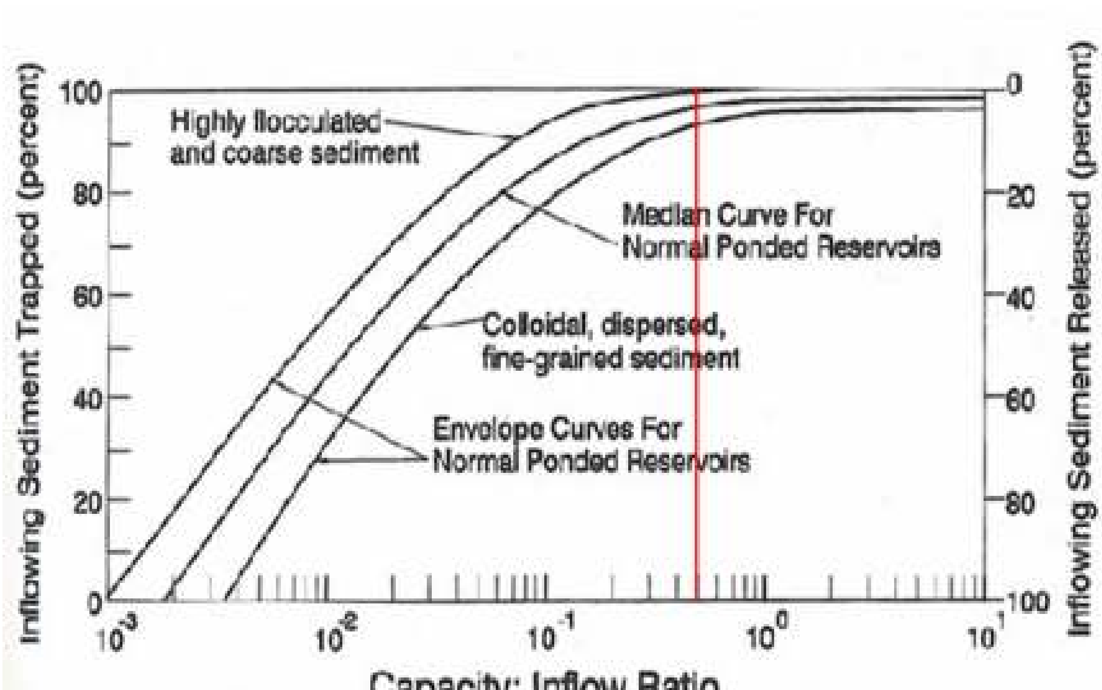


Figure 1-4 Sediment trapping curve developed by Brune (1953) based on dam storage capacity to inflow ratio (C/I). Vertical line is the C/I ratio for Folsom Dam.

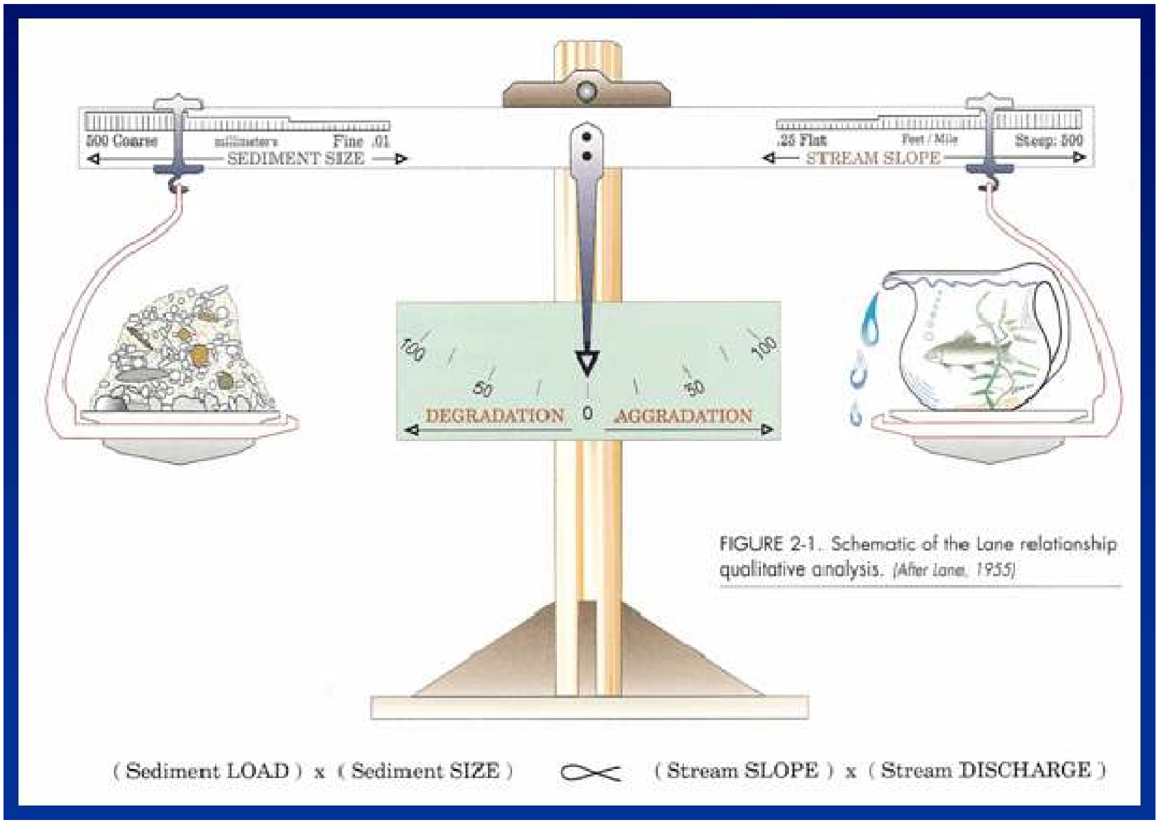


Figure 1-5 The Lane (1955) model helps predict when aggradation and when degradation will occur. (from Grant 2003)

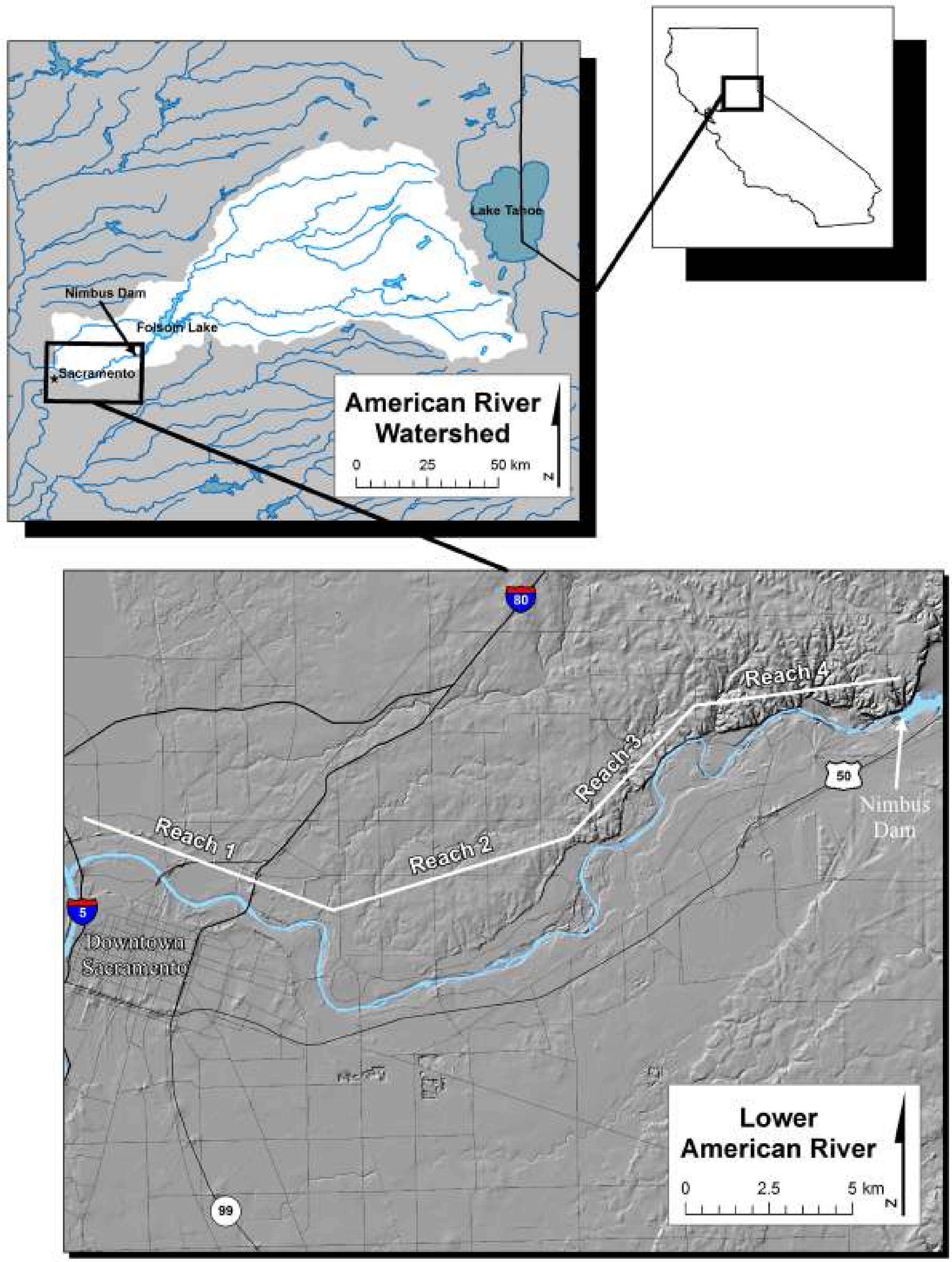


Figure 1-6 Location map of the LAR.

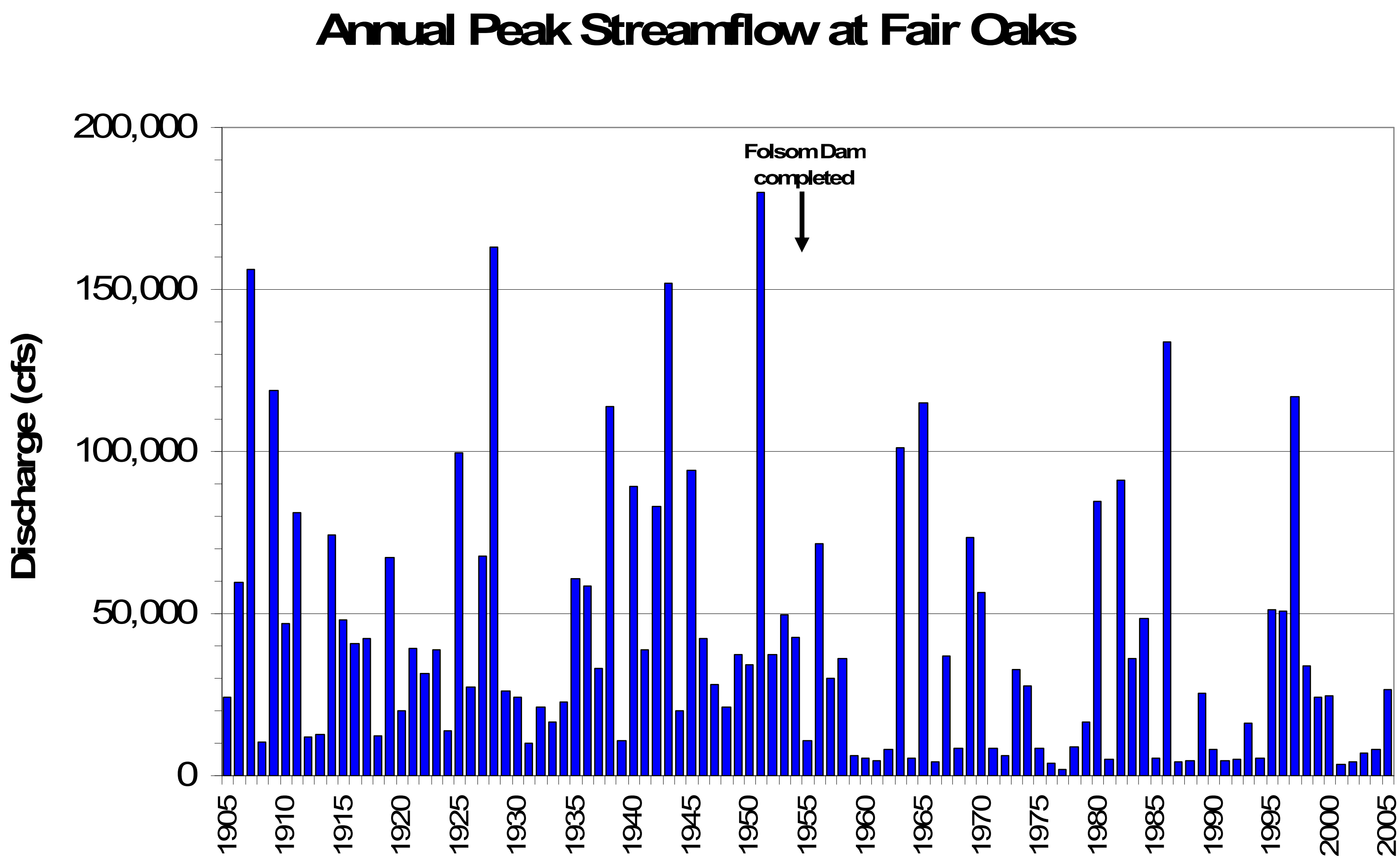


Figure 1-7 Hydrograph of yearly peak flows on the LAR (data obtained from the California Data Exchange Center (CDEC)).

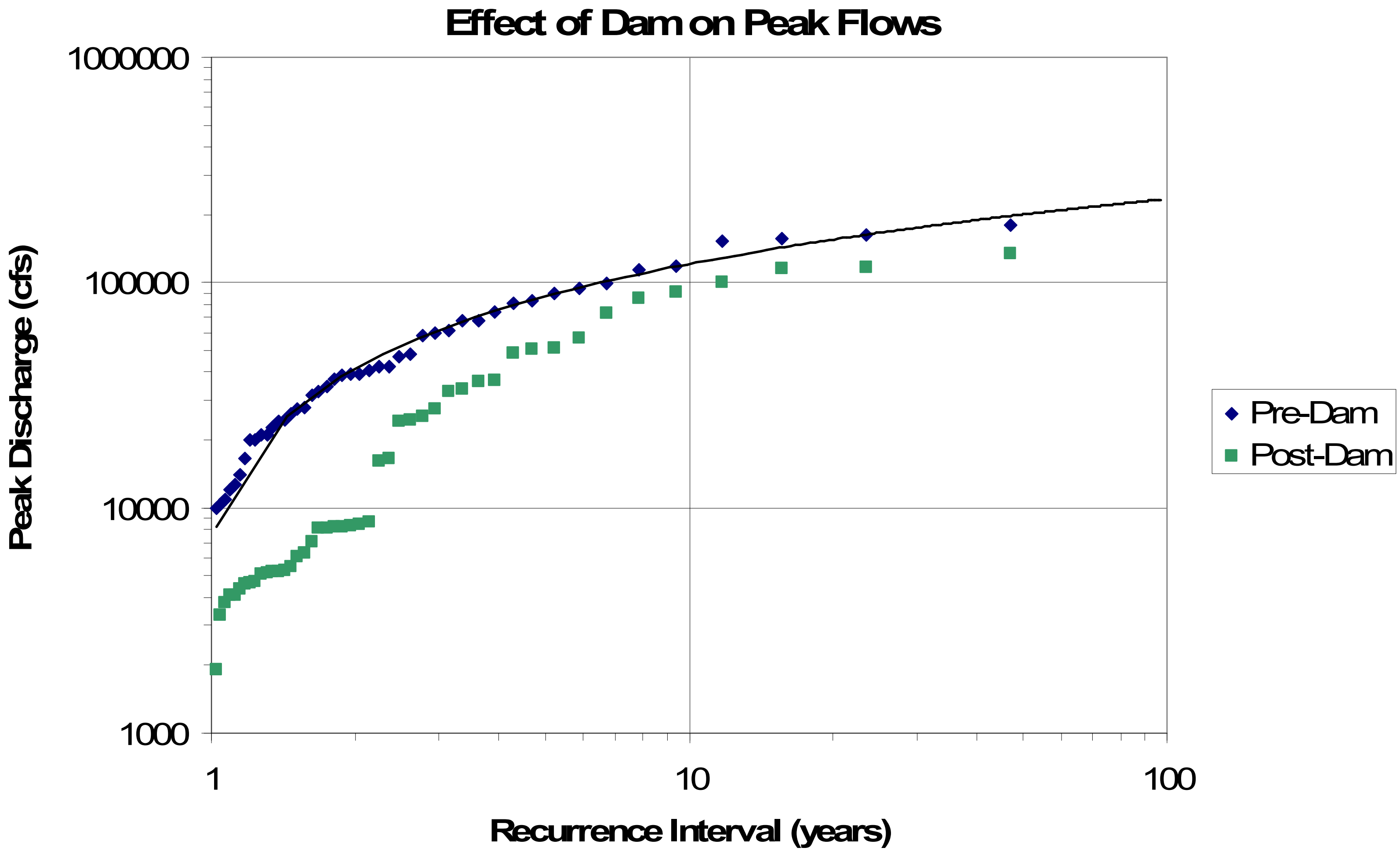


Figure 1-8 Effect of Folsom Dam on peak flows. Events with recurrence intervals (RI) greater than 8 years have been affected less than those with RI less than 8 years (data obtained from CDEC).

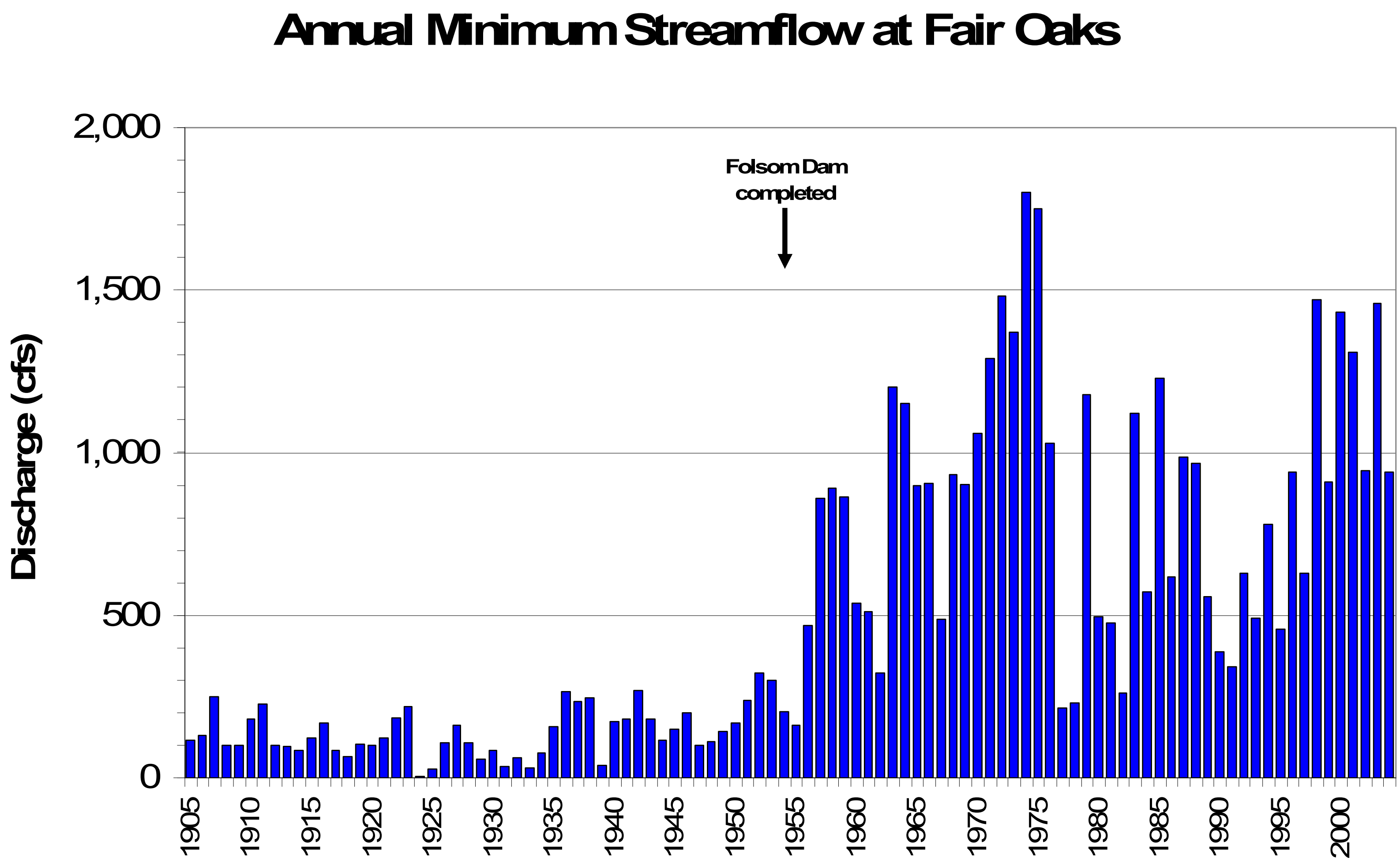


Figure 1-9 Hydrograph of minimum streamflows on the LAR

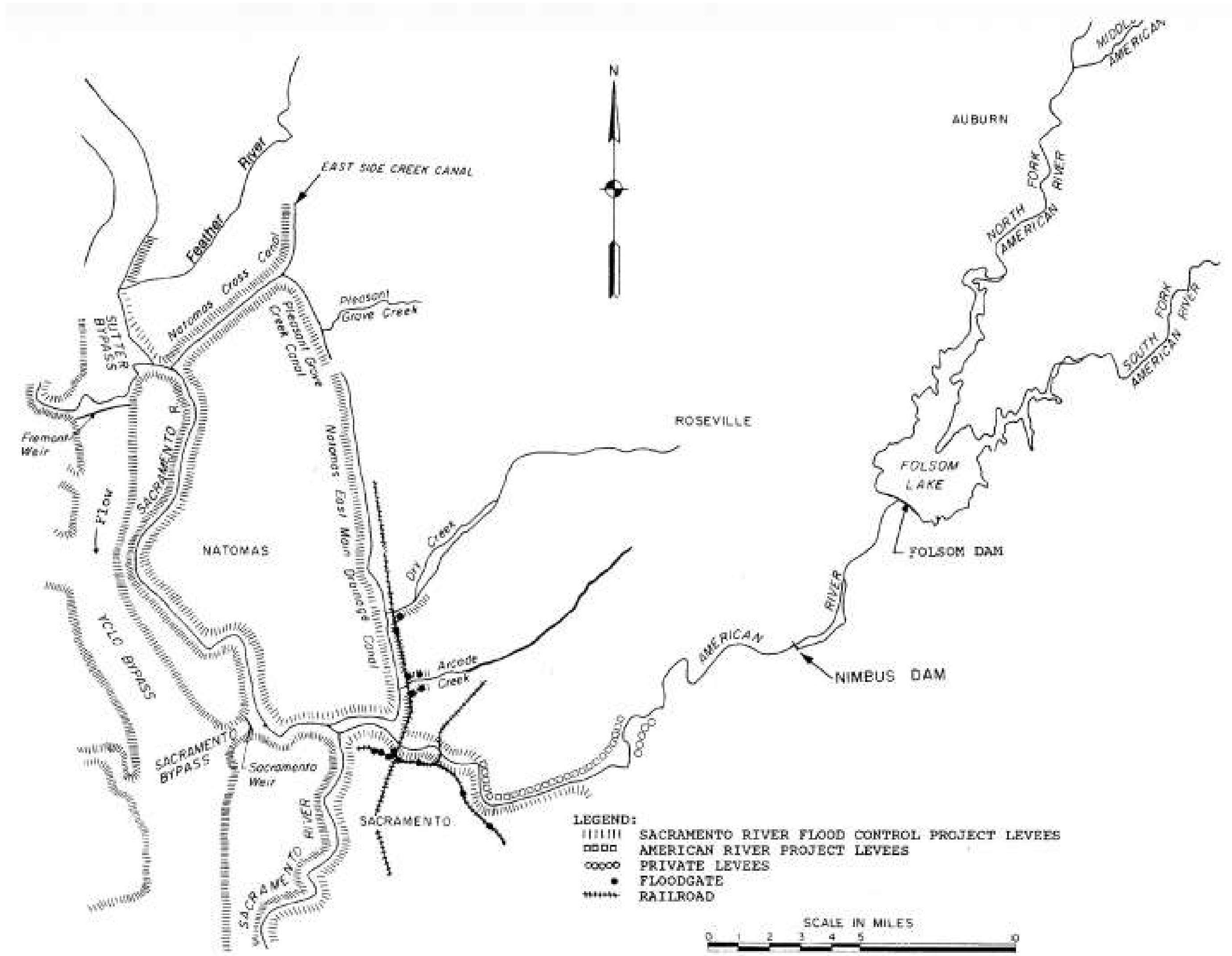


Figure 1-10 Map of levees on the Lower American River (USACE 1991, duplicated from NRC 1995)

Figure 1-11 Hydraulic mining in the Sierra Nevada (Photo: Central Pacific Railroad Photographic History Museum)

Figure 1-12 Aerial photo (1949) of the LAR near the current location of Nimbus Dam showing dredge tailings in and around the channel (Photo courtesy Bureau of Reclamation)

Figure 1-13 Oblique aerial photo of Nimbus Dam and Fish Hatchery (photo: J.C. Dahilig, Bureau of Reclamation, 10/4/1976)

Figure 1-14 Repair of the fish diversion structure at Nimbus Fish Hatchery (photo: D.M. Westphal, Bureau of Reclamation, 8/3/1982)

Chapter 2: Geomorphic trends on the Lower American River

2.1 Introduction

Rivers can display a variety of responses to perturbations. They can degrade or aggrade, widen or narrow, become coarser or finer, meander or straighten, and braid. The response can also change over the time and space of adjustment. The nature of these changes on various rivers was described in detail in Chapter 1, but here the geomorphic trends of the Lower American River (LAR) will be examined in particular.

aerlal phots, maps, and crossrsectlonal data

Table 2-1 shows the maps and photos that were collected for this project, with the oldest being the Rancho Survey from 1865. Maps were also available from 1900, 1906, and 1962, and sets of aerial photographs were available starting in 1937 through the present with about 1 set per decade. In addition to this historical data, current conditions were observed and mapped in the summer of 2006 to produce a map indicating the distribution of bedrock outcrops. This chapter will look at these data qualitatively to determine the nature of channel changes on different scales: from the entire LAR to individual barforms. Then, the current distribution of bedrock outcrops will be examined in light of the geomorphology of the LAR.

2.2 Methods

Each of the scanned images (map or aerial photo) was georeferenced using ArcGIS software. The 2002 images were previously georeferenced and were used as the basis for referencing all other images by linking control points (such as building corners and road intersections) in the older images to the same points on the 2002 photos. Polynomial transformations were then performed. More control points were possible with recent images; therefore, for images after 1950, second-order polynomial transformations (which required at least six control points) were performed. First-order transformations were performed on images older than 1950, which required only three control points. Experience with the images has shown that georeferencing in more recent images is accurate to within about 10 meters, with slightly less accuracy for older photos.

The geometry of the channel was digitized using the georeferenced images. This was done in two ways. For analysis on the scale of the entire LAR, the path of the river in each photo was digitized by approximating the middle of the visible channel with a line feature, while for more detailed analysis (e.g. shorelines and barforms), polygon features were used to locate the edge of the water, which allowed the centroid of features (such as gravel bars) to be located. Changes in channel geometry were then observed on various scales using the georeferenced images and digitized channel geometries. For changes on the scale of the entire LAR, three sets of images were used: 1865, 1900, and 2002. The oldest (1865) and newest (2002) data sets were used in order to analyze changes on the longest time-scale possible (Figures 2-1 and 2-2). The 1900 data set was also used because the 1865 set only covers reaches 3 and 4, and the 1900 set covers the entire LAR (Figure 2-2). Changes on the scale of a few kilometers only occurred at Goethe Park, and therefore the channels from data sets were plotted at this location to observe general trends over time (Figure 2-3). For changes on the scale of less than a kilometer (e.g. barforms), the actual images were used with the digitized shorelines overlain to see small changes to shorelines and downstream movement of gravel bars (Figure 2-4).

A map of the LAR showing exposed units was produced based on aerial photos and field observations in the summer of 2006 (Figures 2-5 through 2-8). Three geologic units were defined. The oldest unit (Ancient fluvial deposits) consists jointly of the miocene-pliocene deposits of the Mehrten, Fair Oaks, Laguna, Modesto, and Riverbank Formations (Shlemon 1967). This unit consists of poorly consolidated siltstone and sandstone, with some conglomerate. The Ancient fluvial deposits within the active channel were mapped by snorkel and GPS. The two more recent units (Plio-pleistocene and Modern river deposits) are the unconsolidated alluvium (sands and gravels) that overlie the Ancient fluvial deposits. The mining debris produced higher in the watershed in the late 19th century is contained within these units. Modern river deposits are differentiated from the Plio-pleistocene deposits by the age of mobilization. Modern river deposits are within the active channel of the LAR and include reworked mining debris and naturally formed features that are currently accessible and mobile during high flow events. Plio-pleistocene deposits are outside of the active channel and represent older, pre-historic positions of the channel and related channel fluvial deposits. Much of the alluvium near the LAR has been reworked by dredge mining operations over the last 120 years. Many of the spoils of these operations are visible outside of the active channel, but these deposits were not differentiated in this study.

2.3 Results

The oldest accurate record of the shape of the LAR is from the 1865 Rancho Survey (Figure 2-1). Although the map only shows reaches 3 and 4 (from Goethe Park to the current location of Nimbus Dam), the channel shows few places where significant changes have occurred (Figure 2-2). There is some difference between the 1865 channel and the 1900 and 2002 channels near the current location of Nimbus Dam, but the most significant changes occurred in the area near Goethe Park. This location will be examined below in more detail.

The second oldest available record of channel shape was a turn of the century topographic map produced by the USGS, obtained in digital form courtesy of the

California Geological Survey. This map covers the entire LAR from the confluence with the Sacramento River to the current location of Nimbus Dam. The channel digitized from this map (Figure 2-2) reinforces the conclusion that there have been few major channel changes over the last 100 years. It indicates that the changes near Nimbus Dam happened between 1865 and 1900 and that changes near Goethe Park occurred in the 20th century. Few changes have occurred in reaches 1 and 2 since 1900.

According to historic accounts (Dillinger et al. 1991), more significant changes may have occurred in reaches 1 and 2 (from the Sacramento River confluence to Goethe Park) prior to 1900. During the late 19th century the channel was straightened in reach 1 and the outlet to the Sacramento River was moved upstream and away from downtown Sacramento (Dillinger et al. 1991). The fact that few changes have occurred in these lower reaches since 1900 may be due to the reinforcement of the leveed banks. Most of the channel in reaches 1 and 2 contains this type of engineering, while only modest amounts of the channel in reaches 3 and 4 are engineered (mostly near bridges and other structures) (NRC 1995).

Near Goethe Park, the general trend is channel straightening and increased braiding. Two meanders in this area have moved inward (toward the midline of the active channel area) (Figure 2-3). The downstream meander has moved incrementally (Figure 2-3), but the upstream meander avulsed in a single event between 1964 and 1966 (Figure 2-4). Flow records from the Fair Oaks Gauge show a peak discharge of 115,000cfs in 1965, which ranks as the eighth highest yearly peak discharge in the 100 years of flow recorded. Barring human causation, this single event was likely to be responsible for the changes at this location. The river has also changed from a single channel to multiple channels in this location (Figure 2-9), although it is unclear to what degree human activities contributed to this change. The main influence is likely to be the steep gradient (knickpoint) and related instability of the channel at that location (Figure 2-10).

Figure 2-10 indicates that the channel bottom has degraded (lowered) throughout virtually the entire LAR. The longitudinal profiles show as much at 9m of degradation in reaches 1 and 2 and as much as 4m in reaches 3 and 4. This degradation has been coupled with channel widening. The length of the channel and surface area of the visible water in aerial photographs (1957 and 2002) were used to calculate average channel widths at moderately low flows (3300 and 2700cfs respectively).

summarizes these results and indicates an increase in width of between 12% and 15% over 45 years. This is a conservative estimate because flows were slightly lower in 2002. Although this study did not measure channel depth directly, it could be inferred the channel depth is generally shallower as a result of channel widening.

Figure 2-11 shows locations in reach 4 where gravel bars have moved significantly since 1957. The Upper Sunrise locality (Figures 2-12 and 2-13) lies at the end of a long, straight section of river where the channel turns to the left as it encroaches on the bluffs of the north bank. The bluff reduces stream velocity and forces gravel to be deposited in nearly, but not exactly, the same position over time. The geometry of the bar has changed over 45 years, but the general size and location is similar (Figures 2-12 and 2-13).

Other gravel bars such as at Sailor Bar (Figures 2-14 through 2-16) and Lower Sunrise (Figures 2-17 through 2-19) have shown downstream migration over time. At Sailor Bar, the 2002 photo shows an in-stream island bar in a location where there was no bar in the 1957 photo (Figures 2-14 and 2-15). The bar outlined in the 1957 photo shows the nearest potential source for the new island. A rate of movement was calculated using the area of the bar, the approximate bar thickness estimated from 1998 bathymetry (Figure 2-16), and the distance between the new island and the potential source.

$$V_b = Ah$$

$$R_g = \frac{V_b}{td}$$

where

V_b = Volume of bar
A = Average bar area
h = Average thickness of bar
t = Time between photographs
d = Distance between centroids
R_g = Rate of gravel movement (volume/unit time/unit distance)

This rate has units of volume/unit time/unit distance, so to get an approximation of the volumes of gravel movement over a stretch of river this rate was multiplied by 6.4km (the length of reach 4) and the time interval between the photos.

$$R_l = lR_g$$

$$V_t = tR_l$$

where

l = Length of reach
R_l = Rate of gravel loss in reach (volume/unit time)
V_t = Total volume lost from reach

These calculations were repeated using the bar movement at Lower Sunrise (Figures 2-17 through 2-19), and give a preliminary approximation of minimum gravel volume movements on the order of 210,000 to 470,000m^3 over the 6.4km of reach 4 from 1957 to 2002 and a time-averaged rate of 4,600 to 10,000m^3/yr (Table 2-3). It should be emphasized that these estimates are minimum volumes because the upstream gravel sources identified were the nearest potential sources, but gravel is also likely to have been transported from further upstream. Chapter 6 will present another, more detailed approach to determine gravel volume losses on the LAR.

2.4 Discussion

The LAR channel has incised, has widened, and (near Goethe Park) has straightened and become more braided. In addition, grain size distributions measured by Horner (2005) show coarsening (armoring) of the bed material below Nimbus Dam as far downstream as Sailor Bar. Gravel is mobile as documented by the downstream migration of bars.

These changes are easily observed on different scales using historic maps and aerial photos, but there are controls or limits to channel changes. The armoring of the bed material below Nimbus Dam may limit the vertical degradation of the channel in that location, and degradation will become limited on more of the channel as it continues to coarsen.

Bedrock outcrops are another factor that may limit both the vertical degradation and the planform geometry of the channel. Bedrock on the LAR consists of cohesive, poorly consolidated silts and sands (Shlemon 1967) and, compared to the unconsolidated sediments that make up the bulk of the channel, it is fairly resistant to erosion. Where exposed, it tends to limit geomorphic change. In this study, outcrops of bedrock were only mapped in reaches 3 and 4 (Figures 2-5 through 2-8), although bedrock is also present in the downstream reaches of the LAR.

The north side of the river has a bluff composed entirely of bedrock that ranges in height from less than a few meters to more than 50m (Figure 2-5). This bluff limits the rate of northward migration of the channel. Within and near the channel, most of the material is recent, unconsolidated gravels and sands. Bedrock is exposed on the outside of meander bends where stream velocities are high and erosional capacity is greatest. Therefore, bedrock controls the rate of meander development on the LAR. In addition, it is likely that bedrock limits the vertical degradation in locations such as San Juan Rapid (Figure 2-7) where extensive amounts of bedrock are visible on the channel bottom.

2.5 Figures and Tables

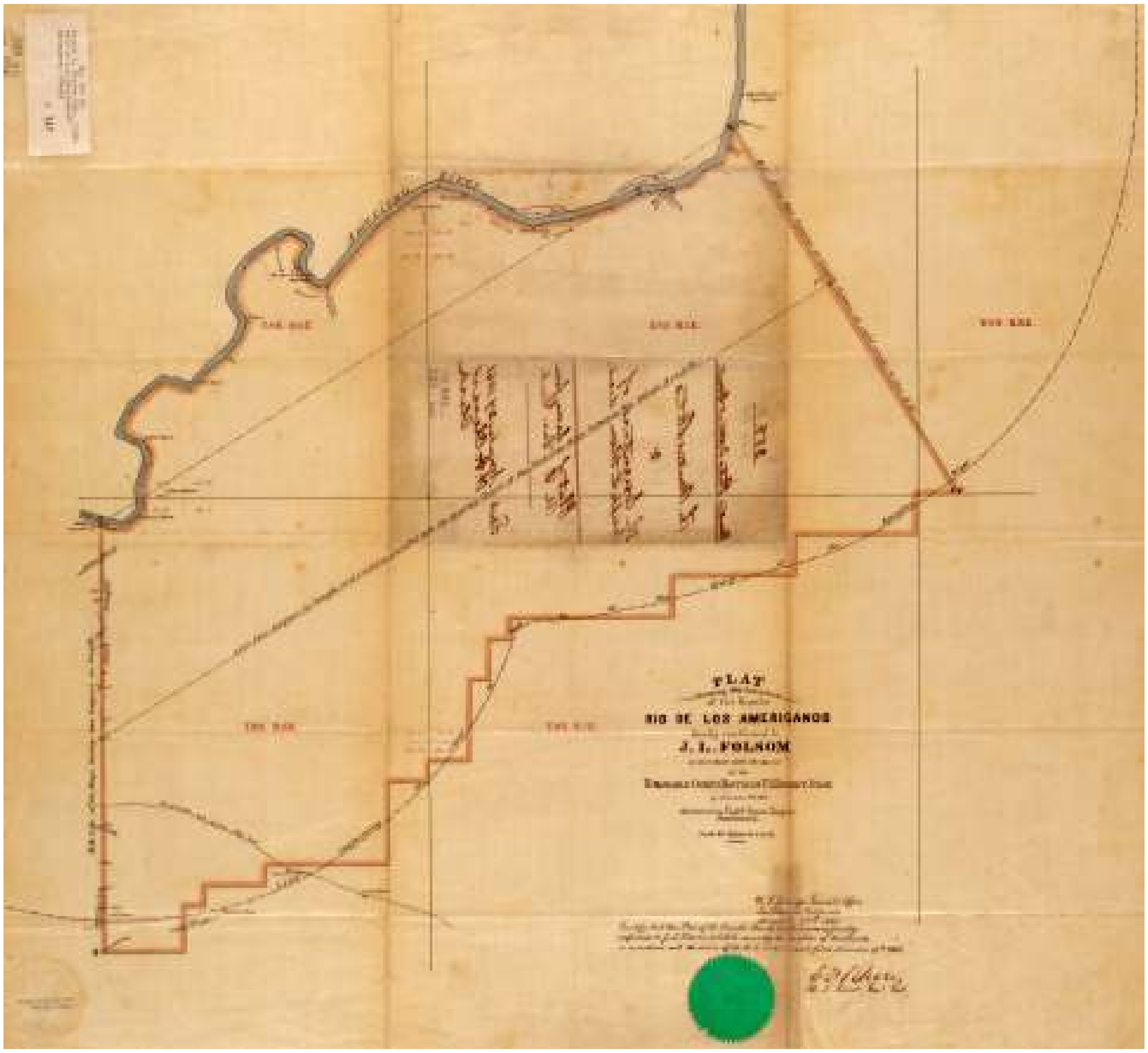


Figure 2-1 Rancho Survey from 1865 (courtesy Water Resources Center Archives, Berkeley, CA)

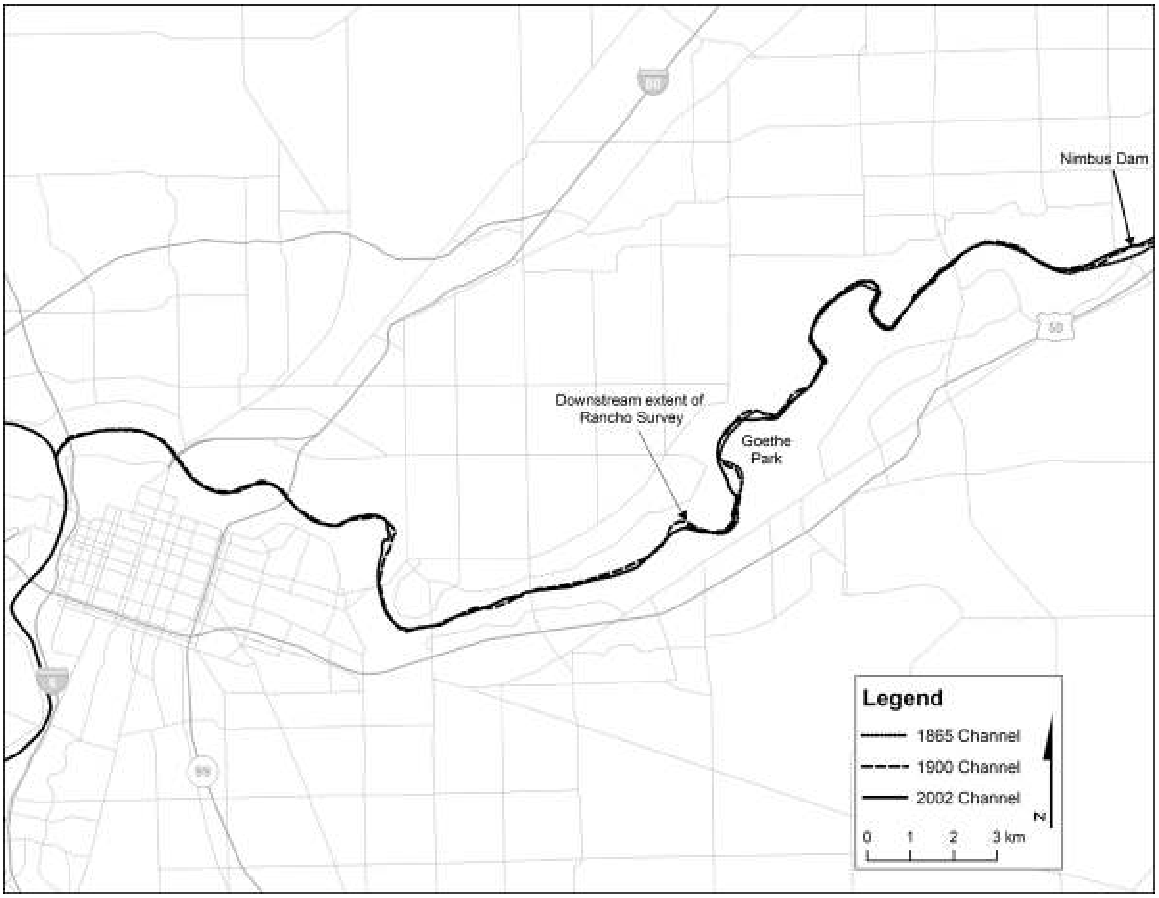


Figure 2-2 Map of the Lower American River showing the changes in planform from 1865 to 2002.

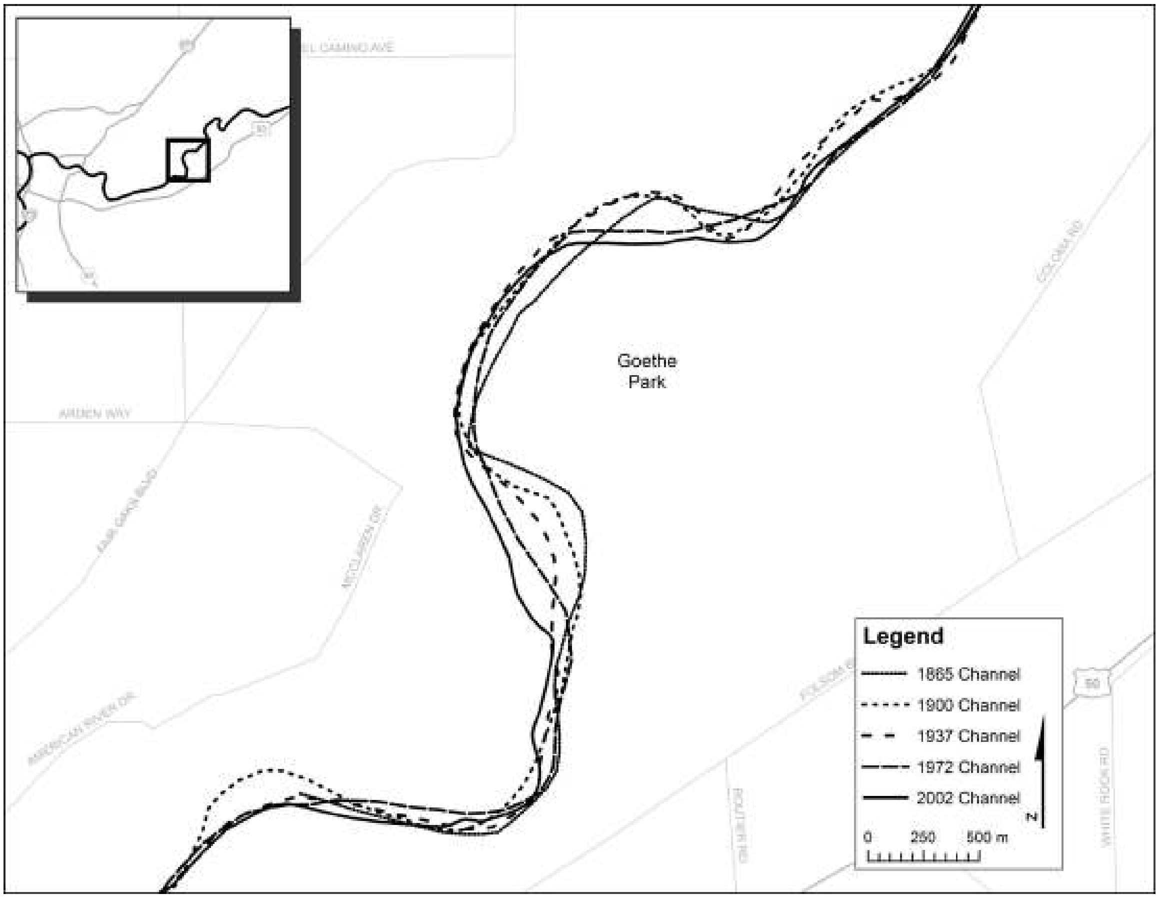


Figure 2-3 Map of Lower American River showing changes in planform near Goethe Park from 1865 to 2002 at about 35 year intervals.

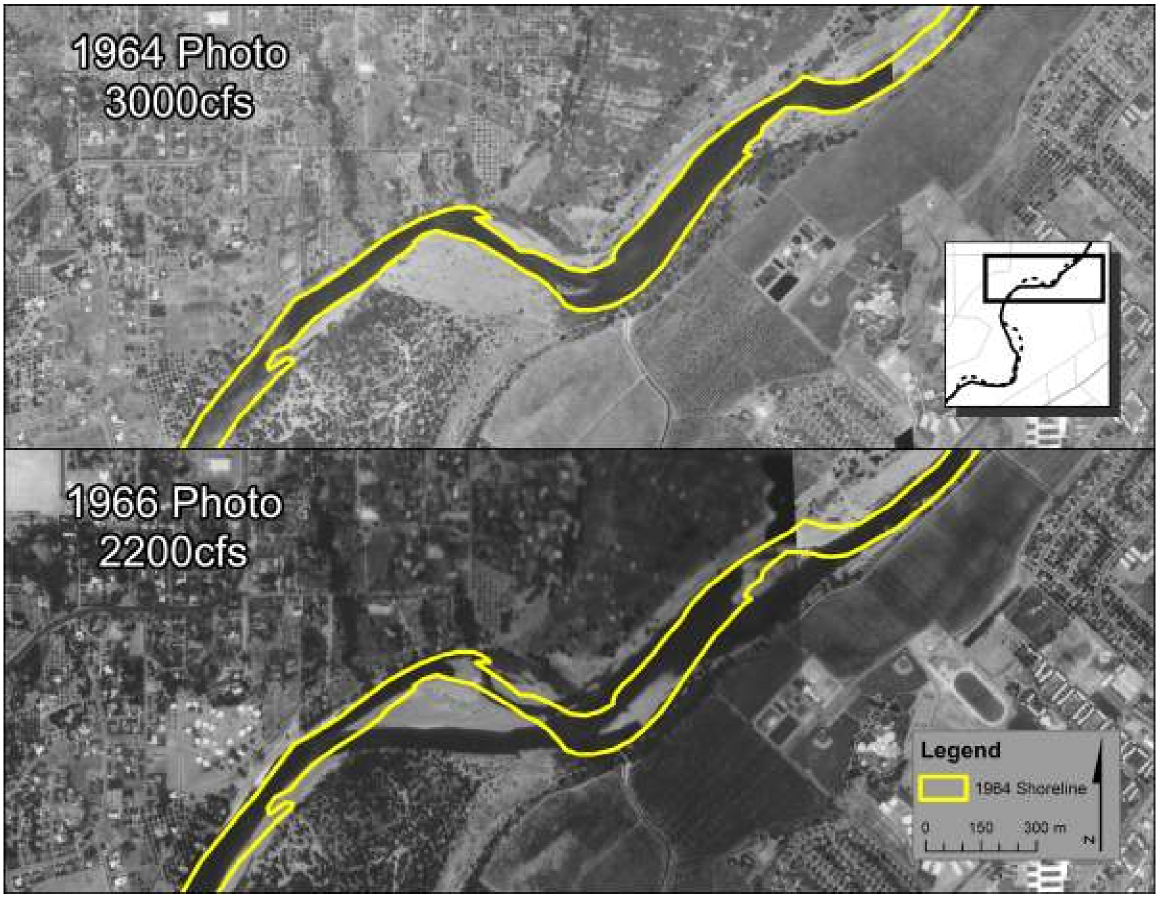


Figure 2-4 Aerial photos showing the channel changes that occurred between 1964 and 1966 between Goethe and Ansel Hoffman Parks. A peak flow of 115,000cfs in 1965 is likely responsible for the straightening of the channel.

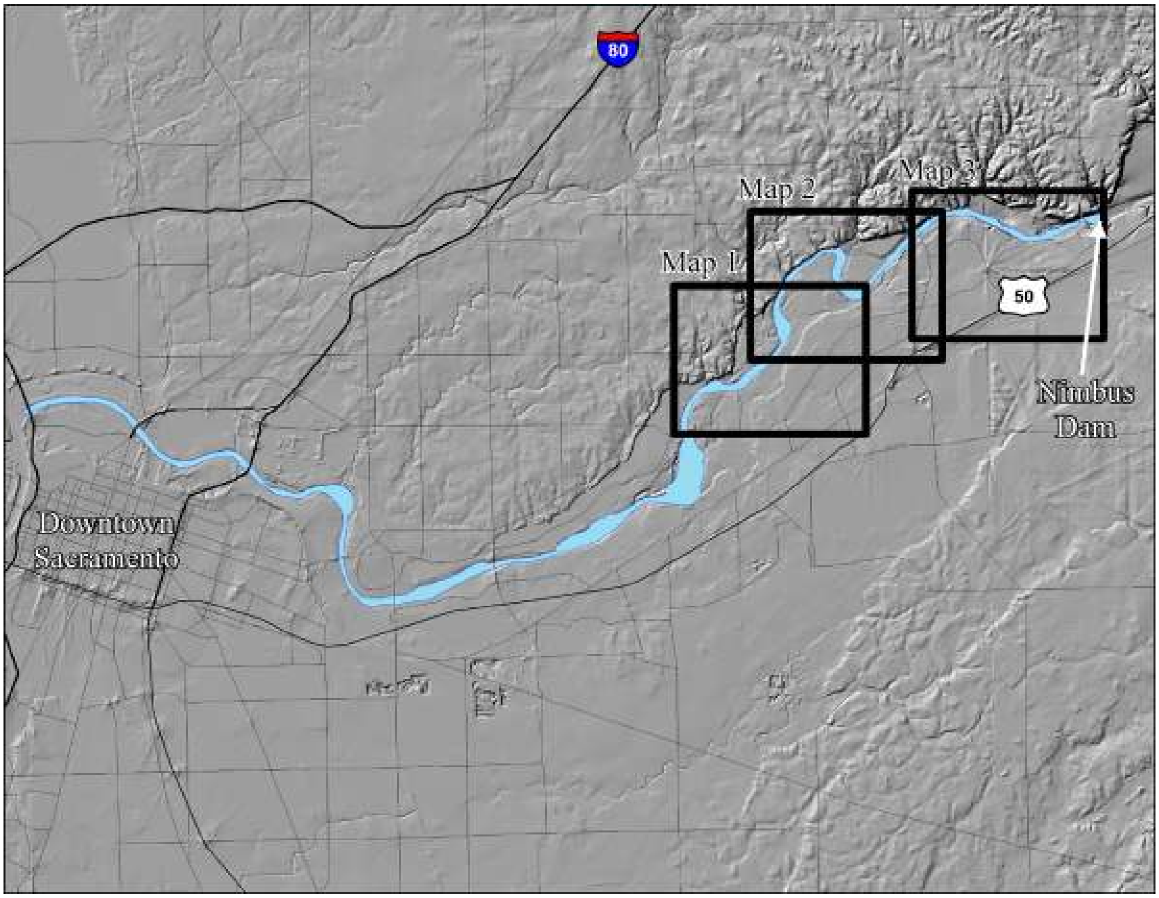


Figure 2-5 Map of the LAR showing the locations of the three geologic maps (Figures 2-6 through 2-19). This part of the study was limited to reaches 3 and 4 where salmonid spawning is most common.

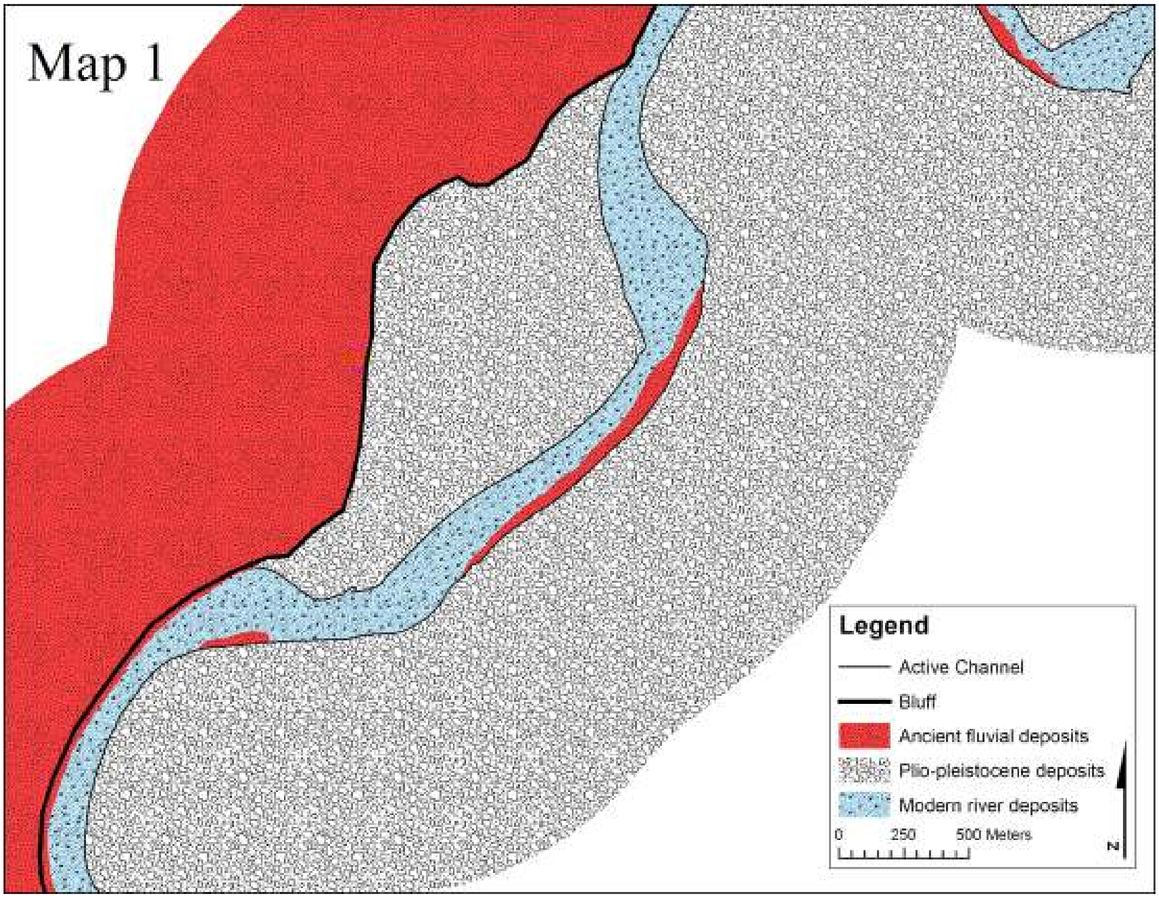


Figure 2-6 Geologic map of reach 3.

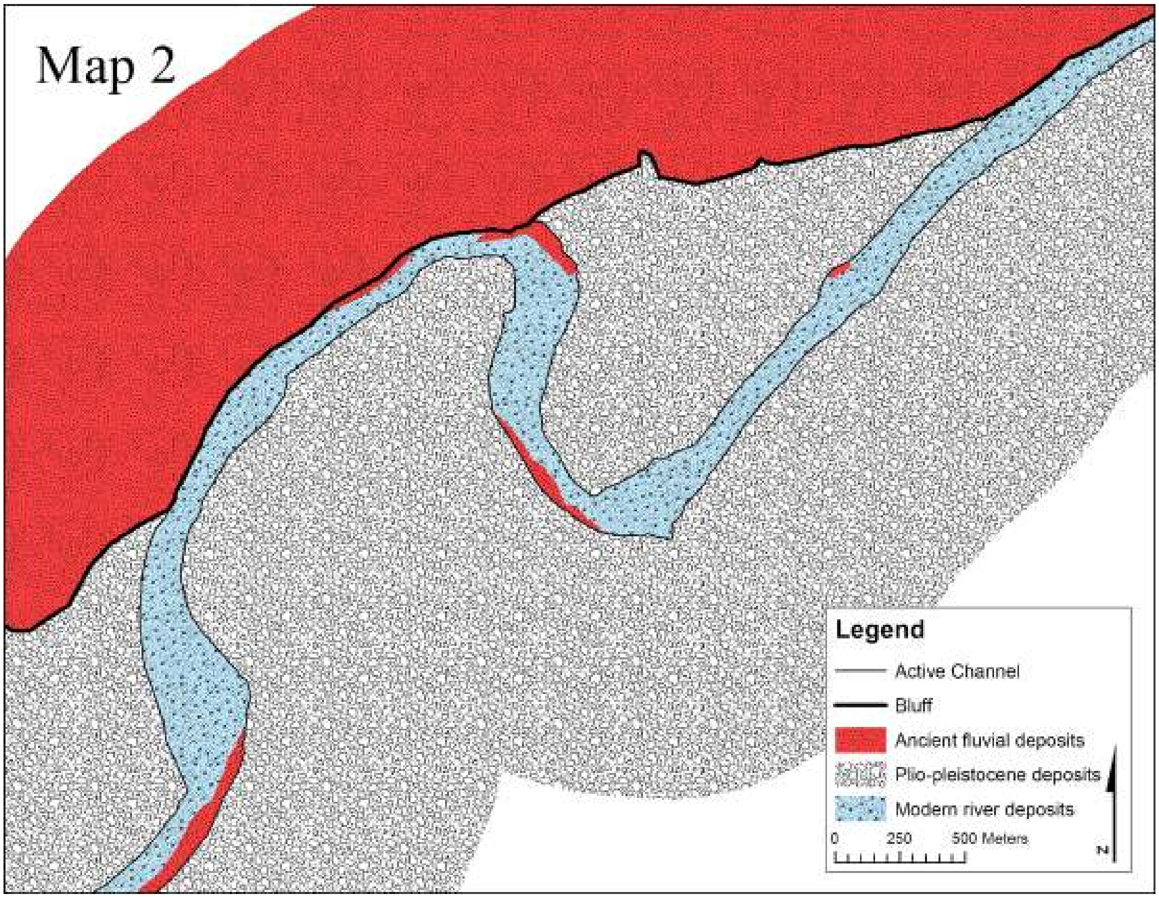


Figure 2-7 Geologic Map of the upstream portion of reach 3 and downstream portion of reach 4. San Juan Rapid is located near the meander bend where the channel meets the bluffs.

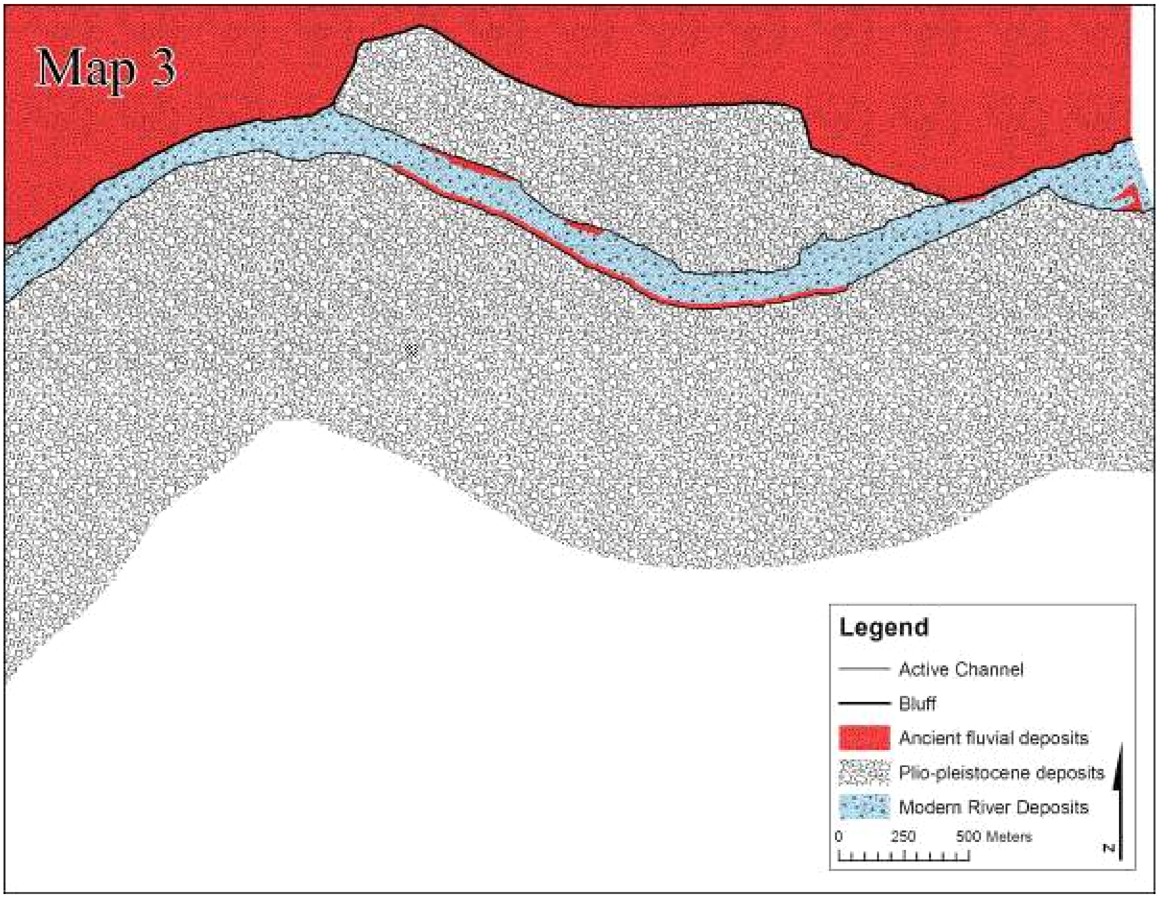


Figure 2-8 Geologic map of reach 4.

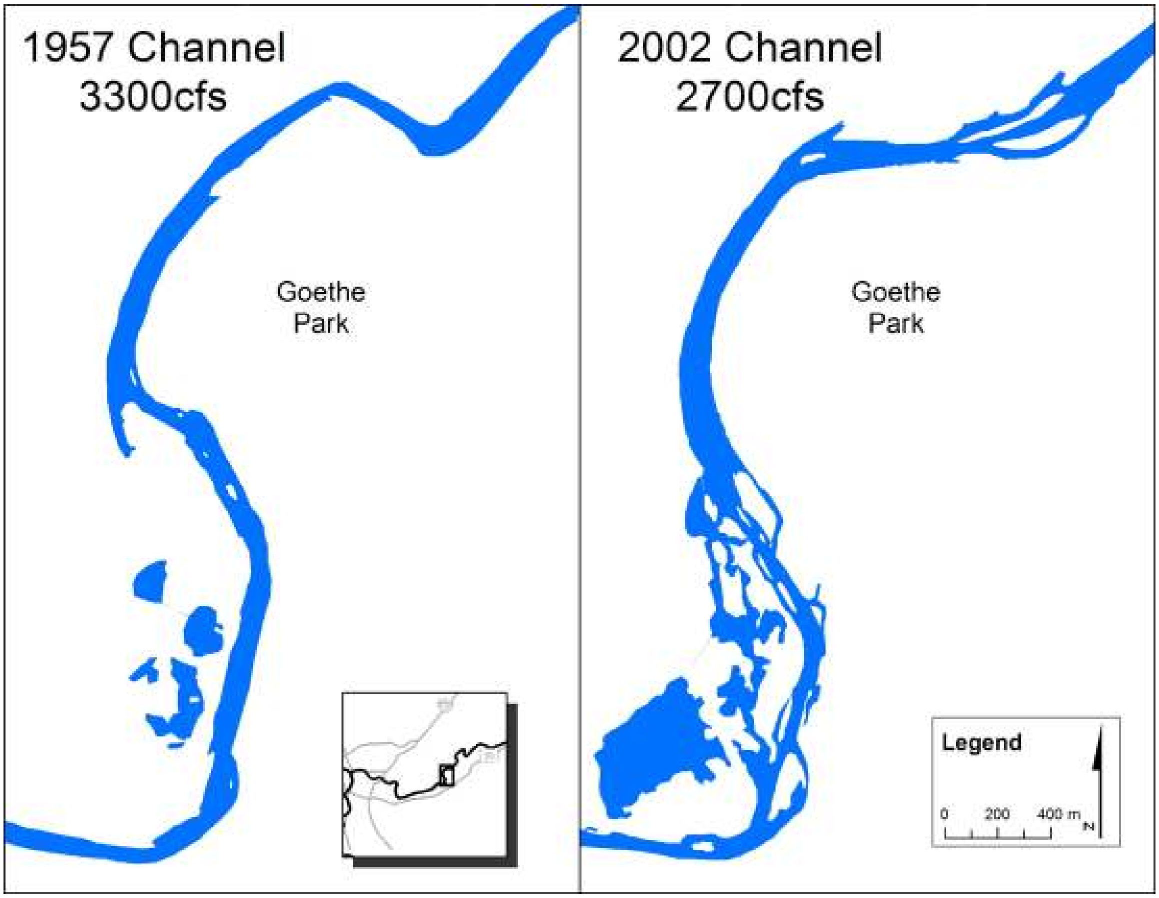


Figure 2-9 Channel shape (based on aerial photographs) near Goethe Park showing an increase in braiding between 1957 and 2002. This is the only location on the LAR that shows these kinds of channel changes.

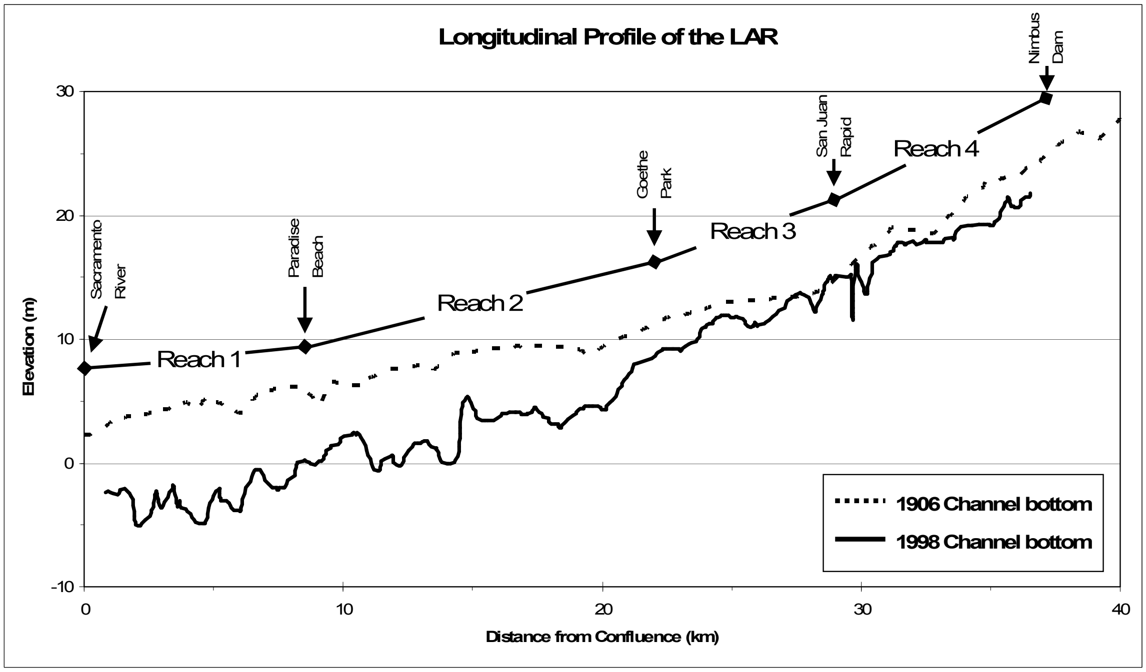


Figure 2-10 Longitudinal profile of the LAR showing the incision since 1906 and the steep gradient (knickpoint) near Goethe Park.

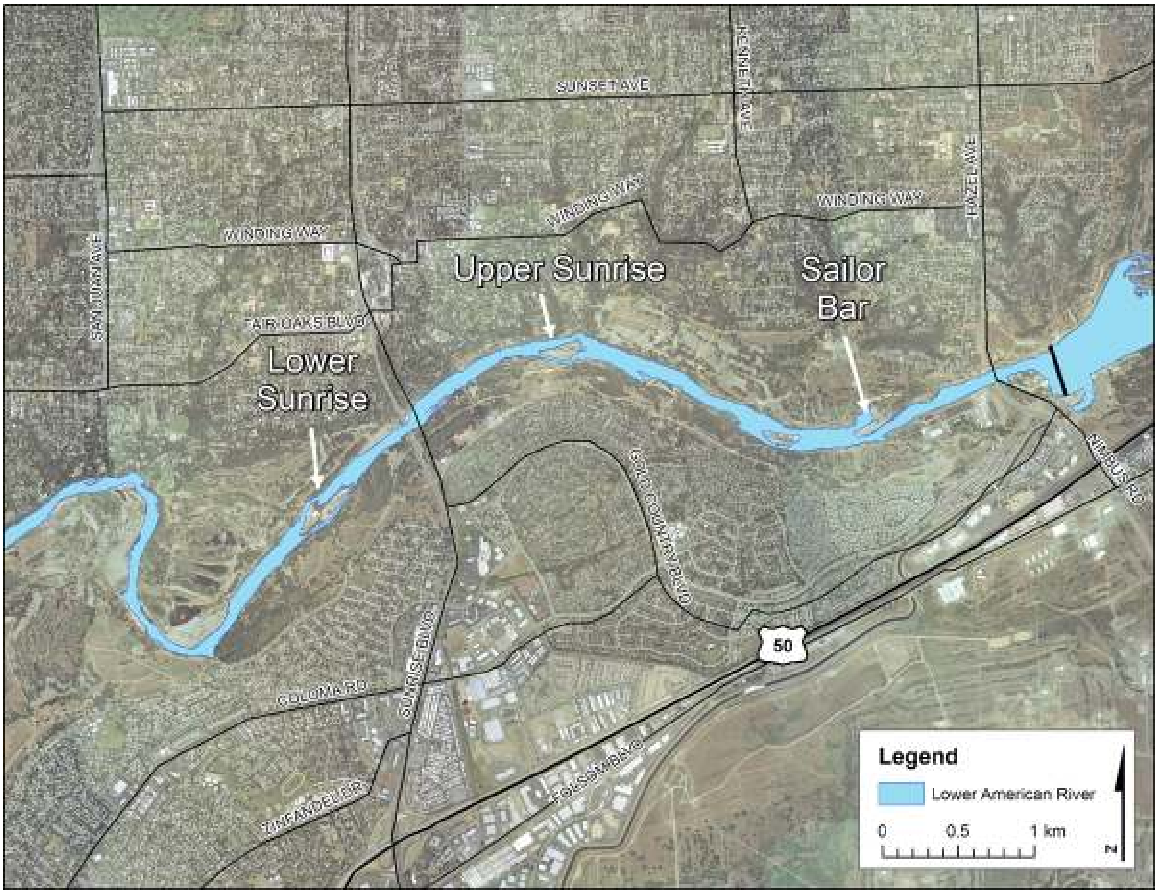


Figure 2-11 Map of reach 4 of the LAR showing three locations where gravel bars have shown significant movement.

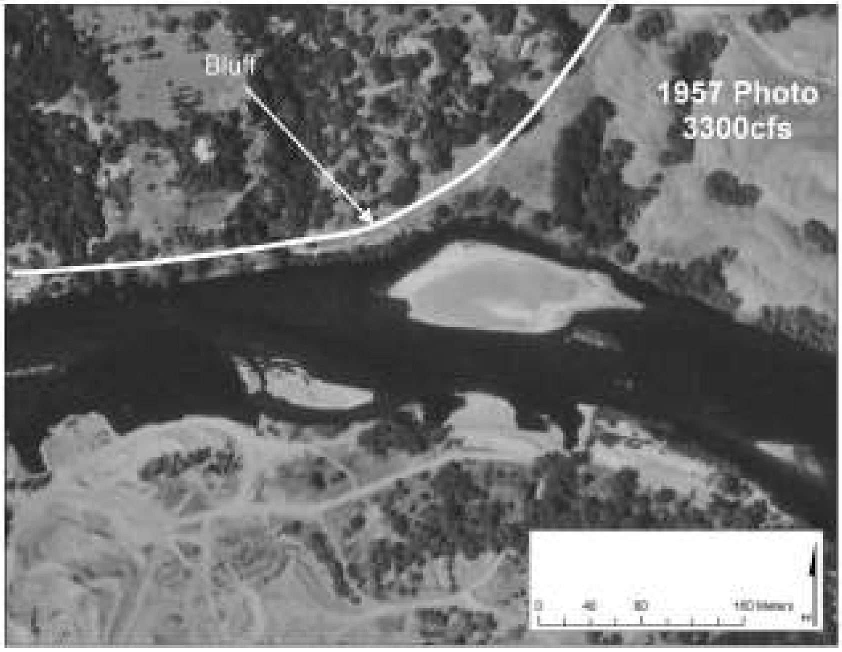


Figure 2-12 Photo of Upper Sunrise showing the location of the gravel bar island in 1957.

Figure 2-13 Photo of Upper Sunrise showing the location of the gravel bar island in 2002. The shape and location changed significantly, but there is no consistent downstream migration due to the localized control of the bluff.

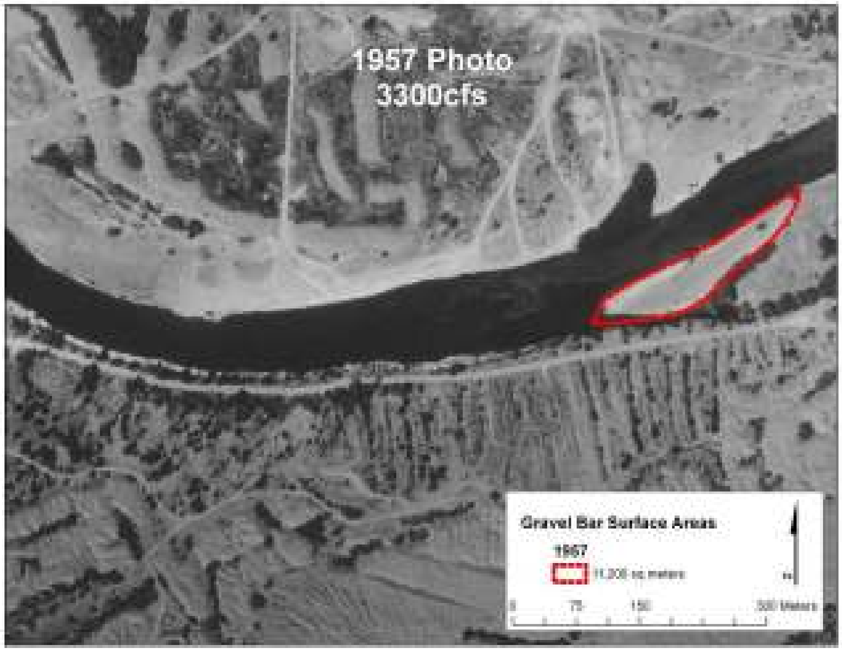


Figure 2-14 Georeferenced photo of Sailor Bar from 1957. The dashed line identifies the likely source of the sediment that forms the island in the 2002 photo (Figure 2-15).

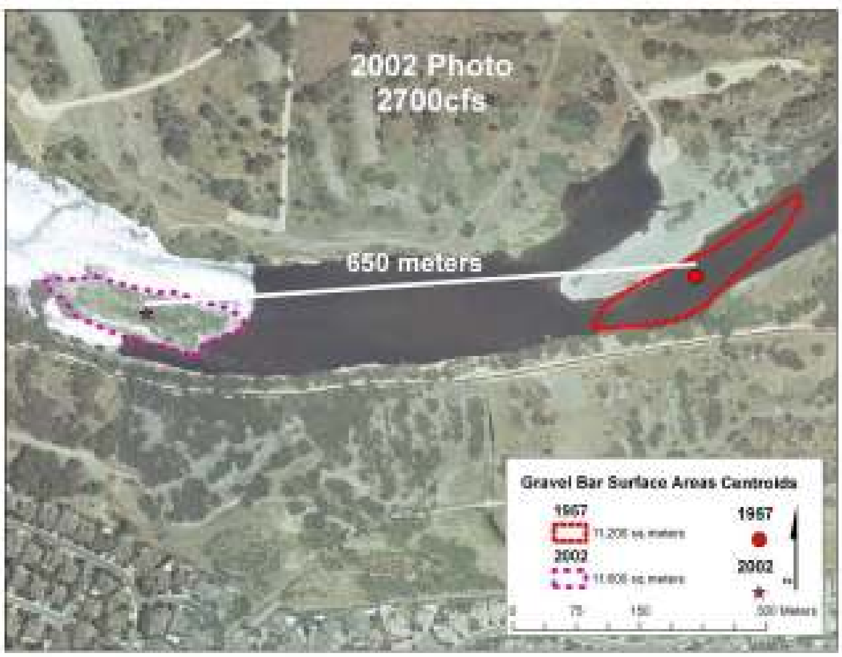


Figure 2-15 Georeferenced photo of Sailor Bar from 2002. The dashed line on the left shows an island bar that has formed since 1957. The surface area of the two bars and the distance between the centroids were measured.

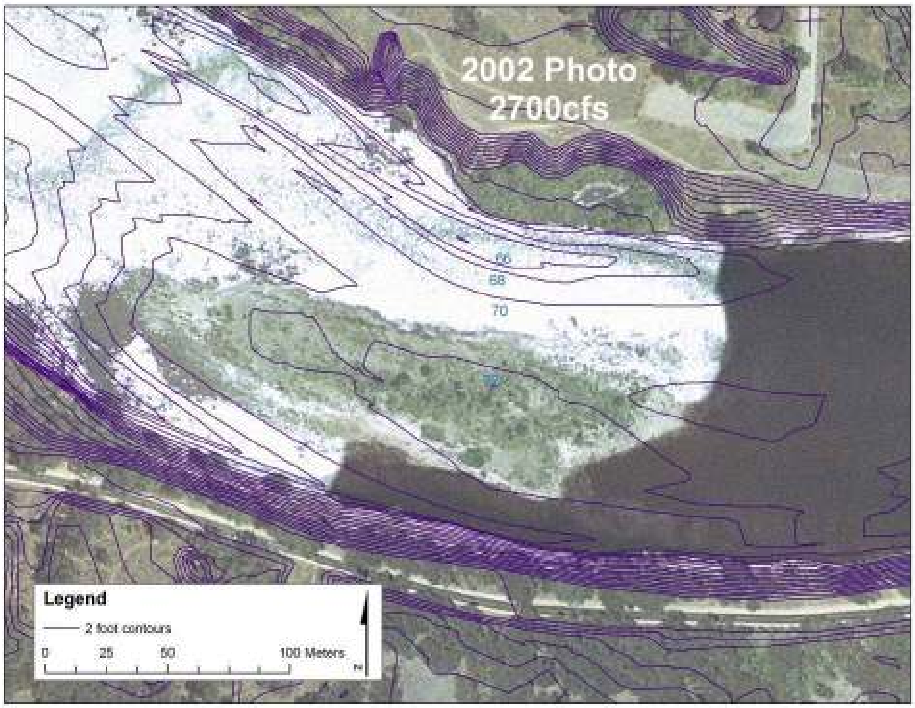


Figure 2-16 Bathymetric contours used to determine the 1.8m (6ft) estimated thickness of the island (USACE 1998).

Figure 2-17 Georeferenced photo of Lower Sunrise from 1957. The dashed line identifies the likely source of the island in the 2002 photo (Figure 2-18).

Figure 2-18 Georeferenced photo of Lower Sunrise from 2002. The dashed line on the left shows the modern location of the island. The surface area of the two bars and the distance between the centroids were measured.

Figure 2-19 Bathymetric contours used to determine the 1.2m (4ft) estimated thickness of the island.

Table 2-1

Available Historic Data

Date	Source	Section	Photo or Map	Flow (cfs)	Cross-sections	Georeferencing (type of transformation)
1865	Rancho Survey	Nimbus to L. Goethe	Map	--	No	Yes (2 control pts)
1900	US Geol Survey (USGS)	Complete	Map	--	No	Yes (1st order)
1906	CA Debris Commission (CDC)	Complete	Map	--	Yes	Yes (1st order)
8/16/1937	US Dept of Agriculture (USDA)	Complete	Photo	300	No	Yes (1st order)
3/31/1949	Bureau of Reclamation (BOR)	Nimbus to Fair Oaks	Photo	3000	No	No
7/23/1953	USDA	Nimbus to A. Hoffman	Photo	1300	No	Yes (2nd order)
8/24/1957	USDA	Complete	Photo	3300	No	Yes (2nd order)
1962	US Army Corps of Eng(USACE)	Complete	Map	--	Yes	Yes (2nd order)
5/29/1964	USDA	Nimbus to Goethe	Photo	3000	No	Yes (2nd order)
8/4/1966	USGS	Complete	Photo	2200	No	Yes (2nd order)
9/19/1966	CA Dept of Fish&Game (DFG)	Complete	Photo	1000	No	Yes (2nd order)
7/6/1972	USDA	Complete	Photo	3100	No	Yes (2nd order)
4/20/1984	WAC Corporation	Nimbus to CSUS	Photo	2400	No	Yes (2nd order)
4/24/1999	WAC Corporation	Nimbus to CSUS	Photo	4500	No	Yes (2nd order)
3/12/2001	BOR	Complete	Photo	1500	No	Yes (2nd order)
5/9/2002	BOR	Complete	Photo	2700	No	Yes

complete means from Nimbus Dam to the confluence with the Sacramento River

Table 2-2

Changes in Channel Width (1957-2002)

Year	Reaches	Water Surface Area (m^2)	Channel Length (m)	Average Width (m)	Percent Increase
1957 (3300cfs)	1-2	2,434,000	21,600	113	
	3-4	1,272,000	15,130	84	
	1-4	3,706,000	36,730	101	
2002 (2700cfs)	1-2	2,729,000	21,630	126	12%
	3-4	1,436,000	14,800	97	15%
	1-4	4,164,000	36,430	114	13%

Table 2-3

Gravel Movement Results (Reach 4 only)

Location	A (m^2)	h (m)	V_b (m^3)	d (km)	R_g (m^3/yr/km)	R_l (m^3/yr)	V_t (m^3)
Sailor Bar	11,000	1.8	20,800	0.650	710	4,600	210,000
Lower Sunrise	8,800	1.2	10,700	0.115	2,100	13,000	600,000

t = 45yrs l = 6.4km

Chapter 3: Gravel mobility and the effects of Folsom and Nimbus Dams

3.1 Introduction

Although sediment budgets are typically concerned with the volumes of sediment entering, exiting, and stored within a reach, it is also useful to analyze the flow conditions under which transport occurs. This is especially important in gravel-bed rivers such as the Lower American River (LAR), where coarse sediment transport is typically limited to large magnitude flood events (Parker 1980). A thorough understanding of the magnitude of flow required to mobilize coarse sediment gives managers the predictive ability to design releases that minimize negative impacts and enhance positive effects.

The primary habitat concern on the LAR is the reduction of spawning gravel supply, although there are also positive impacts of gravel mobility. Periodic movement of gravel beds helps to winnow away excess fine material, improve permeability, and reduce armoring (Horner 2005). Ideally, dam releases could be designed in such a way that gravel beds are periodically mobilized, but without significant loss of gravel from the river. This scenario is only possible with detailed understanding of the relationship between flows and gravel movement.

The most thorough study to date on gravel mobility on the LAR was done by Ayres Associates (2001). They produced a detailed 2-dimensional hydraulic model of the LAR from Nimbus Dam to the confluence of the Sacramento River. From this model, they were able to determine the spatial distribution of shear stresses at each of four modeled flows: 30, 50, 80, and 115 thousand cubic feet per second (tcfs). They used grain size distributions (D_{50} values) from 28 sites to determine whether the bed would be mobile at each flow. Of the 28 sites, one showed mobility at 30 tcfs, six at 50 tcfs, 11 at 80 tcfs, and 14 at 115 tcfs. Those that showed no mobility at any modeled flow were either located where the river was not capable of moving the material (outside of the main channel or in a slower stretch of river) or contained very large grains that were beyond the transport capacity of the river even at high flows. They concluded that gravel is generally immobile for flows below 50 tcfs. This figure has been valuable for river managers as the minimum value for bed mobility. However Ayres Associates' work also indicates that not all beds become mobile at this flow and as discharge increases above 50 tcfs the amount of bed mobility within the river also increases. But does this mean that no gravel is transported below 50 tcfs? Entire beds may not be mobile, but empirical observations show that significant movement does occur at lower flows.

In December 2005, discharge of 36 tcfs was maintained for 11 days. This was done to reduce reservoir storage and help with flood control for a major storm that impacted the area on New Year's Day (Figure 3-1). When flows were lowered at the end of January 2006, significant erosion was observed at the island near Lower Sunrise Access (Figure 3-2). The shorelines of the river were logged using a GPS (Trimble GeoExplorer CE with real-time differential correction) in Feb 2005 and Jan 2006. The changes in these shorelines illustrate that the high flows caused incision of two small channels on the gravel bar and gravel deposition on the downstream end of the island.

A tracer rock study was also begun in February 2005. Brightly painted rocks of three size gradations (Table 3-1) were deployed by boat along six transects (Figure 3-3). Gravel movement was measured by wading near and downstream of the transects and logging the location of tracer rocks with a GPS after flow events with magnitudes of 8 and 26.5 tcfs (Figure 3-4). The locations of tracer rocks found at each of the six sites are shown in Figures 3-5 through 3-10. No gravel movement was detected after the 8 tcfs event, but the 26.5 tcfs event was able to move some large (yellow) grains a distance of 25 meters (Figure 3-6) and some medium (red) grains at least 75m (Figure 3-9). Few of the small (red) grains were found. It is assumed that these rocks were generally mobilized during the larger (26.5 tcfs) event, but were transported too far to be recovered.

All of the above methods are good indicators of gravel movement but are not direct indicators of volumes of gravel loss from the system. During a particular event, it is possible for a gravel bar to become mobile and then re-deposit a few meters downstream. Movement of this scale may not be significant in terms of gravel supply on the river. In order to identify the events that caused major volumetric gravel loss, scour and downcutting were used as a proxy for volumetric change. These changes were observed by using repeated, fixed cross-sections.

3.2 Method

Stream discharge was measured by the USGS on a regular basis in order to maintain an accurate stage-discharge relationship for the Fair Oaks Gauge. Because these measurements were made at the same location each time, repeated cross-sections were plotted and compared with peak discharge records from each water year to determine the effect of peak discharge on channel shape.

The Fair Oaks gauge has been operated and maintained since November 3, 1904 (USGS 2004). It was originally located near the town of Fair Oaks, but was moved 3.5km upstream to a site near Hazel Avenue on December 6, 1957 after the construction of Folsom and Nimbus Dams (Figure 3-11). Measurements were made from cableways located just downstream of the gauge, which ensured that the cross-sections were compiled in identical places at each site. Measurements contained the depth of the water and the horizontal distance from an arbitrary starting point along the cable. The elevation of the channel bottom was calculated by subtracting the depth of the water from the river stage recorded by the gauge during the measurement. This resulted in an accurately referenced elevation assuming that the water surface is the same at the gauge and the cableway. Because the horizontal datum was arbitrary during each discharge measurement, the cross-sections were adjusted horizontally until a best fit was achieved.

One cross-section was produced for each year that USGS stream-gauging data were available. Measurements made in summer or early fall were used to ensure that changes in channel cross-section resulted from the peak discharge of a particular water year (the Mediterranean climate of the area precludes the yearly peak flow from occurring in summer or early fall). Results were grouped by time period to summarize significant downcutting events from 1944 to 2004.

3.3 Results

Figure 3-12 shows the effect of the impoundment of the LAR on the magnitude of flood events. Although the construction of Folsom and Nimbus Dams has generally reduced the magnitude of floods on the LAR, the effect on the largest events (> 8 year recurrence interval) has been minimal. This is important because large events are likely to cause most gravel loss. Figure 3-13 shows the events that caused deepening or widening of the cross-section at the Fair Oaks Gauge. Details of the cross-sectional changes are described below.

Figure 3-14 shows the changes observed at the Fair Oaks gauge before the regulation of the river by Folsom and Nimbus Dams (pre-1955). With the exception of 1951, the channel changed little from year to year. Most notably, a flood of 94.4 tcfs in 1945 caused almost no change in the channel shape. The only significant downcutting event was the 180 tcfs event in 1951 (the flow of record).

Several major downcutting events occurred after the completion of Folsom and Nimbus Dams in 1955. The modern gauge location near Hazel Avenue had a consistent channel shape from 1958-60, 1963-1964, and 1965-1968 (records were unavailable for 1961-62) (Figure 3-15). The major changes in this period appear to have been caused by the large magnitude events of 1963 (101 tcfs) and 1965 (115 tcfs); the former causing widening of the channel and the latter causing over 2m of downcutting.

There were no flood events greater than 100 tcfs in the period from 1965 to 1983 and no channel changes indicating downcutting or widening (Figure 3-16). The only significant changes during this time period were two episodes of aggradation in 1969 and 1980-1983 (no records were available for 1980 and 1982). It is possible that the moderate events in 1969 (73.4 tcfs), 1980 (84.8 tcfs), and 1982 (91.1 cfs) were large enough for material from Nimbus Basin (500 – 600m upstream) to be mobilized and deposited at the cableway. However, it is also possible that the aggradation resulted from maintenance of the fish weir 250m upstream. Figure 3-17 shows that large material was added to reinforce the weir on 8/3/1972. If some of this loose material was transported downstream, it may have been deposited at the cableway site.

Two events have caused downcutting in more recent times: 1986 (134 tcfs) and 1997 (117 tcfs) (Figure 3-18). There have been no other significant channel changes in the last 22 years despite moderately large flows of 51 tcfs in 1995 and 1996.

3.4 Discussion

Quantifying gravel mobility is difficult, but the topic has been studied with a variety of techniques on the LAR. The Ayres Associates (2001) study provides guidance on minimum flows necessary to mobilize beds, but its usefulness is limited for quantifying volumes of gravel movement because it is a hydraulic and not a sediment transport model. A sediment transport model would be extremely useful, but is beyond the scope of this project.

Empirical evidence verifies that gravel does move regularly on the LAR, perhaps with flows as low as 26.5 tcfs. Gravel discharge at these lower flows, however, is likely to be small compared with low frequency events (10 – 20 year floods) (Figure 3-12). As the magnitude of the floods increases, the rate of gravel discharge should also increase. If the relationship were a simple proportionality, then managing discharges to minimize gravel loss would be a matter of avoiding any large discharges. However, because gravel mobility relies on the concept of incipient motion (the minimum flow necessary to mobilize gravel) at a site, there is likely to be a threshold discharge above which virtually all gravel in the reach is mobilized and gravel discharge is significant.

Changes in channel geometry occur after these threshold events, and there is little change below the threshold. With the Fair Oaks gauge cross-sections as a proxy (Figure 3-13), the five largest events were the only ones that caused significant channel deepening or widening, suggesting that 100 tcfs is the threshold for complete bed mobility, scour, and significant gravel loss from the LAR.

3.5 Figures and Tables

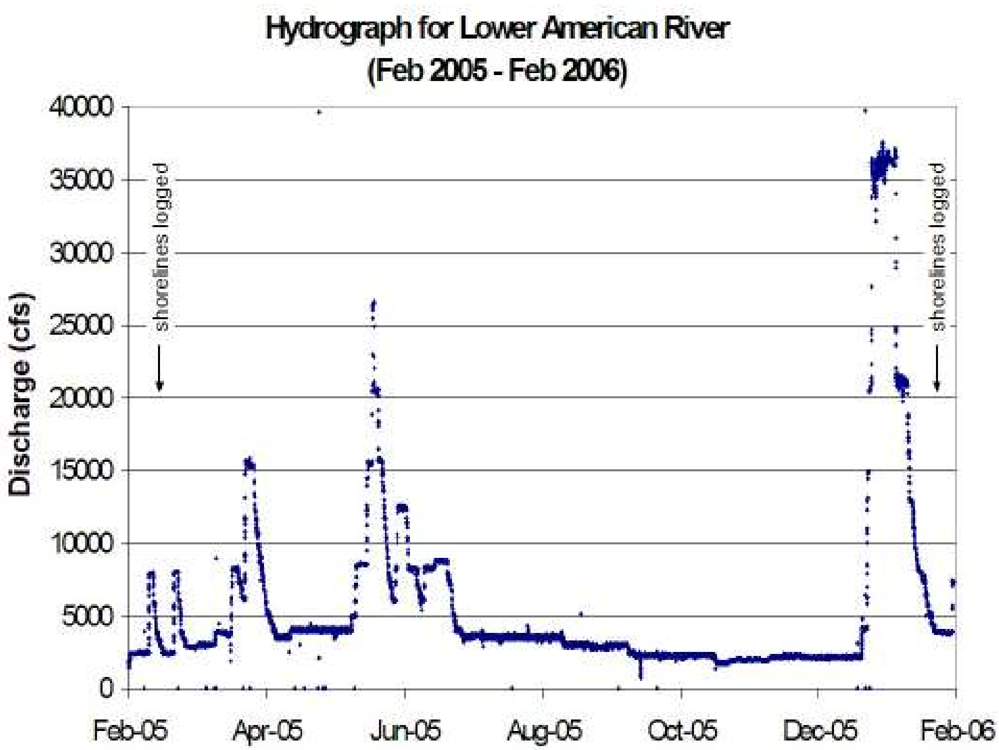


Figure 3-1 Hydrograph showing the flood control releases in December 2005 to January 2006.

Figure 3-2 Changes in the shorelines during the 36 tcfs event of December 2005 to January 2006. Gravel was deposited on the downstream end (lower left) of the bar and two small channels were incised in the gravel bar.

Figure 3-3 Locations of tracer rock deployment lines. Rocks were deployed on February 4, 2005.

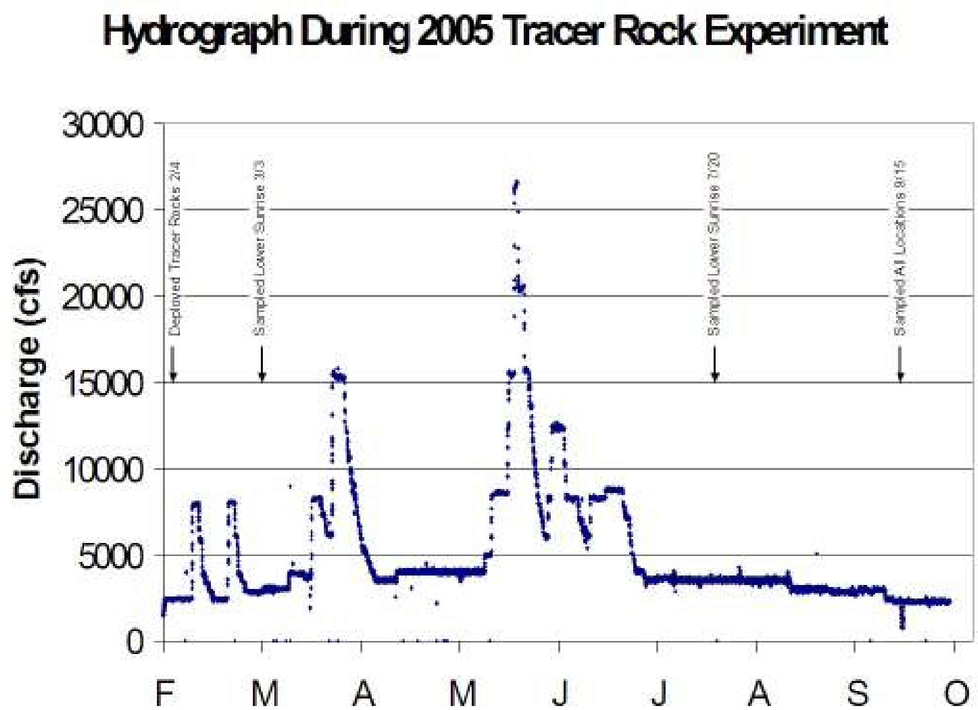


Figure 3-4 Hydrograph showing flows during 2005 tracer rock experiment.

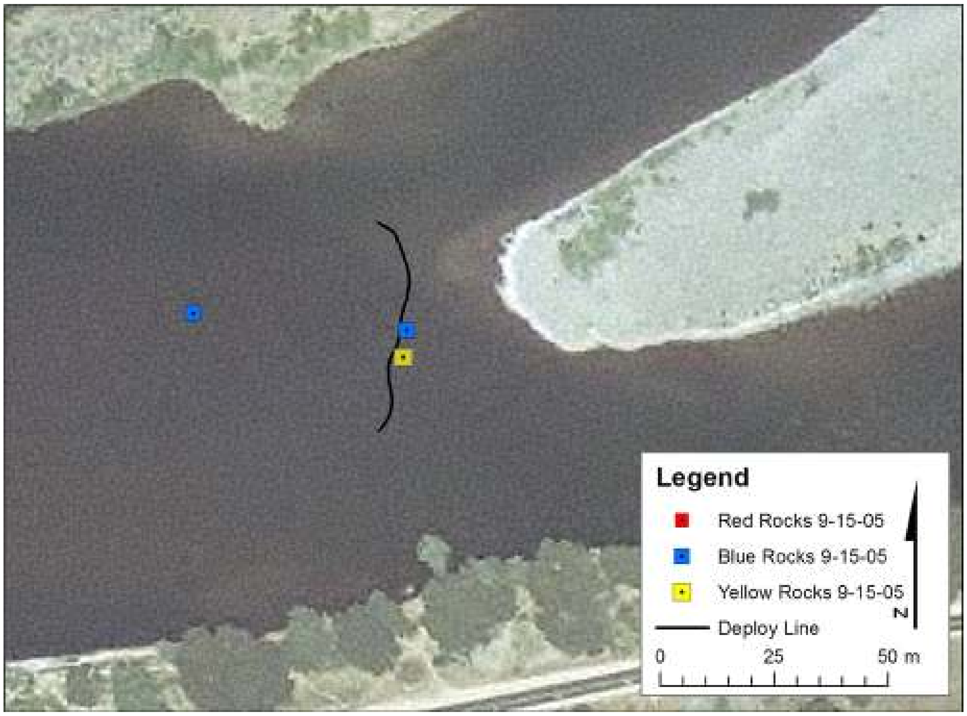


Figure 3-5 Tracer rocks found at Sailor Bar.

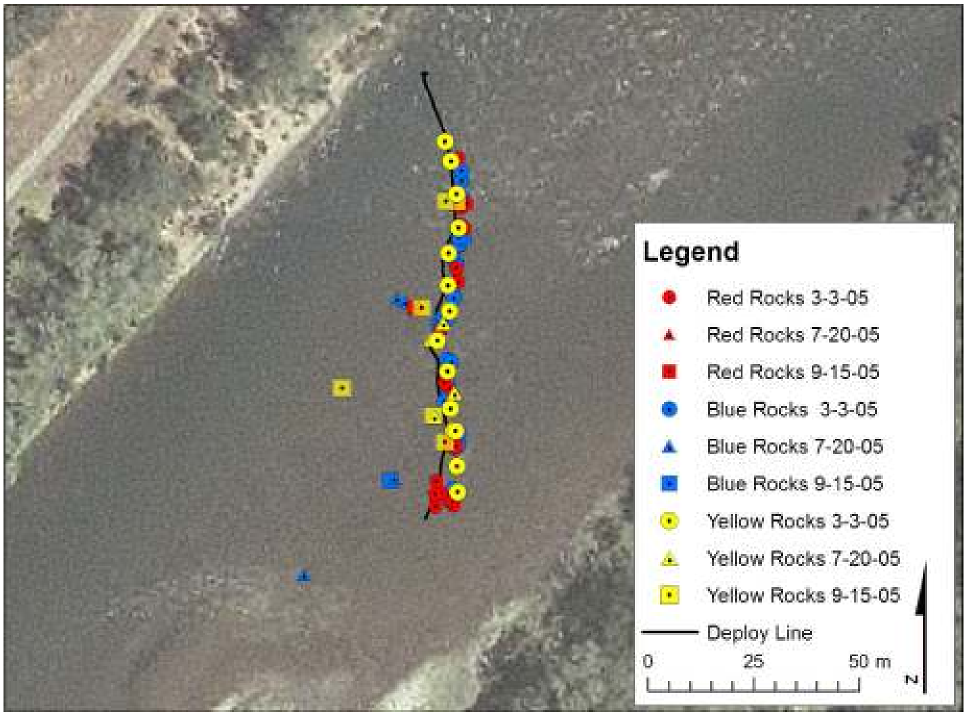


Figure 3-6 Tracer rocks found at Lower Sunrise upstream site.

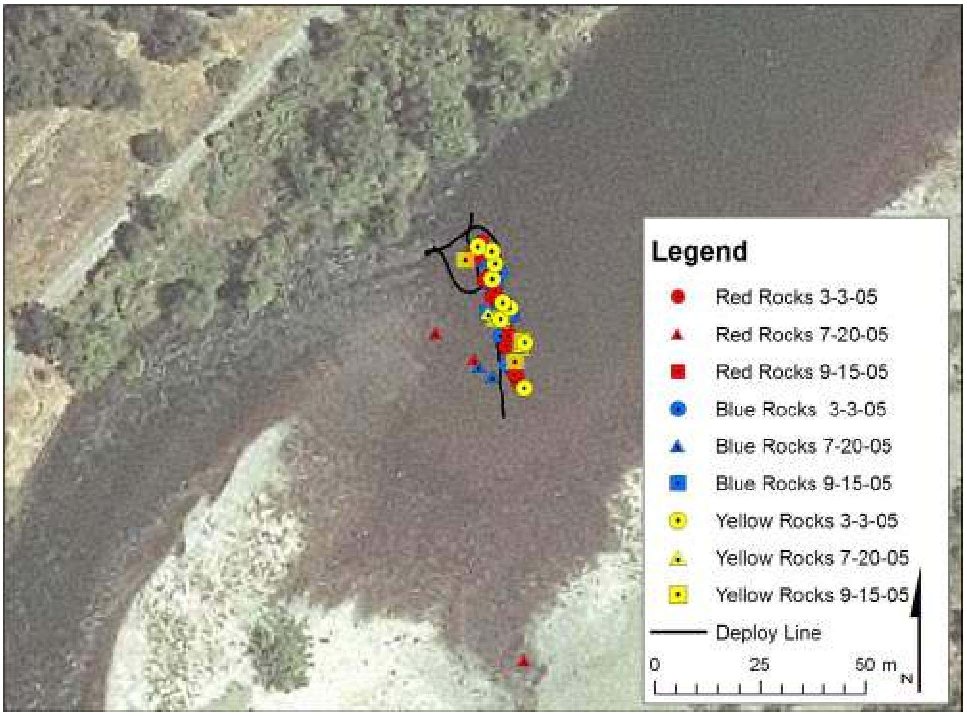


Figure 3-7 Tracer rocks found at Lower Sunrise downstream site.

Figure 3-8 Tracer rocks found at Lower Sunrise side channel site.

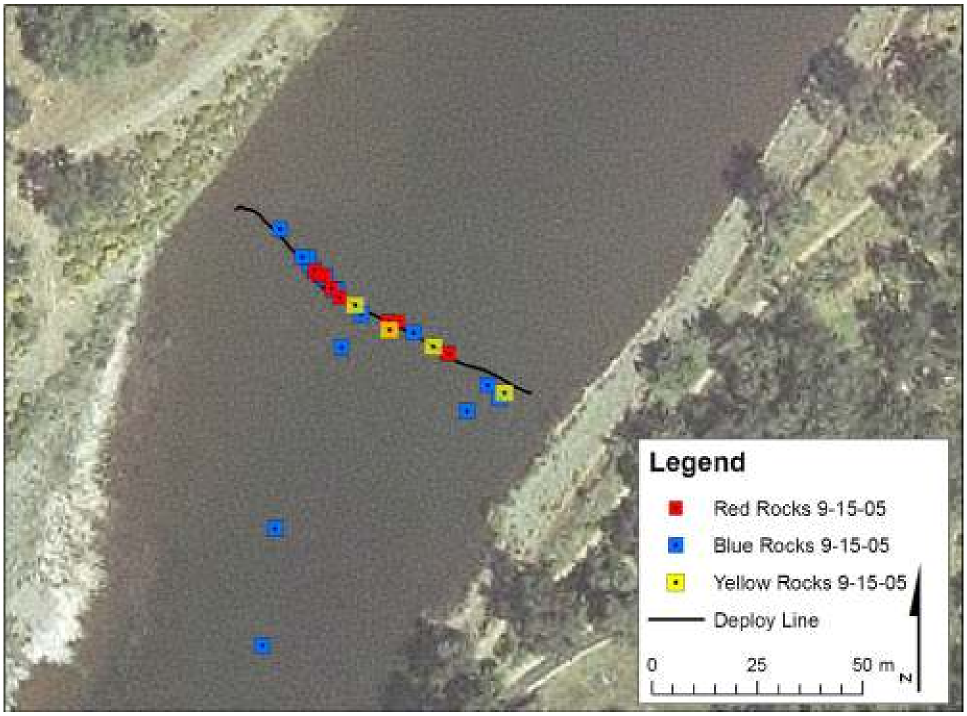


Figure 3-9 Tracer rocks found at Sacramento Bar upstream site.

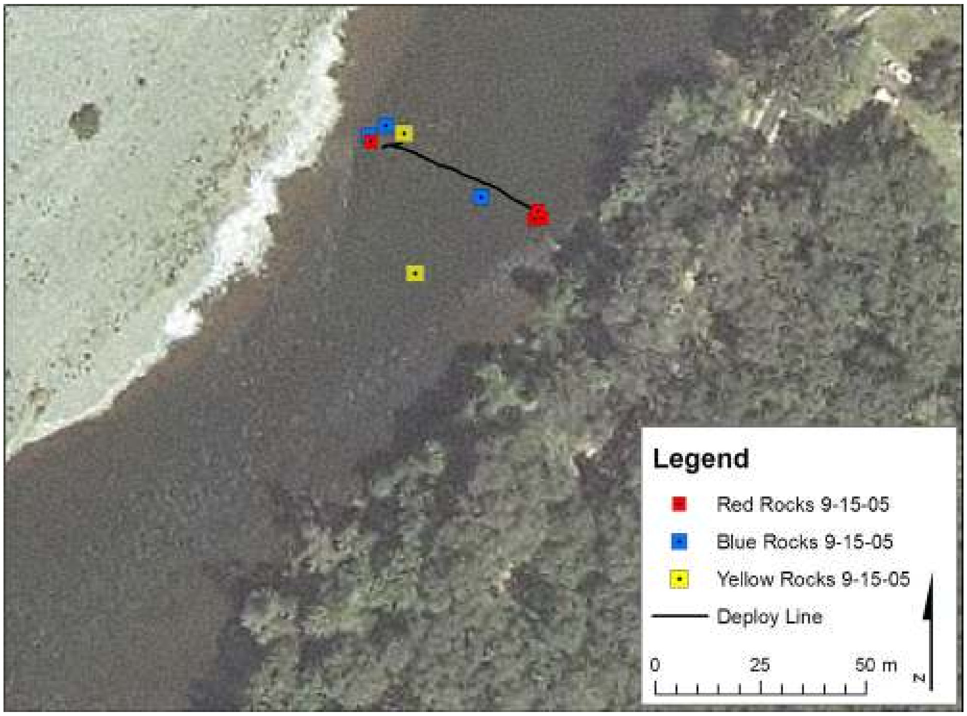


Figure 3-10 Tracer rocks found at Sacramento Bar downstream site.

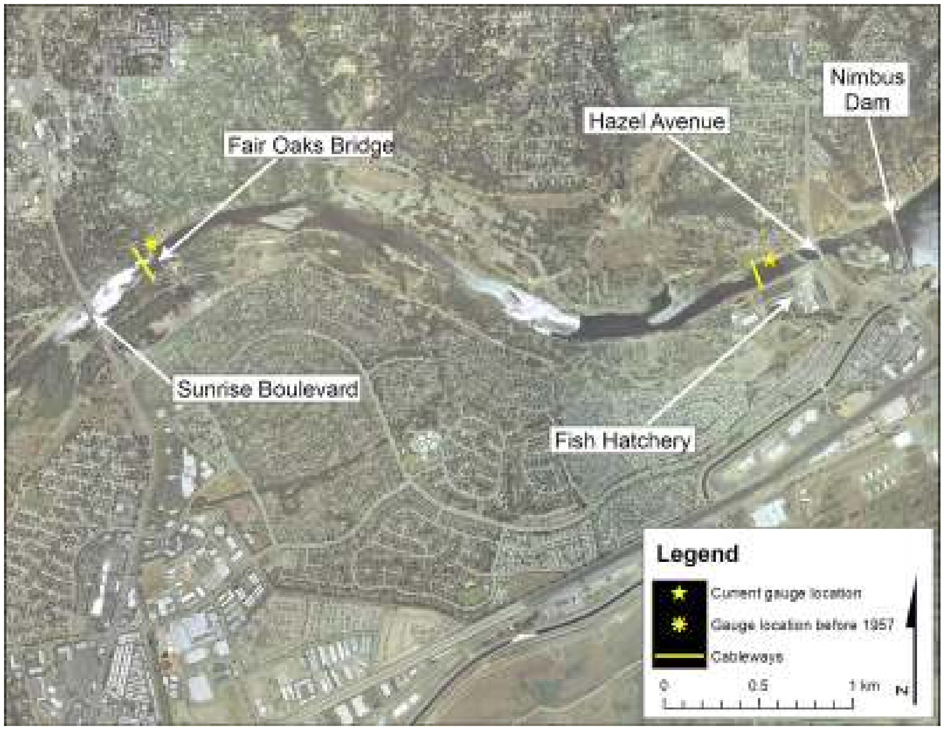


Figure 3-11 Location of Fair Oaks gauge. Prior to 1957 it was located near the Fair Oaks Bridge. The modern location is Near Hazel Avenue.

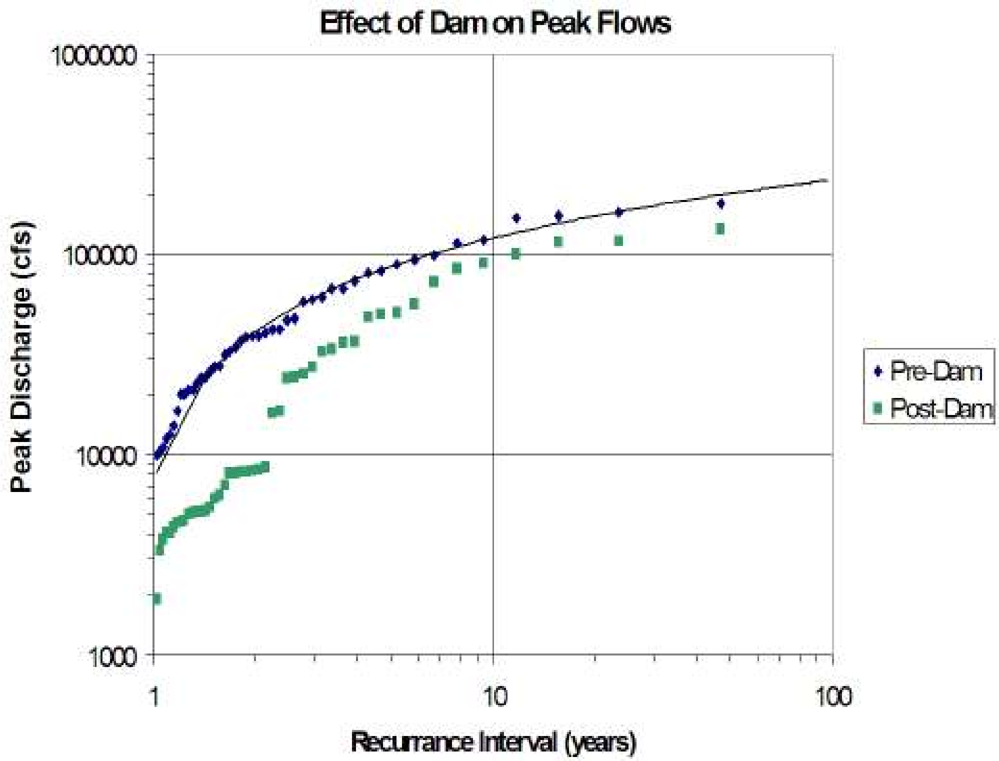


Figure 3-12 Recurrance intervals of flood events at Fair Oaks gauge before and after dam emplacement. Dams have significantly decreased the magnitude of the high frequency events (1 – 5 year recurrence interval), but the effect on low frequency events (> 8 year recurrence interval) is much less pronounced.

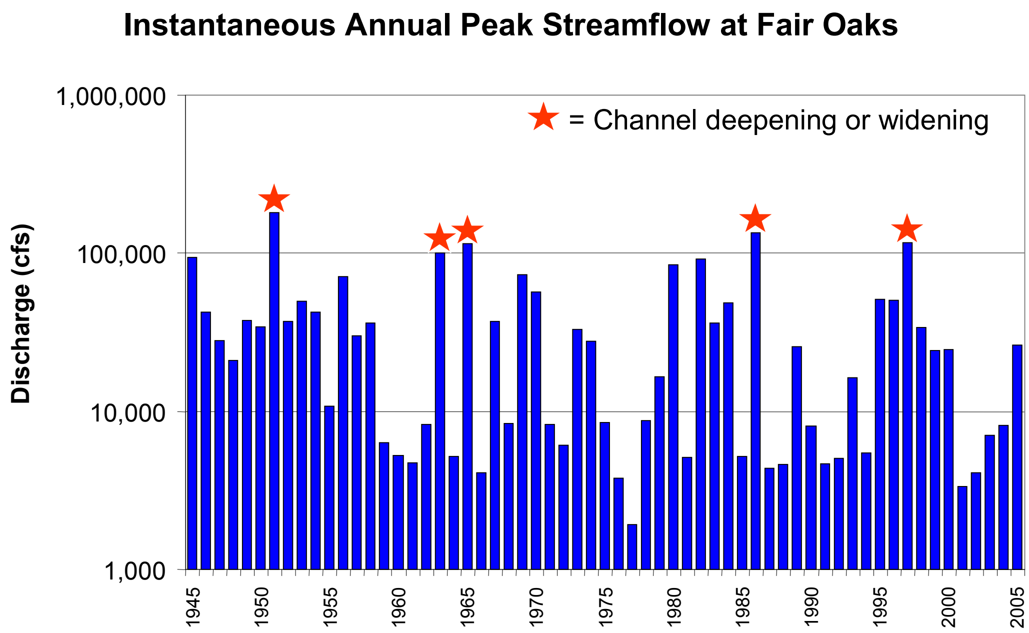


Figure 3-13 Events that showed deepening or widening. All of these events were over 100 tcfs.

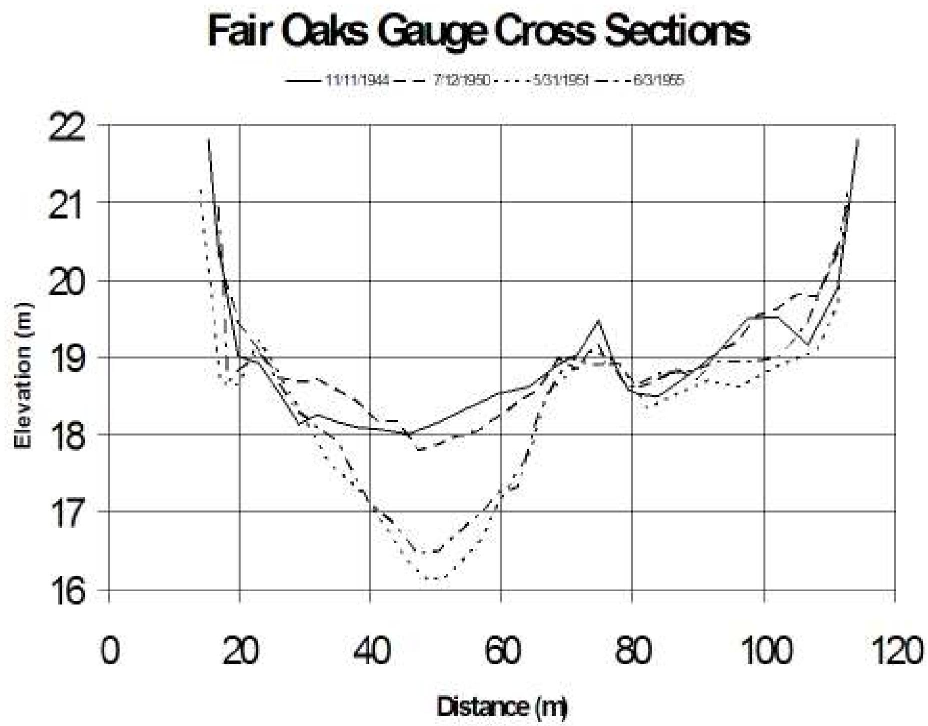


Figure 3-14 Cross-sections before the emplacement of the dam (at gauge site near the Fair Oaks Bridge). Very little change is observed except in 1951 (180 tcfs event).

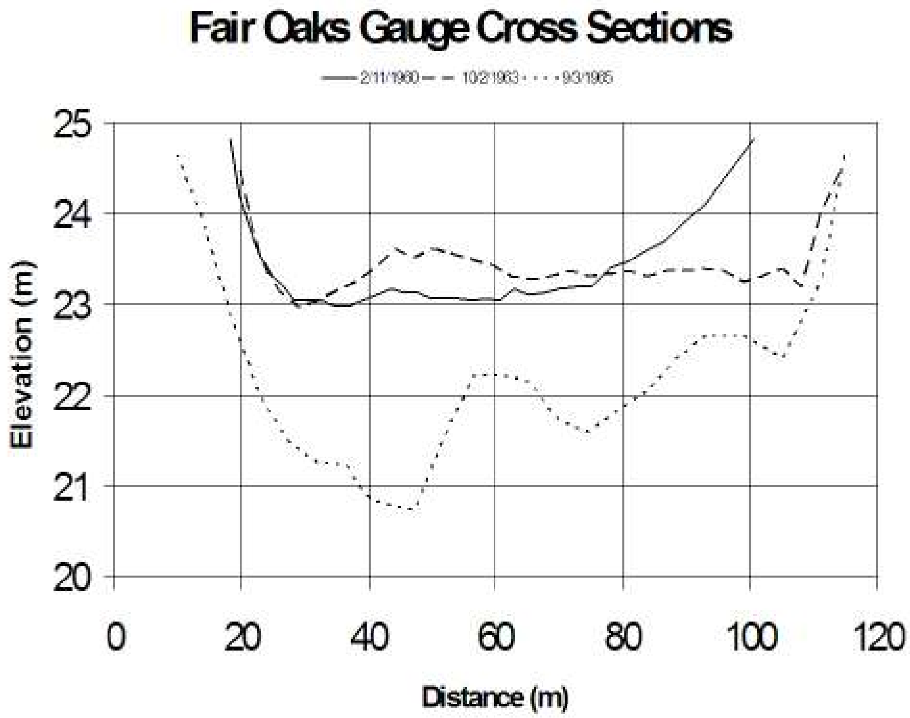


Figure 3-15 Cross-sections after the emplacement of the dams. Little change was observed except widening in 1963 (101 tcfs event) and a major downcutting in 1965 (115 tcfs event).

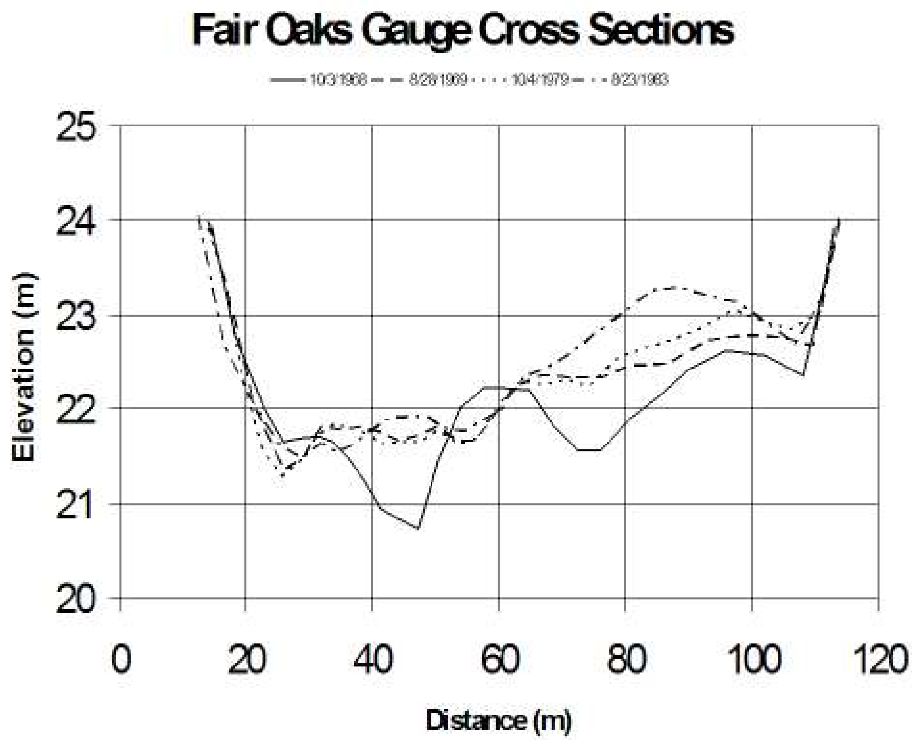


Figure 3-16 Cross-sections from the late 1960's to the early 1980's. No widening or downcutting was observed, but aggradation took place in 1969 (73.4 tcfs event) and 1979 – 1983 (84.8 tcfs and 91.1 tcfs events).

Figure 3-17 Rock fill being placed upstream of fish weir to facilitate repair. 8/3/82 D.M. Westphal, Photo (Bureau of Reclamation).

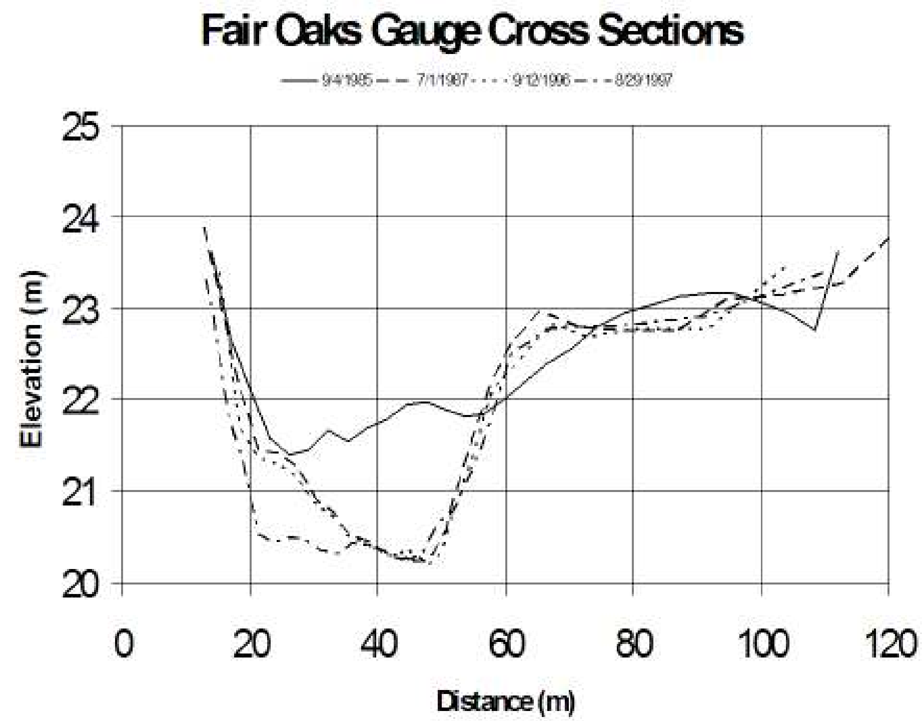


Figure 3-18 Cross-sections from the mid-1980’s to present. Changes were from the 1986 (134 tcfs) and 1997 (117 tcfs) events.

Table 3-1
Tracer Rock Sizes

Color	Diameter Range
Red	1.6 – 3.2 cm
Blue	4.4 – 6.4 cm
Yellow	8.9 – 10.8 cm

Chapter 4: Volumetric estimate of gravel inputs

4.1 Introduction

An important component of a sediment budget is the volumetric gravel input to the reach of interest. Measurement of this volume is difficult, but is made significantly easier when only considering gravel, because gravel is much more difficult to transport into the reach than fine material. Potential sources are limited to locations close to the reach itself (requiring little or no transport) or to locations drained by streams with flow velocities capable of transporting gravel into the reach of interest.

Reid and Dunne (1996) identify 9 processes for the introduction of sediment into streams (Table 4-1). Source 9 (bank erosion) is a significant source of gravel to the Lower American River (LAR) and will be discussed in detail later. Sources 3 through 7 do not apply to gravel and were ignored. Sources 1, 2, and 8 only apply to relatively steep terrain and cases where these activities occur close enough to the river that the gravel may be entrained. The terrain adjacent to the LAR is relatively gentle, with the exception of the bluffs on the north side of the river. The river encroaches on these bluffs in several locations (Figures 4-1 and 4-2), but aerial photographs show negligible retreat at all locations. The bluff formations are primarily silty sands with several units containing gravelly intervals, however these coarse deposits are no more than a few meters thick and would not contribute significant amounts of gravel to the river unless the banks retreated a great deal (which they have not). For these reasons, sources 1, 2, and 8 were also ignored.

In this part of the study we considered reaches three and four of the LAR (Figure 4-3). Because we are considering these discrete reaches and not an entire drainage basin, we must also account for gravel transported into these reaches from upstream and by tributaries. Neither is a significant source of gravel to the LAR. There are few tributaries to the LAR and those that do exist are small (no larger than small creeks), have a gentle gradient, and are therefore incapable of transporting the large material needed for spawning. Gravel supply from upstream is also unlikely since Nimbus and Folsom Dams were emplaced in the mid-1950's. Large dams such as Nimbus and Folsom are effective sediment traps. Additionally, the sediment of interest in this study is coarse and virtually impossible to suspend. Sediment trapping curves developed by Brune (1953) relate the trap efficiency to the ratio of reservoir capacity to average yearly inflow (Figure 4-4). Using the capacity of Folsom Dam (975,000 ac-ft) and the inflow from the 2004 water year (1,811,00 ac-ft) gives Folsom Dam a ratio of 0.5. This corresponds to a trapping efficiency of more than 90% for fine, colloidal sediment and much higher efficiency for coarse sediment.

One final source of gravel that must be considered is human input. The only major project involving gravel addition occurred in 1999. At this time, gravel augmentation experiments were conducted by the California Department of Fish and Game at three sites, including Sailor Bar, Lower Sunrise, and Sacramento Bar. A total of 3,300m^3 of gravel was added at these sites (Horner 2005).

In terms of gravel input to the LAR, bank erosion is likely to be the only major contributor. This chapter looks at the volume of gravel that has been introduced to the LAR by bank erosion.

4.2 Method

Areas of bank erosion were identified by comparing the historic location of the active channel boundary with the current boundary location. This was achieved using aerial photography from 1957 and 2002. Photos from these years were chosen because they span the timeframe of interest after the completion of Folsom and Nimbus Dams and because the photos have similar discharge (3300 cfs and 2700 cfs, respectively).

Because the wetted perimeter in the photograph does not necessarily define the entire active channel, the channel boundary was often drawn outside of the photo's water line. Three criteria were used to define the active channel: the water line in the photo, type and density of vegetation, and soil shading. Low brush and ground cover are possible within the active channel, but taller vegetation does not persist on the American River in areas that are regularly inundated. Where there is no vegetation, the shading of the ground surface was used to identify the active channel. Areas that had not been inundated recently are slightly darker. As an example of how these criteria were used, Figure 4-5 shows the right (north) bank at the Fish Hatchery with no vegetation in 1957 and vegetated in 2002.

The aerial photos were georeferenced as raster data and the channel boundaries digitized as vector polygon features. A geometric subtraction was performed on the polygons to identify those parts of the 2002 channel that were not part of the 1957 channel, signifying erosion. A 10m cluster tolerance (maximum distance at which the channel boundaries are considered coincident) was set in the GIS software so that slight differences in the channel boundary between the two photos were ignored. Figures 4-1 and 4-2 show the locations of significant bank erosion in reaches 4 and 3, respectively.

In addition to identifying the locations of significant erosion, the GIS software also calculated the surface area of each eroded bank. To determine the volumes, estimates of the height (thickness) of each eroded section were measured in the field (Figure 4-6). Because of the complexities of bar forms and bank shapes, simply multiplying the surface area by the bank height may not accurately describe the volume of an eroded bank. All of the eroded banks are now fairly steep. If the bank had a gentle slope before erosion, as in the case of a point bar (Figure 4-7B), then the cross-sectional geometry resembles a triangle, and the formula $V_e = \frac{1}{2}Ah$ gives a reasonable estimate of the volume of sediment eroded (where V_e = volume eroded, A = area eroded as measured from photographs, and h = height of eroded bank measured in the field). However, if the bank was already steep, as in the case of the erosion of a cut bank (Figure 4-7C), then a rectangular eroded cross-section gives a better estimation and the formula $V_e = Ah$ should be used. Therefore, for each site a determination was made whether to use the triangular or rectangular calculation method. This determination was based on two factors: the remaining (un-eroded) geometry of the bank upstream and downstream from the eroded areas, and the location of the erosion relative to meanders, with the inside of meanders likely being point bars (triangular) and the outside of meanders likely being cut banks (rectangular). The height of each eroded site was determined using a Jacob's Staff and hand level along each eroded bank (Figure 4-6). These measurements were used to determine one representative height for each site (Table 4-2).

The percent gravel in the bank at each site was estimated in the field. Percentages less than 100% reflect excess fines. At these sites there were either excess fines in the gravel matrix, or there were layers of fines interspersed with layers of suitable gravel. The volume of eroded sediment at each site was calculated by multiplying the percent gravel (decimal equivalent) times the volume of eroded sediment (Table 4-2).

4.3 Results

Five locations of significant bank erosion were identified on air photos in reach 4 (Figure 4-1) and four locations were identified in reach 3 (Figure 4-2). Each site was visited to verify evidence of erosion, measure the height of the bank, verify the type of bank (point bar or cut bank), and make an estimate of the percentage of spawning gravel.

The Fish Hatchery erosional site (Figure 4-5) is located at river km 36.2 on the left (south) bank of the river about 1 km below Nimbus Dam. This site is about 500m below the removable weir that diverts fish into the hatchery during spawning season. The eroded bank is 500m long and has receded up to 50m. Just upstream of the erosion, the right (north) bank runs up against a 50m tall bluff, then diverges from the bluff and the thalweg shifts to the south side (where the erosion has occurred). The site has recently been stabilized with riprap 1 to 2 meters in diameter to prevent further encroachment on the hatchery. The eroded stretch of river is relatively straight. The height of the bank was measured at 9 different locations with bank heights ranging from 4.5 to 8.5 meters, and an average value of 6 meters was used for volume estimates. The riprap made it difficult to observe the percent gravel within the bank, but exposures at the top of the bank showed primarily gravel with a small amount of fines, resulting in an estimated 90% gravel content. Using the surface area of 14,000m^2 and the triangular (point bar) calculation method, an estimated 38,000m^3 of gravel has been eroded from the Fish Hatchery site since 1957 (Table 4-2).

The Sailor Bar erosional site (Figure 4-8) is located on the right (north) bank at river km 35.3, where 1000m of shoreline has receded up to 100m. The location is on the inside of a meander bend, so triangular (point bar) geometry was used for sediment volume calculations. The height was measured at 9 different locations and ranged from 4 - 6.5m with an average height of 6m. The bank was composed exclusively of gravel sizes appropriate for spawning. With 100% gravel content and a surface area of 46,000m^2, an estimated 126,000m^3 of gravel has been eroded from the Sailor Bar site since 1957 (Table 4-2).

A small amount of erosion occurred on the left bank at Upper Sunrise (Figure 4-9) near river km 33.7. At this location, 120m of shoreline has receded 20m. The erosion occurred in a side channel opposite from the high bluffs. In earlier photographs of this area, a gravel operation existed to the southwest. The erosion is clearly on the inside of a meander bend, so triangular (point bar) geometry was used for volume calculations. Seven height measurements were made along the eroded bank, with results ranging from 4 to 6m and averaging 5m. The bank contained abundant fine sediment interspersed with gravel, resulting in an estimated gravel content of 25%. Using the 2000m^2 surface area, an estimated 1000m^3 of gravel has been eroded from Upper Sunrise since 1957 (Table 4-2).

Significant erosion has occurred on the right bank at Lower Sunrise access (Figure 4-10). This site is at river km 31.7 and air photos show that 450m of shoreline has receded up to 65m since 1957. The overall channel is relatively straight at this location, but during low to moderate flows the river is diverted around a mid-channel bar feature, causing erosion on the north bank. There is also a side channel on the south bank that goes dry at flows below 3000cfs. Because the channel is relatively straight overall, the eroded bank is typical of neither a point bar nor a cut bank; however, the north bank both upstream and downstream is not particularly steep, so triangular geometry was used for volume calculations at this site. Thirteen height measurements were made along the bank with results ranging from 2 to 5.5m and averaging 4m. Gravel content varied throughout the eroded bank, with predominantly fine-grained material in the upstream portions, gravel in the middle, and a mixture of fine and coarse sediment in the downstream portions, resulting in an estimated overall gravel content of 50%. Using the surface area of 15,000m^2, an estimated 15,000m^3 of gravel has been eroded from the Lower Sunrise site since 1957 (Table 4-2).

The erosion on the right bank at San Juan Rapid (river km 29.0) is slightly different than the other locations, because the river makes a pair of sharp bends before meeting the 30m tall bluffs on the north side for a third time (Figure 4-11). Two sections in the area have eroded a total of 460m of shoreline and have retreated up to 50m. The eroded banks are part of a cut bank, so rectangular (cut bank) geometry was used for calculations. The height of the bank and gravel content was estimated using a hand level from the opposite bank. The height was estimated at 7m and the gravel content 25%. This bank has yielded approximately 22,000m^3 of gravel since 1957 (Table 4-2).

The Lower Rossmoor erosional site is located at river km 26.5 on the left bank. At this site, 700m of shoreline has receded up to 57m (Figure 4-12). The bank height was measured at 6 locations ranging from 3.5 to 7m with an average of 6m. The upstream part of the eroded section is on the inside of a meander bend and the downstream part is on the outside, however, the bank generally seems to have a gentle slope in adjacent areas, so triangular geometry was used. The bank was primarily fines (10% gravel), yielding only 7,000m^3 of gravel from the 24,000m^2 section. (Table 4-2)

The erosion at Hagan Park is located on the left bank where the stream has straightened due to a meander cutoff downstream between 1964 and 1966 (Figure 4-13). The bank adjacent to the eroded section is very steep, so rectangular geometry was used for calculations. 800m of bank have receded up to 91m and is 7m thick, translating the 51,000m^2 of erosion into 167,000m^3 of gravel, which is the largest contribution of gravel from a single site in this study (Table 4-2).

The meander at Upper Goethe was cut off between May 1964 and August 1966, based on aerial photographs from those times. The sharp bends that existed before were straightened, and minor erosion occurred on the north bank with more significant erosion of the point bar on the south bank (Figure 4-14). The 570m of shoreline on the south bank receded up to 122m yielding an area of 37,000m^2 and a volume of 61,000m^3 (Table 4-2).

The Lower Goethe erosional site is the furthest downstream in reach 3 (Figure 4-15). The erosion occurred on the inside of a broad meander bend, so triangular (point bar) geometry was used. The bank receded 61m, was 640m long, and consisted of primarily fine sands and silts. The sediment contained 10% gravel, so the 24,000m^2 of erosion only yielded 6000m^3 of gravel (Table 4-2).

Summing the gravel eroded from all nine sites gives a total eroded gravel volume of 440,000m^3 (Table 4-2). The volume added by humans (3000m^3) was therefore insignificant and below the two significant digits in these measurements.

4.4 Discussion

A typical meandering river will naturally erode on the outside of meanders (cut bank) and deposit on the inside (point bar) (Mount 1995). Most of the erosion on the LAR, however, has occurred in straight reaches or on the inside of meander bends (Figures 4-1 and 4-2). It is difficult to identify a specific geomorphic process that would cause this, but it suggests that the dynamics of the river may have changed due to incision, the damming of the river, and reduced sediment supply from upstream.

It is also interesting to note that significant erosion on the LAR occurs in upstream and downstream locations. Sailor Bar and Hagan Park are the sites of maximum sediment erosion, and are located on the upstream and downstream margins of the study area respectively (reaches 4 and 3 of the LAR). This suggests that two mechanisms may be responsible for the degradation: incision and sediment removal that progressed downstream (mouthward) from the dam, and channel degradation in the lower reaches that may have progressed upstream (headward) from below the study area.

In describing the downstream effects of dams, Collier, et al. (1996) have observed that virtually all rivers incise and degrade directly below dams and that this degraded area will lengthen downstream (mouthward) over time until it reaches an equilibrium (or a tributary supplies more sediment). The large amount of gravel eroded from the bank at Sailor Bar (just 2km below Nimbus Dam) is consistent with this model and suggests that the degraded area on the LAR is at least 2 km long.

The downstream boundary of reach 3 was chosen primarily because it represented a knickpoint (location where the river elevation drops sharply) that separates the low gradient of reach 2 from the higher gradient upstream (Figure 4-3). Knickpoints tend to progress upstream very rapidly (in geologic terms), due to the steep gradient, high velocity, and high stream power, unless they are controlled by an erosion-resistant feature such as a dam or resistant layer of bedrock (Mount 1995). The meander cutoff and subsequent erosion of the nearby banks (Upper Goethe and Hagan Park) could be attributed to this process of headward progressing erosion. Figure 4-3 shows the change in gradient between reaches 2 and 3. In addition, the channel widens here and the sediment load changes from primarily gravel upstream to primarily fine sediment downstream (based on qualitative field observations).

These two processes, headward and mouthward erosion, may be happening simultaneously on the LAR. But regardless of the mechanism, banks of the LAR have eroded and significant volumes of gravel have been added to the channel as a result. It is unlikely, however, that these volumes are significant enough to make up for the loss of supply from upstream. As the results from chapter 6 will show, channel degradation (incision) has occurred in reaches 3 and 4, and these gravel losses are much larger than the inputs described in this chapter.

4.5 Figures and Tables

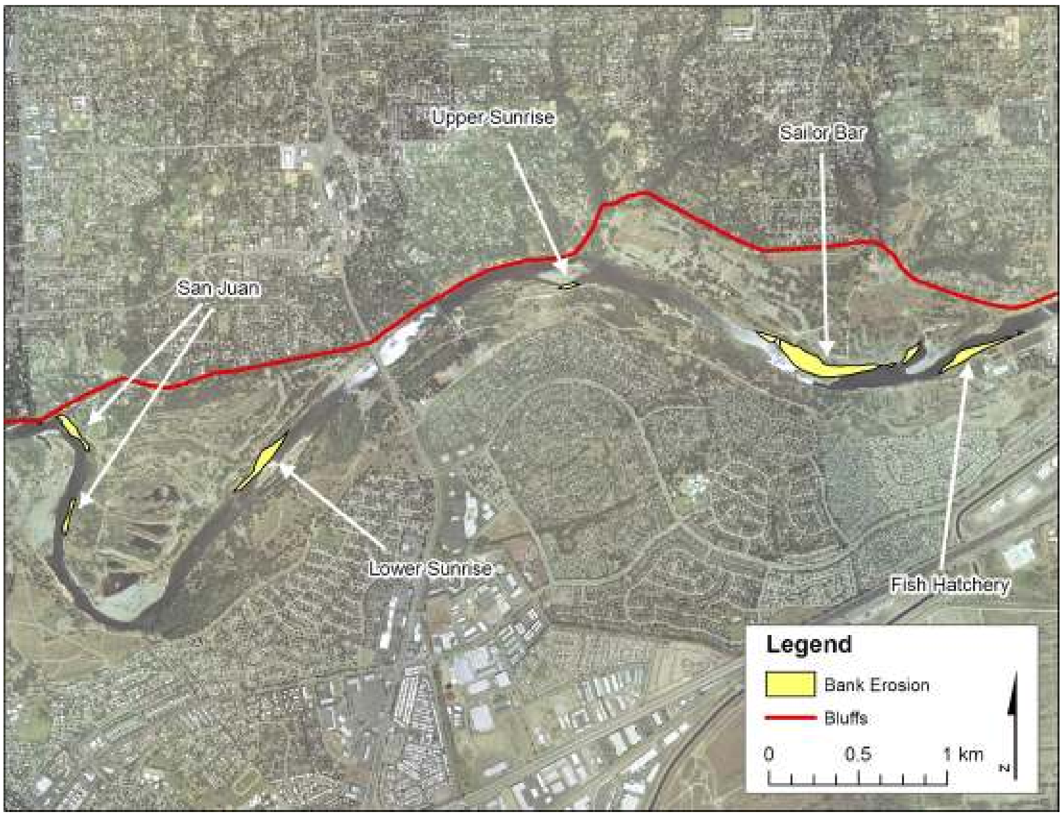


Figure 4-1 Locations of significant erosion in reach 4 of the LAR. The location of the bluffs to the north are indicated.

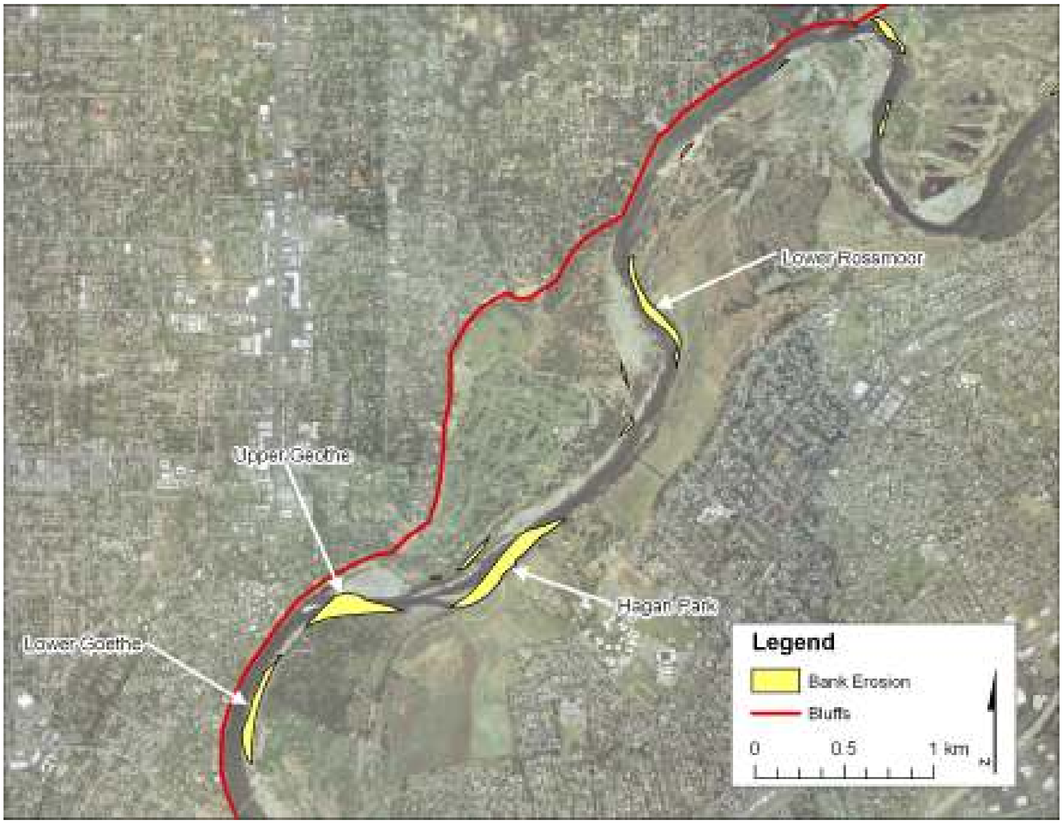


Figure 4-2 Locations of significant bank erosion in reach 3 of the LAR. The location of the bluffs to the north are indicated.

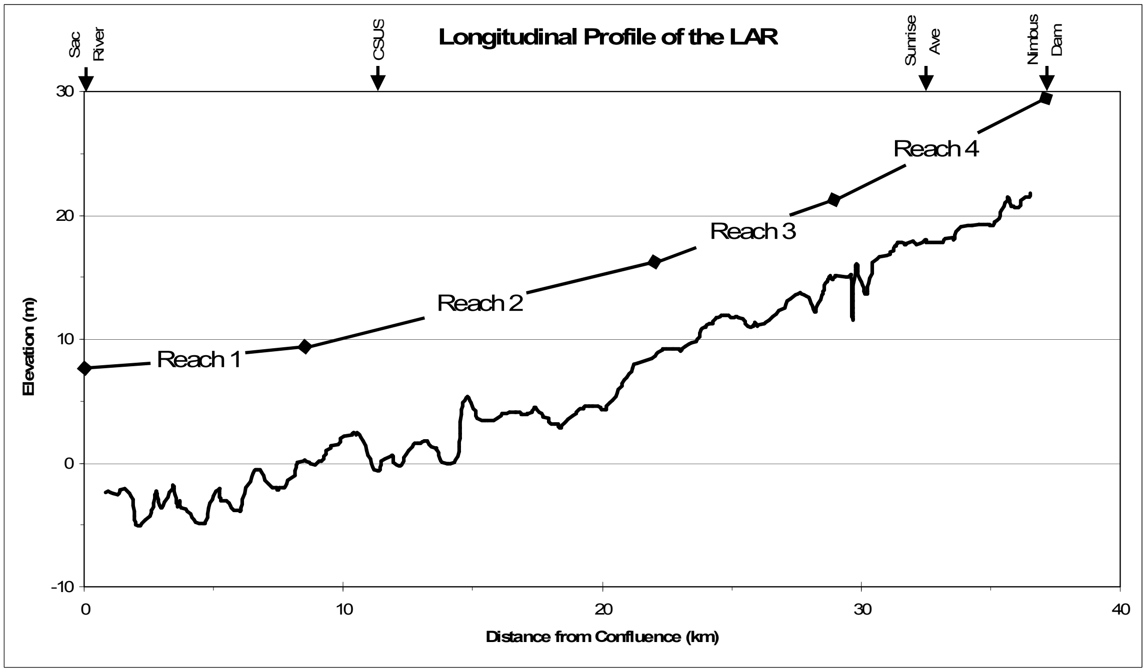


Figure 4-3 This longitudinal profile of the LAR from the confluence with the Sacramento River to Nimbus Dam is from 1998 based on channel bottom elevations from 2-foot contours produced by the Army Corps of Engineers (USACE 1998).

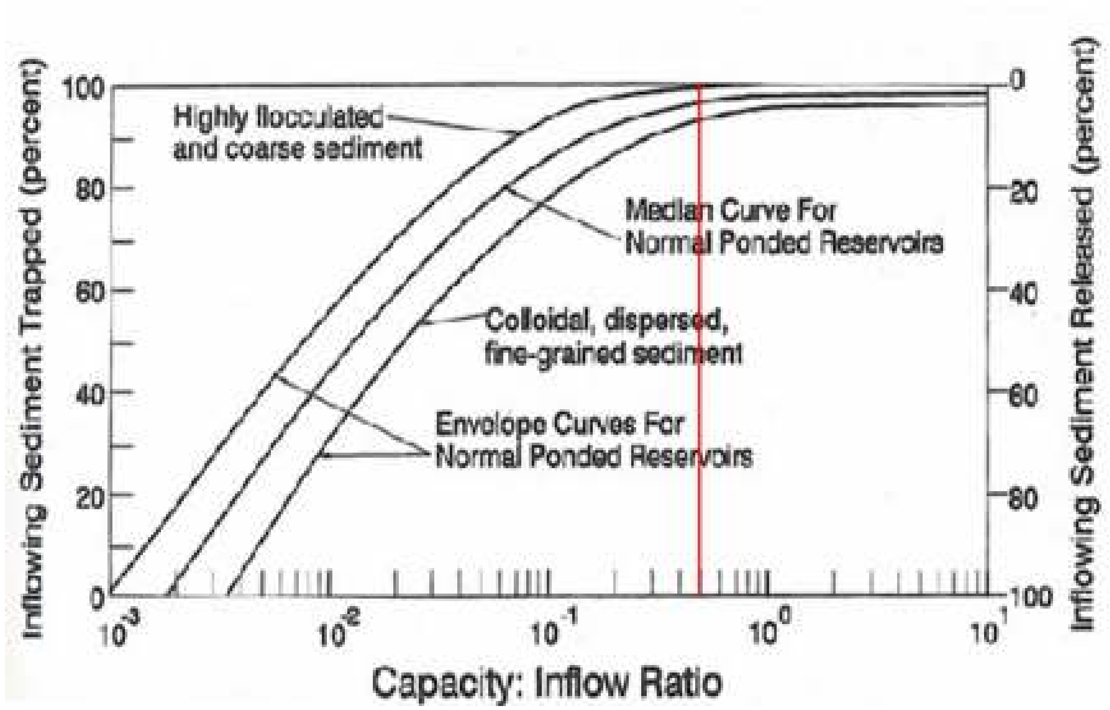


Figure 4-4 Brune (1953) sediment trapping curve. The vertical line indicates the capacity to inflow ratio of Folsom Dam.

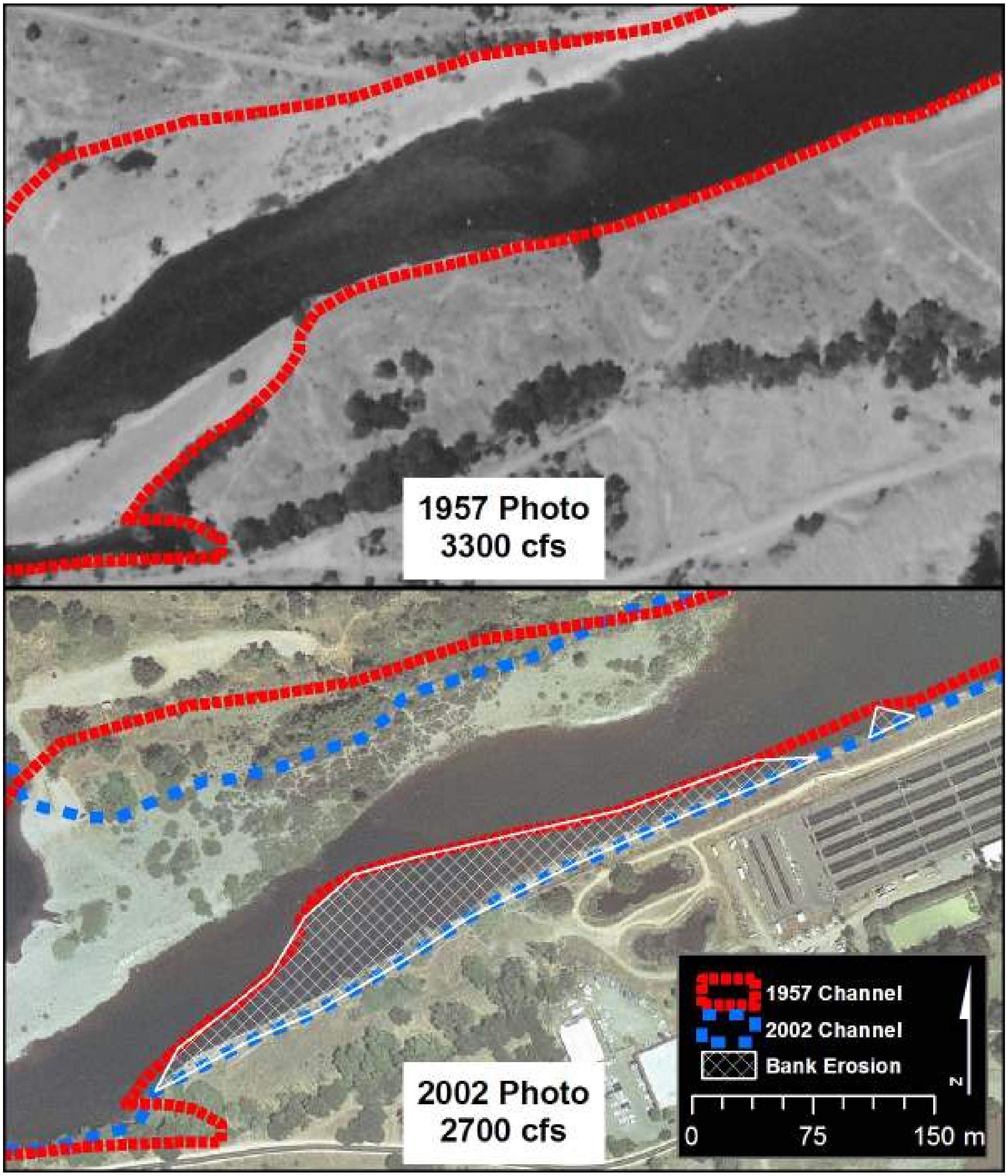


Figure 4-5 Fish Hatchery. A significant area ($14{,}000 m^2$) was eroded on the left bank before it was armored to prevent encroachment on the hatchery structures. The bank is 6 meters high and contains 90% gravel.

Figure 4-6 Bank heights were measured using a Jacob’s Staff and hand level. Black marks on the staff are 50 cm apart.

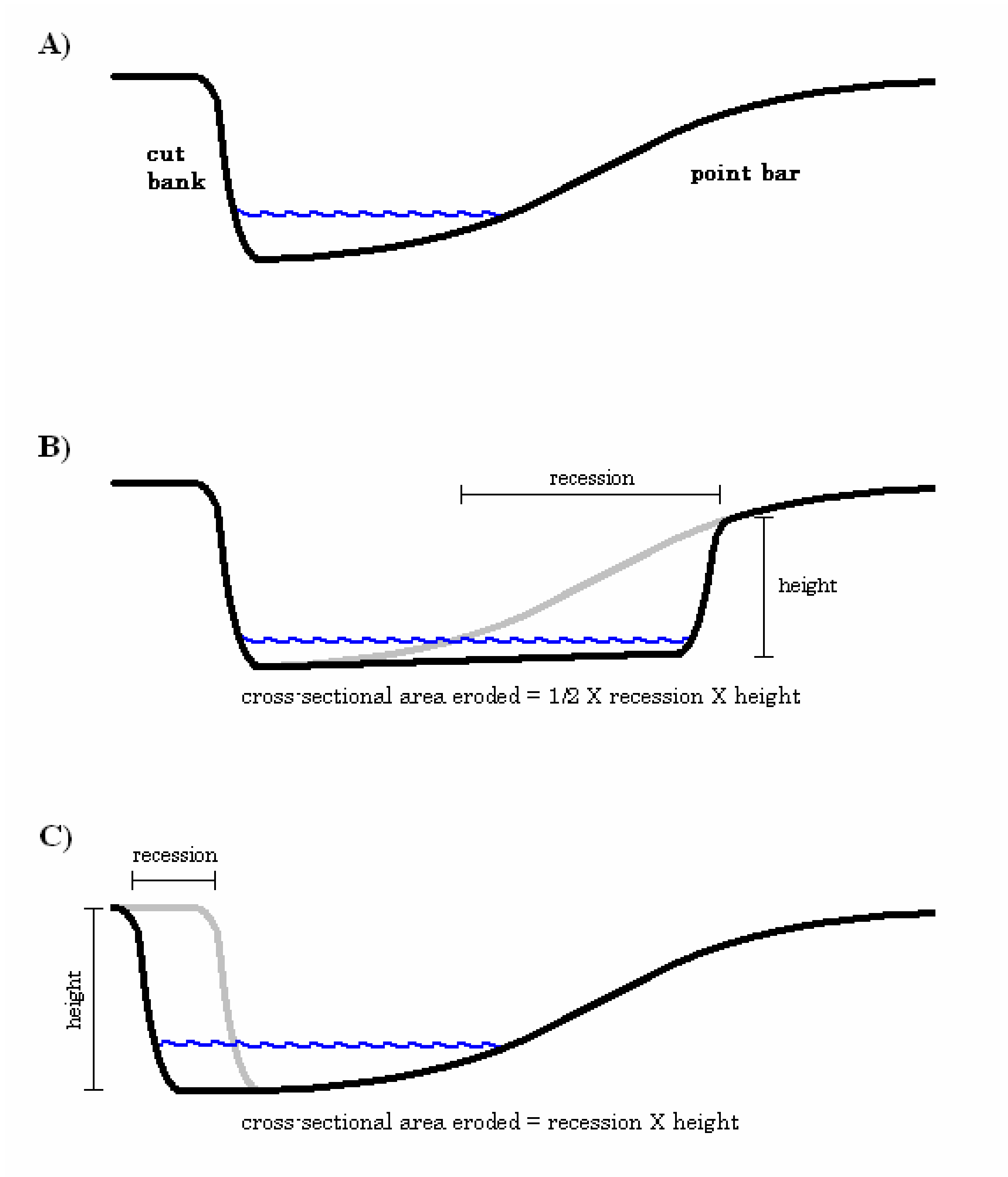


Figure 4-7 Geometry of bank erosion. Erosion of a point bar approximates a triangle (B), while cut bank approximates a rectangle (C). Point bar erosion calculations use the formula ½Ah, while cut bank calculations us Ah.

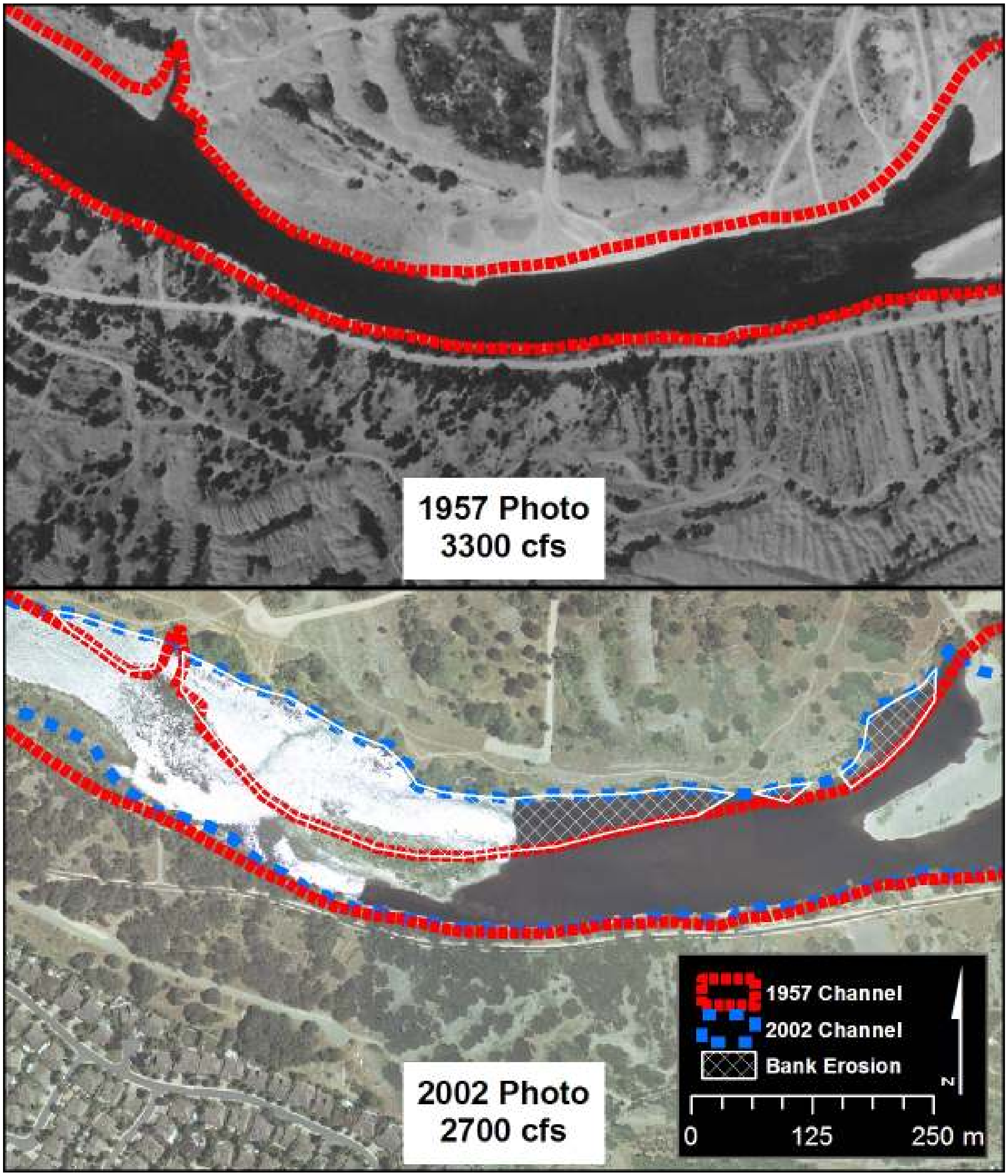


Figure 4-8 Sailor Bar. The right bank at this location has contributed most of the gravel input in the upper reach of the river because it contains 100% gravel, is 6 meters high and 46,000m^2 has eroded.

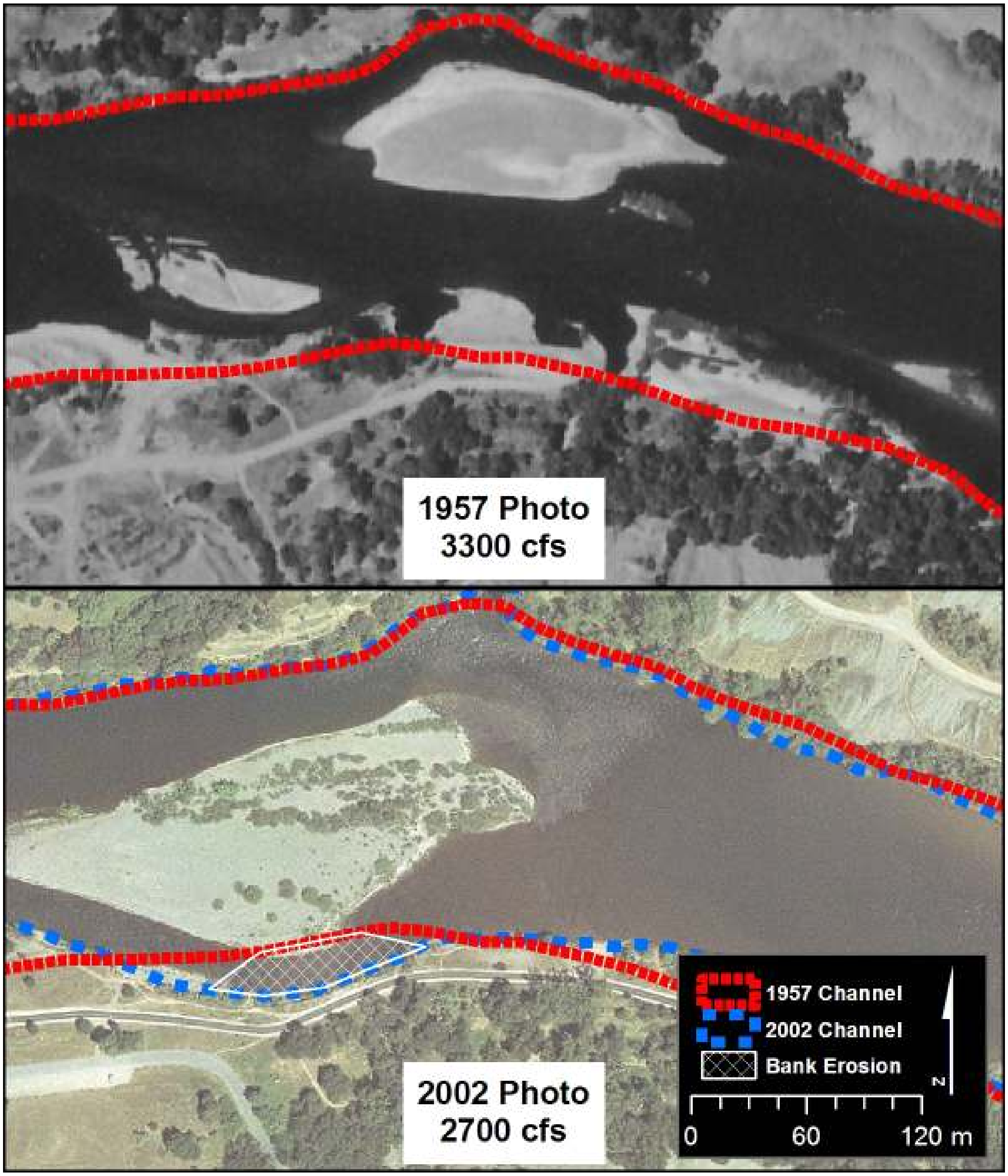


Figure 4-9 Upper Sunrise. The left bank at this location has lost an area of 2000m^2. The bank is 5 meters high and contains 25% gravel.

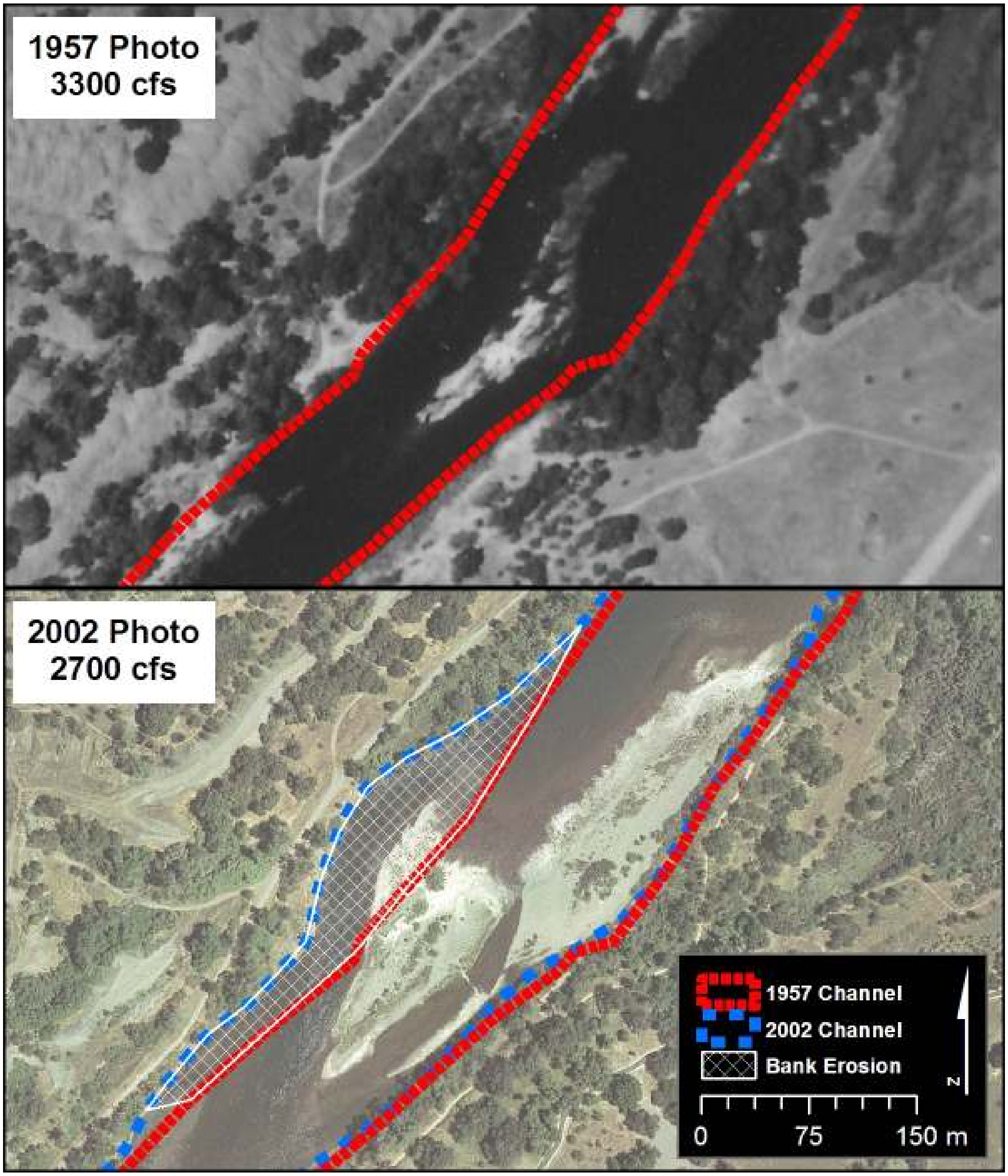


Figure 4-10 Lower Sunrise. The main flow of the river has shifted from the left bank to the right bank where it has eroded 15,000m^2 of gravel. The bank is 4m high, and contains 50% gravel.

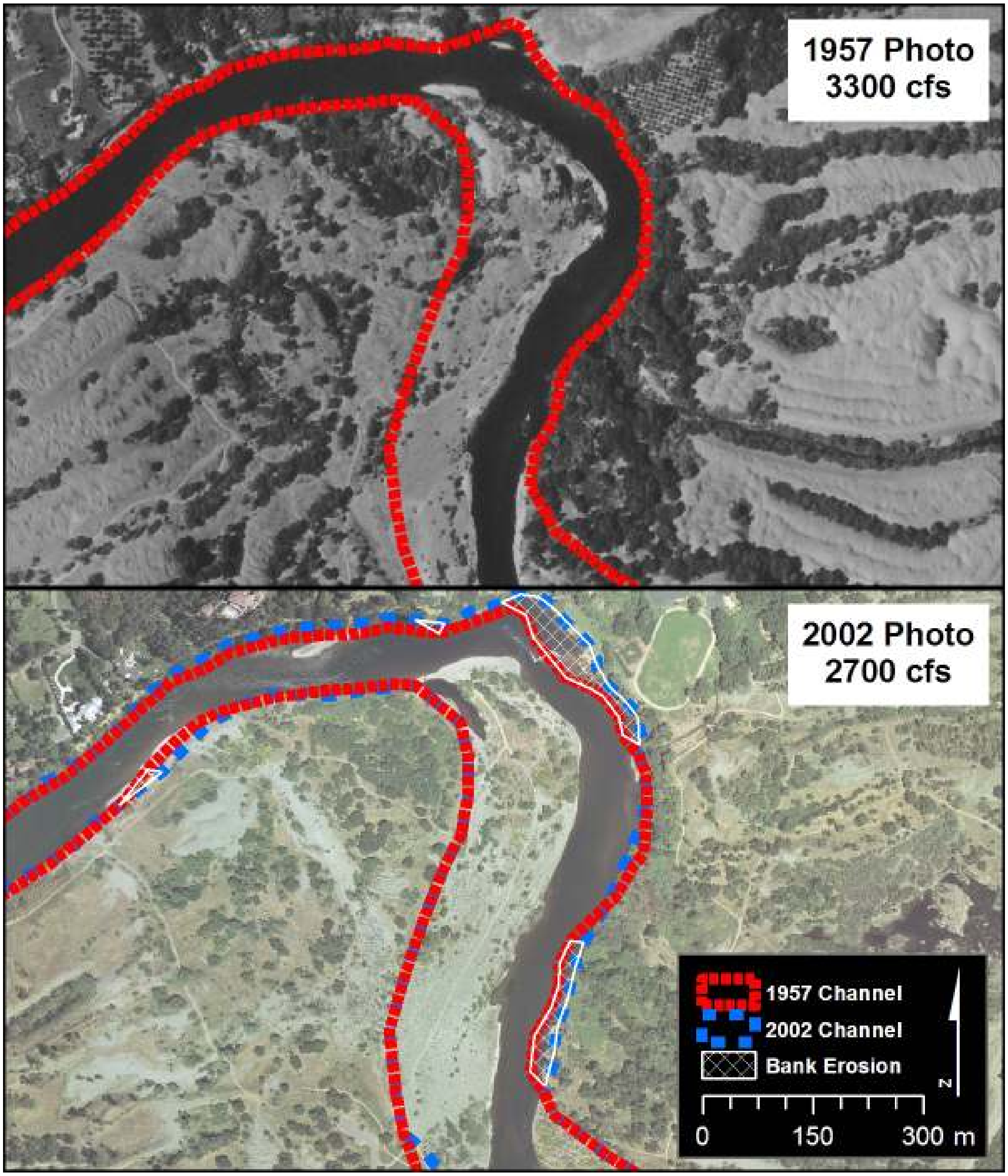


Figure 4-11 San Juan. The right bank of this sharp bend in the river has eroded a net area of 13,000m^2 between the two locations. It is 7m high and contains 25% gravel.

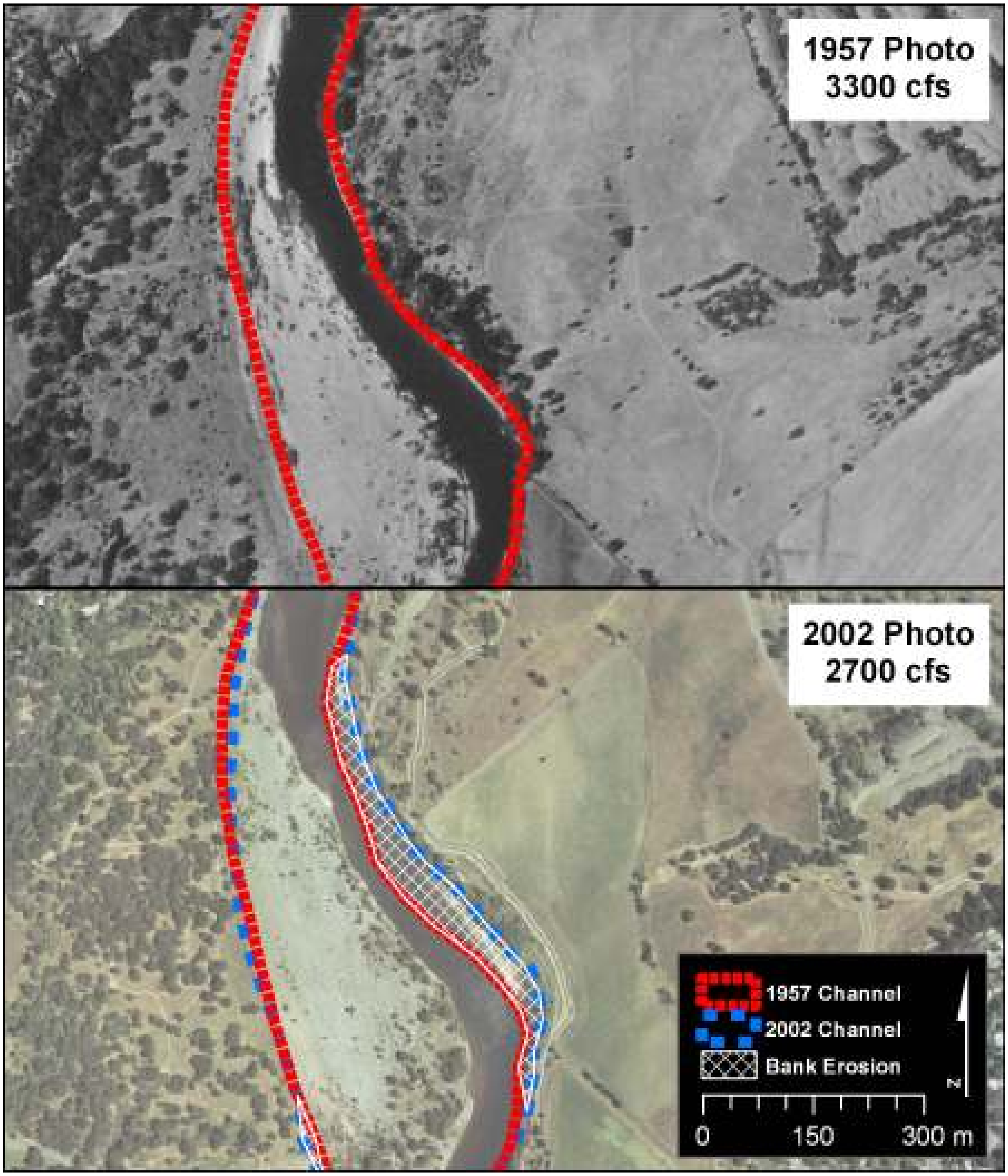


Figure 4-12 Lower Rossmoor. The left bank has lost an area of $24{,}000 m^2$. The bank is 6 meters high and contains only 10% gravel.

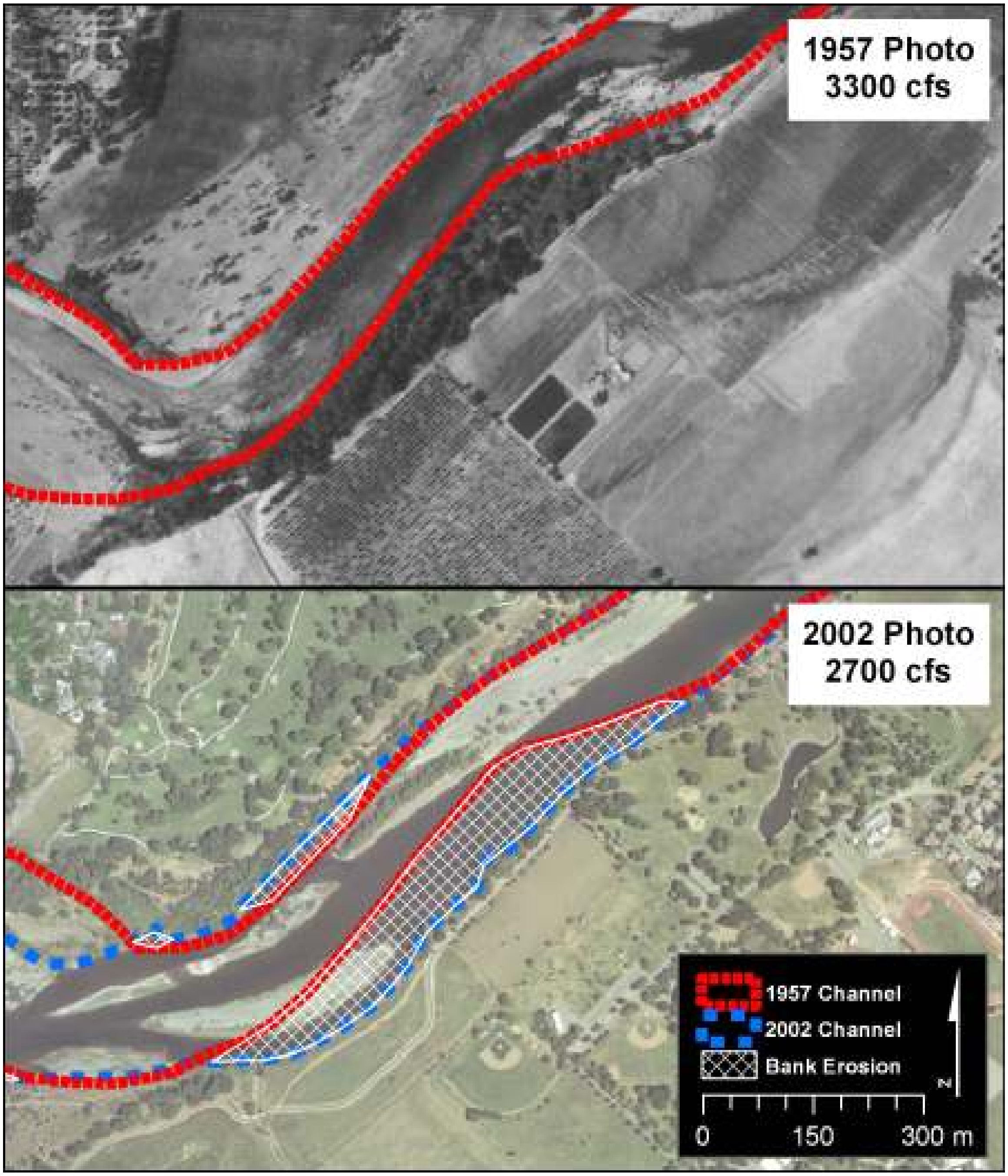


Figure 4-13 Hagan Park. The left bank has lost an area of $51,000m^2$. The bank is 7 meters high and contains 50% gravel.

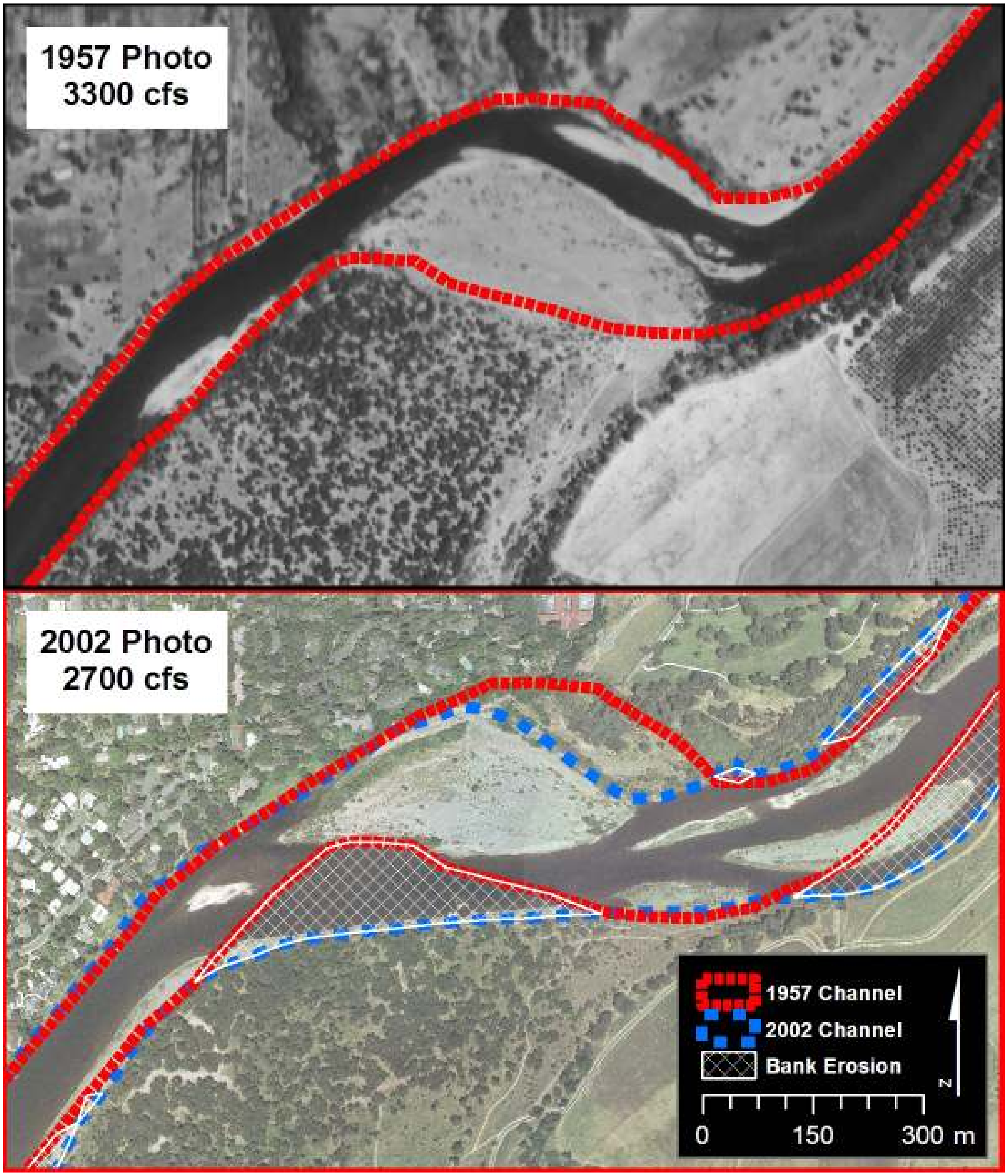


Figure 4-14 Upper Goethe. The meander at this location was cut off between 1964 and 1966. The eroded section has an area of 37,000m^2, has a height of 7m, and is 50% gravel.

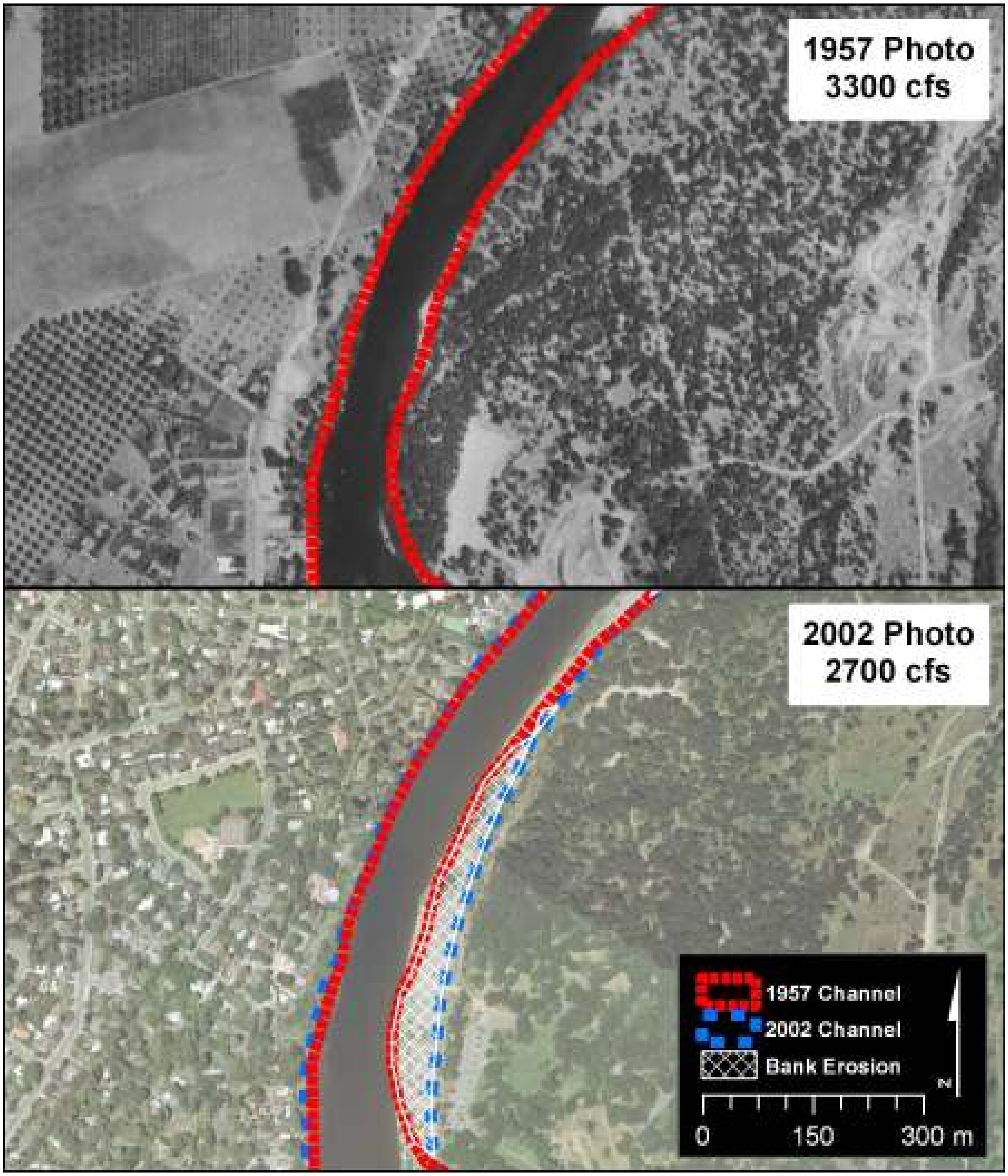


Figure 4-15 Lower Goethe. The left bank has an eroded area of 24,000m^2. The bank is 5 meters high and has 10% gravel.

Table 4-1 Potential sediment sources for rivers (Reid and Dunne 1996) and whether they apply to gravel.

	Source	Does it apply to gravel?
1	Landslides	Maybe
2	Debris Flows	Maybe
3	Gullies	No
4	Treethrow	No
5	Animal burrows	No
6	Sheetwash erosion	No
7	Wind erosion	No
8	Dry ravel	Maybe
9	Bank erosion	Yes

Table 4-2

Gravel Input Calculations for Reaches 3 and 4

Location	Triangular or Rectangular	Surface Area Eroded (m^2)	Estimated Thickness (m)	Sediment Volume (m^3)	Estimated Gravel Content	Gravel Volume (m^3)		
Fish Hatchery	T	14,000	6	42,000	90%	38,000		
Sailor Bar	T	46,000	6	126,000	100%	126,000		
Upper Sunrise	T	2,000	5	5,000	25%	1,000		
Lower Sunrise	T	15,000	4	31,000	50%	15,000		reach 4
San Juan	R	13,000	7	90,000	25%	22,000	200,000 m^3	subtotal
Lower Rossmoor	T	24,000	6	73,000	10%	7,000		
Hagan Park	R	51,000	7	334,000	50%	167,000		
Upper Goethe	T	37,000	7	121,000	50%	61,000		reach 3
Lower Goethe	T	24,000	5	60,000	10%	6,000	240,000 m^3	subtotal

440,000 m^3 **TOTAL**

Chapter 5: Volumetric estimate of gravel loss

5.1 Introduction

A natural, undisturbed reach of gravel-bed river that is in equilibrium, has relatively constant gravel content over short time scales (tens to hundreds of years). Downstream gravel transport occurs on a statistically regular basis, but this “gravel out” is offset by “gravel in” (transport from upstream and tributaries, or by bank erosion) (Mount 1995).

The Lower American River (LAR), however, is a disturbed, regulated river, and the amount of gravel changes over time as it adjusts to new flow regimes, sediment supply, and channel changes. The history of the LAR (see Chapter 1) includes several episodes of disturbances, starting with the huge influx of hydraulic mining sediment in the late nineteenth century, then dredging in and near the channel in the early twentieth century, and finally the impoundment of the river in 1955. In addition, changes to the Sacramento River have had a profound impact on the LAR by way of change in base elevation. The Sacramento River is reported to have aggraded by over 3m with mining sediment in the late nineteenth century, and then degraded as sediment supply was reduced by the construction of dams in the upper Sacramento Valley watershed (Dillinger et al. 1991; NRC 1995). The Sacramento River was also been dredged for navigation (Mount 1995). In addition, the mouth of the American River was moved upstream and the last few miles of the channel were straightened for flood control in the nineteenth century (Dillinger et al. 1991).

The production of mining sediment in the Sierras peaked before the turn of the century (Gilbert 1917). Gilbert (1917) proposed a symmetrical sediment wave model for the movement of this debris through the foothills and into the delta, although more recent studies (James 1993) have found vast amounts of mining debris still in foothill locations. James (1993) proposed an asymmetrical, right-skewed sediment wave model as a more accurate representation. Regardless, the typical response to excess sediment load would be downcutting and degradation with higher incision rates soon after the disruption and lower rates later on (Gilbert 1917; James 1991; James 1993).

Is gravel being lost from the LAR and if so, how fast? This is probably the most important question to river managers that is being addressed in this study. The historic events of the river suggest that the volume of spawning gravel is likely to have been reduced over the last hundred years, but it is difficult to estimate this loss. If the volume of gravel transported out of the LAR were known, then the volume loss could be calculated by subtracting the gravel output from the gravel input that was measured in Chapter 4 (Figure 1-1). However, because the gravel output is difficult to measure accurately, gravel loss was measured empirically in this study using historic geometry of the channel (cross-sections and longitudinal profiles) and comparing it to the modern geometry. This approach gives the most accurate view of gravel loss regardless of the accuracy of gravel input measurements from Chapter 4. This will then allow the gravel output component of the budget to be calculated.

5.2 Method

To measure gravel loss in the LAR (ΔS in Figure 1-1), changes in the volume of gravel within the channel were determined using four steps and several types of available data, including historic cross-sections and longitudinal profiles. First, the difference in cross-sectional area between historic cross-sections and modern ones was measured. This yielded the “cross-sectional area eroded”. Second, the “cross-sectional area eroded” was multiplied times the length of the reach for which the cross-section was determined to be representative. This was done to extrapolate the cross-sectional area to a volume and yielded the “sediment volume eroded”. Third, the historic and modern longitudinal profiles were used to verify that the change at the cross-section was truly representative of the entire reach. The difference in elevation between the historic profile and the modern one (incision) was estimated, and the average incision for the reach was compared to the incision at the cross-section and the volume of gravel loss was adjusted. This yielded the “adjusted sediment volume eroded”. Finally, to account for the fact that not all eroded sediment was gravel, the percentage of gravel was estimated for each reach and its decimal equivalent was multiplied by both the “sediment volume eroded” and the “adjusted sediment volume eroded” to yield the “gravel volume eroded” and “adjusted gravel volume eroded”, respectively.

Cross-sections for estimates of gravel loss came from three different data sets; two historic (CDC 1907; USACE 1963) and one modern (USACE 1998). The historic cross-sections were from 1906 and 1962 (but published one year later) and were obtained in digital form from the Water Resources Center Archives at the University of California, Berkeley and the U.S. Army Corps of Engineers, Sacramento District, respectively. The modern data (USACE 1998) were obtained from the U.S. Bureau of Reclamation, but were originally collected and produced by the U.S. Army Corps of Engineers, Sacramento District. The 1962 data included four cross-sections spaced along the LAR, and four corresponding cross-sections from 1906 were chosen (Figure 5-1) to allow comparison between 1906 and 1962. The 1998 data consists of a GIS shapefile with seamless topography and bathymetry (2-foot contour interval) which was used to produce modern cross-sections in the same location as each historic cross-section (Figures 5-2 to 5-9). The difference in area between the cross-sections was calculated by using a linear interpolation of each section, summing the differences in elevation at 1.5m intervals, and multiplying by 1.5m. This calculation was done only for the area within the modern active channel and produced an estimate of the cross-sectional area eroded at each cross-section location.

This area was then multiplied by the length of the reach to estimate the sediment volume eroded for each reach. This required the LAR to be divided into 4 reaches, ideally with each reach having characteristics similar to the corresponding cross-section location. Geomorphic characteristics were used in defining these reaches. Descriptions of each reach can be found in Chapter 1. To determine the length of each reach, the thalweg distance was measured on a map (USACE 1998).

Multiplying by the length of the reach assumed that the erosion that occurred at the cross-section was representative of the entire reach. To verify the validity of this assumption and adjust the volume accordingly, the incision measured between historic and modern longitudinal profiles was used as a proxy (Figure 5-10). The difference in elevation between the historic and modern profile (incision) was sampled (using a linear interpolation) at 30m intervals throughout each reach and an average incision calculated. This was compared to the incision calculated at the cross-section. The ratio of average incision for the reach to incision at the cross-section was multiplied by the “sediment volume eroded” to yield the “adjusted sediment volume eroded”. Two types of profiles were available: channel bottom (CB) and water surface (WS). However, both were not available for every year (Figure 5-10). Incision from 1906 to 1998 was calculated using CB, while incision from 1906 to 1962 was calculated using WS. Incision from 1962 to 1998 was estimated using the difference between the 1906 to 1998 (CB) incision and the 1906 to 1962 (WS) incision.

The final step in determining gravel volume loss was to take the previous calculations and account for the fact that not all sediment eroded was gravel. The percentage of the eroded material that was gravel was determined by estimating the percentage of gravel within the modern channel for each reach (Table 5-1). Based on field observations, the bed material in downstream reaches (1 and 2) was determined to be primarily sand while the upstream reaches (3 and 4) were determined to be primarily gravel. The “gravel volume eroded” and “adjusted gravel volume eroded” were calculated by multiplying the “percent gravel” (decimal equivalent) by the “sediment volume eroded” and the “adjusted sediment volume eroded” respectively for each reach.

5.3 Results

Gravel losses in reaches 3 and 4 have a much larger impact on spawning habitat because virtually all of the spawning activity occurs in these upper reaches (Vyverberg et al. 1997). Therefore, gravel losses from reaches 1 to 4 and losses from reaches 3 and 4 were summed separately (Table 5-1). About 6.1 million m^3 of gravel were eroded from reaches 1-4 since 1906 (about half of this occurring since 1962) and about 3.2 million m^3 eroded from reaches 3&4 since 1906 (also with half of this occurring since 1962). It should be noted that the division of the LAR into four reaches does not imply that inputs and outputs were summed separately for each reach of the river.

The channel has incised in all four reaches of the LAR, but the lower reaches (1&2) have seen more incision and sediment loss than the upper reaches (3&4). However, the majority of the gravel loss occurred in the upper reaches because the bed material in these reaches has a much higher fraction of coarse material.

In general, adjusting the volumes using the longitudinal profiles indicate that simply multiplying the cross-sectional area by the length of the reach slightly overestimated the amount of channel erosion. This resulted in the adjusted values being lower than the unadjusted. The exception to this is for reaches 1&2 from 1962-1998.

Once the volumes of gravel loss for discrete time periods were known, rates of gravel loss were calculated (Table 5-2). Three time periods were considered based on the availability of cross-section and longitudinal profile data: one primarily before the construction of Folsom and Nimbus Dams in 1955 (1906-1962), one primarily after dam construction (1962-1998), and one that spans the entire range (1906-1998). The gravel volume eroded for 1906-1962 was calculated by subtracting the 1962-1998 volume from the 1906-1998 volume. The rates estimated using unadjusted gravel volumes (i.e. using only cross-section data) indicate that all three time periods had similar rates of gravel loss. According to these data, 87,000 to 88,000m^3/yr were eroded from the entire LAR (reaches 1 to 4) and 55,000 to 58,000m^3/yr were eroded just from reaches 3 and 4. However, the adjusted gravel volumes (i.e. using both cross-sectional and longitudinal profile data) indicate a higher rate after dam construction; an increase from 51,000 to 90,000m^3/yr for the entire LAR and an increase from 32,000 to 44,000m^3/yr for reaches 3 and 4.

5.4 Discussion

The results of this part of the study indicate very clearly that gravel has been lost from the LAR over the last 100 years. All of the cross-sections show incision, and the longitudinal profiles show very few places where the channel has aggraded or even stayed the same in elevation (Figure 5-10). Downstream reaches 1 and 2 show the greatest amount of incision, and the only location where the channel elevation has stayed marginally stable is just downstream of San Juan Rapid at the upstream end of reach 3.

These data further support the idea of two mechanisms of channel degradation, one progressing downstream from Nimbus Dam and one progressing upstream from the confluence with the Sacramento River. The only location that seems to have been unaffected by either mechanism is near San Juan Rapid at the boundary between reaches 3 and 4. This location may have some controlling factor that renders it immune to degradation, possibly a geologic control with cohesive, ash-rich bedrock that is difficult to erode. The two sharp bends that the river takes at this location are unlike any other feature on the river.

Table 5-2 could suggest that the dam may be partially responsible for the reduction in gravel supply on the LAR because the "adjusted rate of gravel loss" is higher after 1955. However, two factors challenge the validity of this claim. First, two significant figures have been assigned to all of these measurements. This level of accuracy may not be justified, and one significant digit may be more appropriate. Rounding these numbers to one digit makes the difference in rates seem much less pronounced. Additionally, the measurements were adjusted by using longitudinal profiles from the three data sets. Each data set had a different source and the level of accuracy is largely unknown but is assumed to be high. The types of profiles are also not the same which may account for the difference in rate (Figure 5-10).

Regardless, the data from this project suggest that the LAR has been incising throughout the twentieth century and the rate of incision has not decreased. Both models for mining debris transport through this area (Gilbert 1917, James 1993) imply that the rate of incision should go down over time. The fact that it has not may be enough evidence to claim that Folsom and Nimbus Dams are at least partially responsible for the reduction in gravel on the LAR.

5.5 Figures and Tables

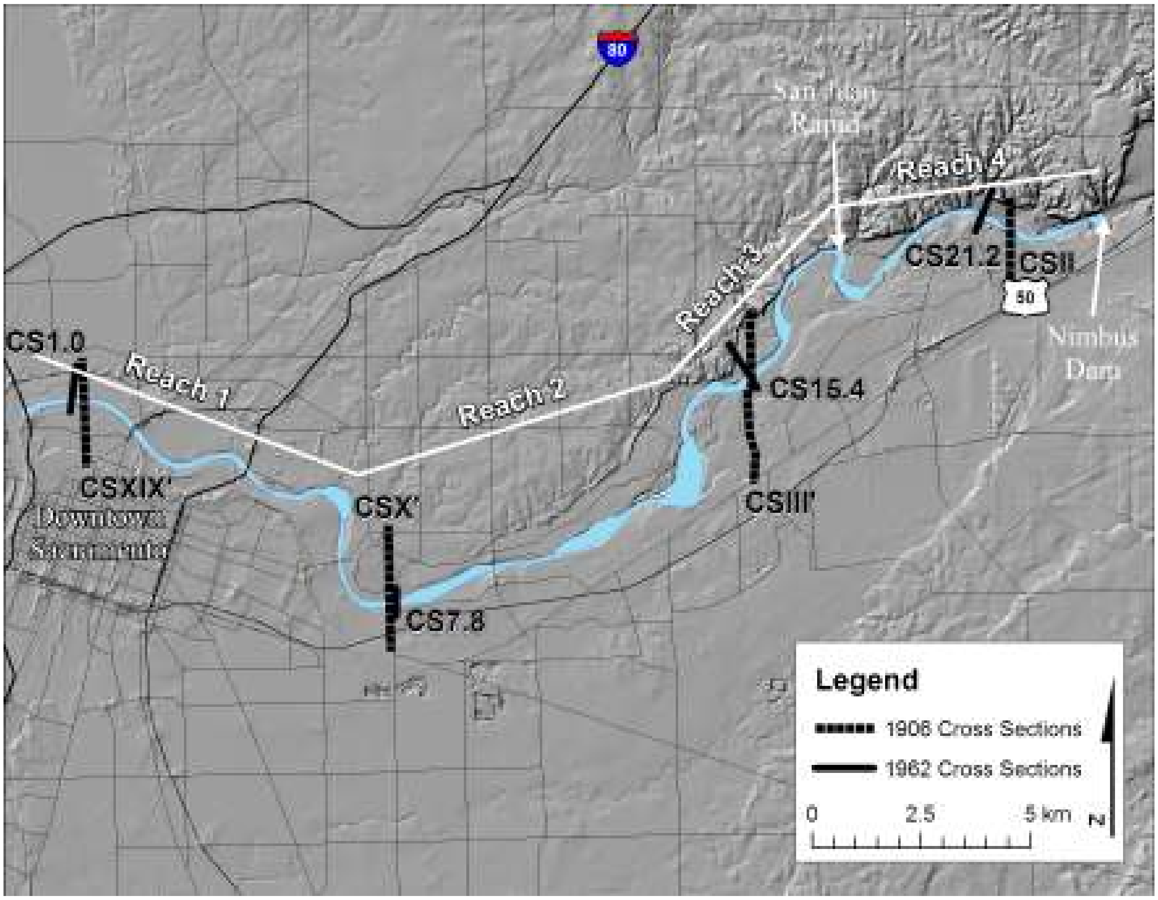


Figure 5-1 Location map for the LAR showing the location of the four reaches and cross-sections that were used to measure gravel loss. The cross-section IDs with Roman numerals are from 1906, while the IDs with Arabic numerals are from 1962.

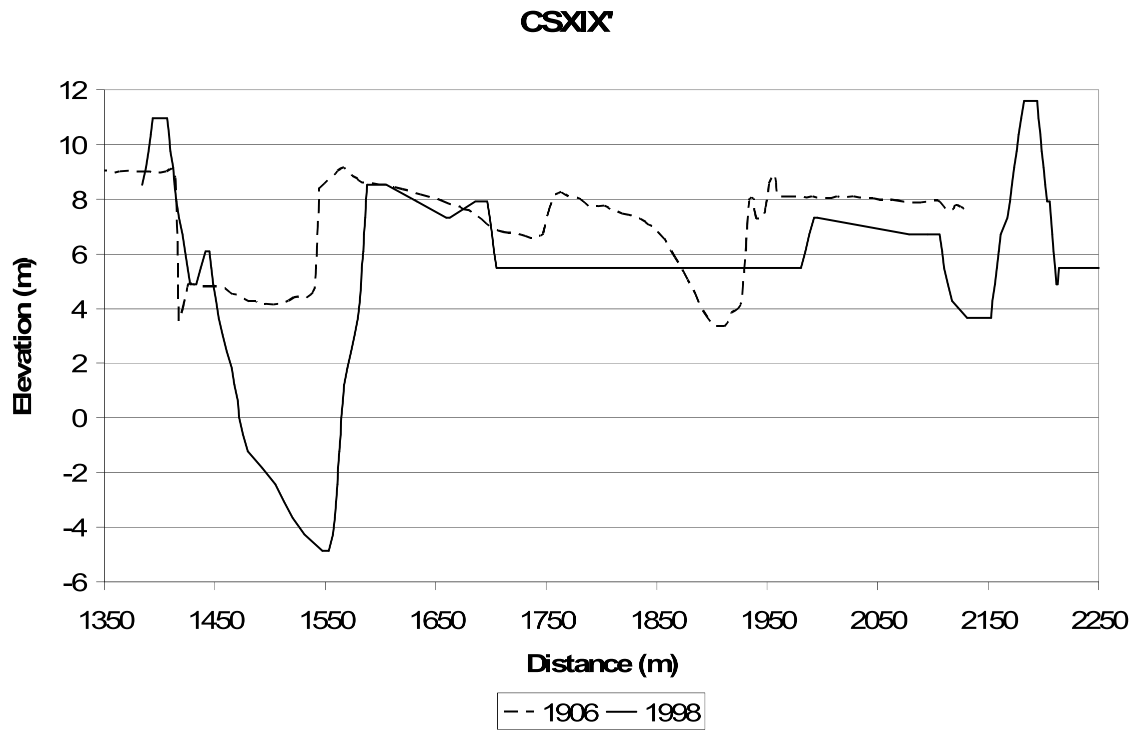


Figure 5-2 Cross-sections showing erosion between 1906 and 1998 in reach 1 at river kilometer 1.6 (CDC 1907; USACE 1998).

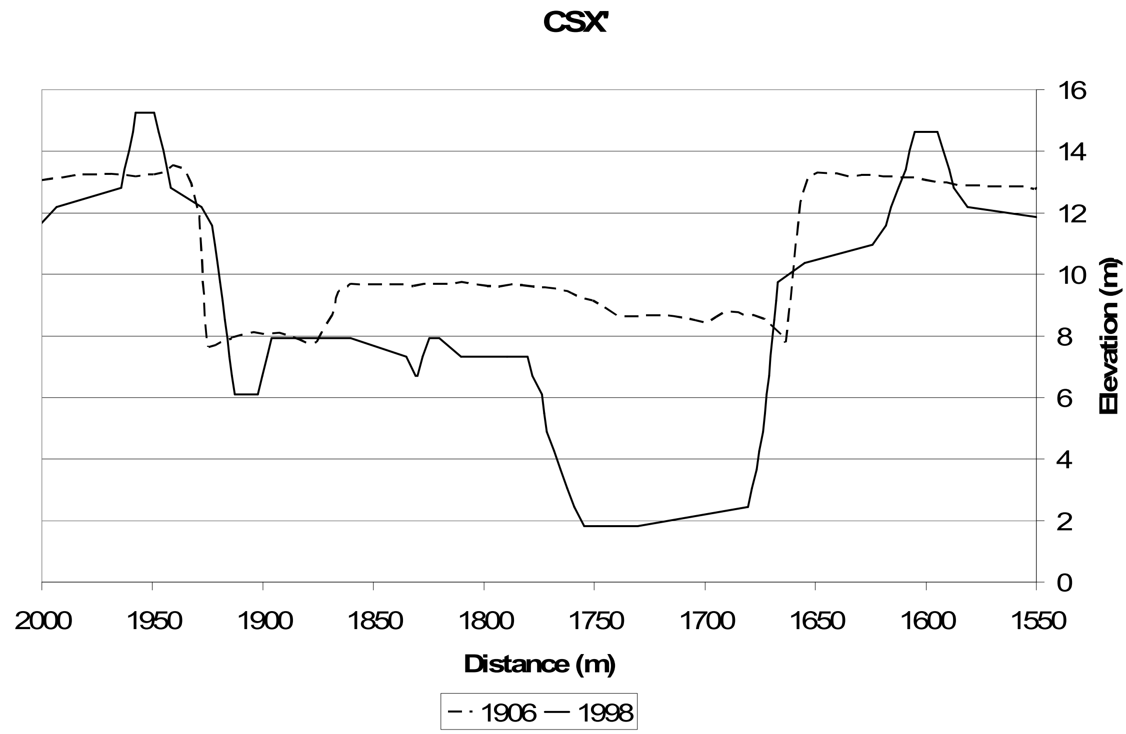


Figure 5-3 Cross-sections showing erosion between 1906 and 1998 in reach 2 at river kilometer 12.6 (CDC 1907; USACE 1998).

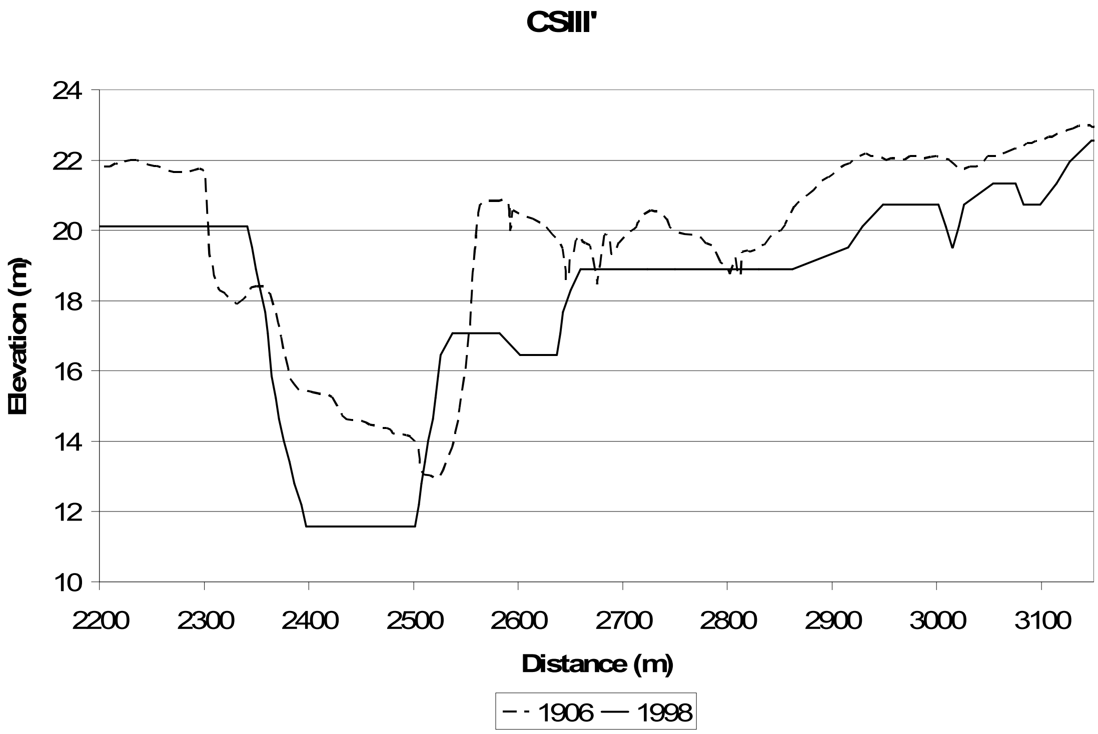


Figure 5-4 Cross-sections showing erosion between 1906 and 1998 in reach 3 at river kilometer 24.8 (CDC 1907; USACE 1998).

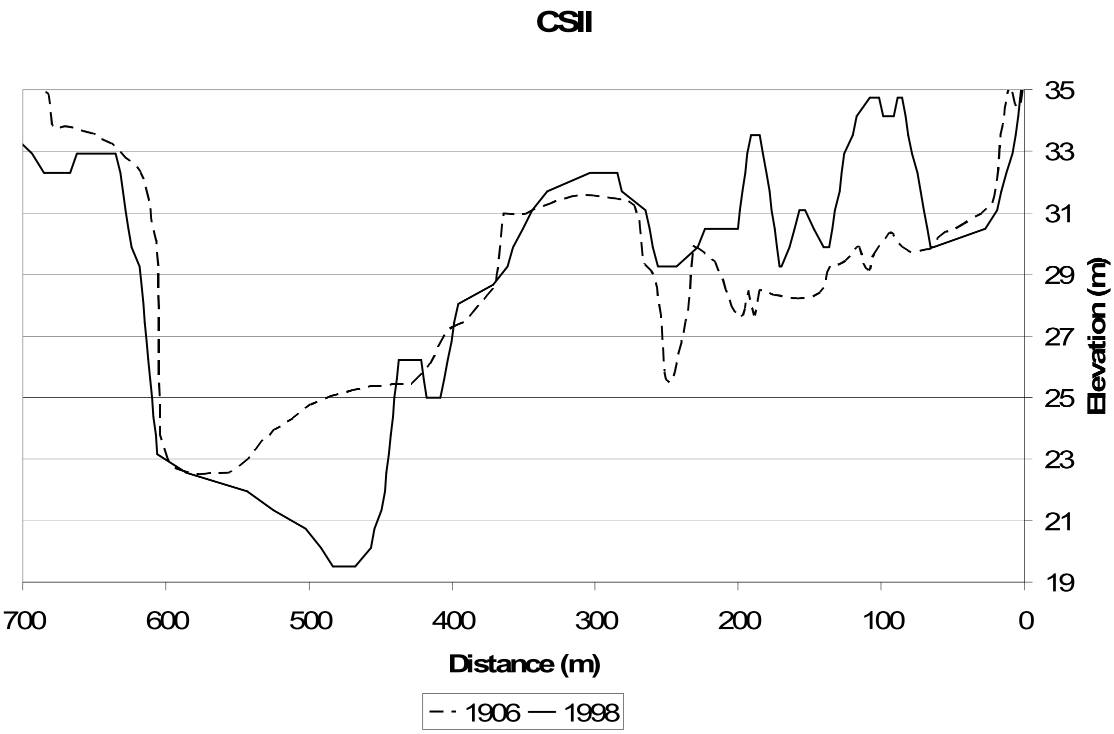


Figure 5-5 Cross-sections showing erosion between 1906 and 1998 in reach 4 at river kilometer 34.1 (CDC 1907; USACE 1998).

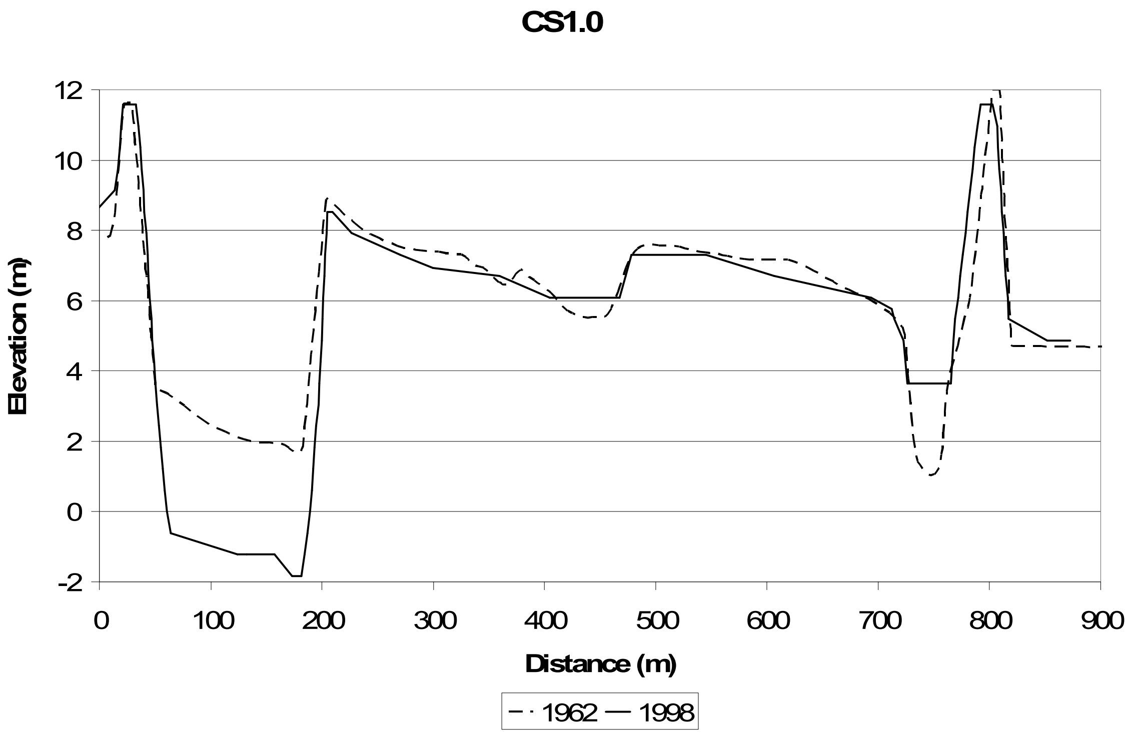


Figure 5-6 Cross-sections showing erosion between 1962 and 1998 in reach 1 at river kilometer 1.6 (USACE 1963; USACE 1998).

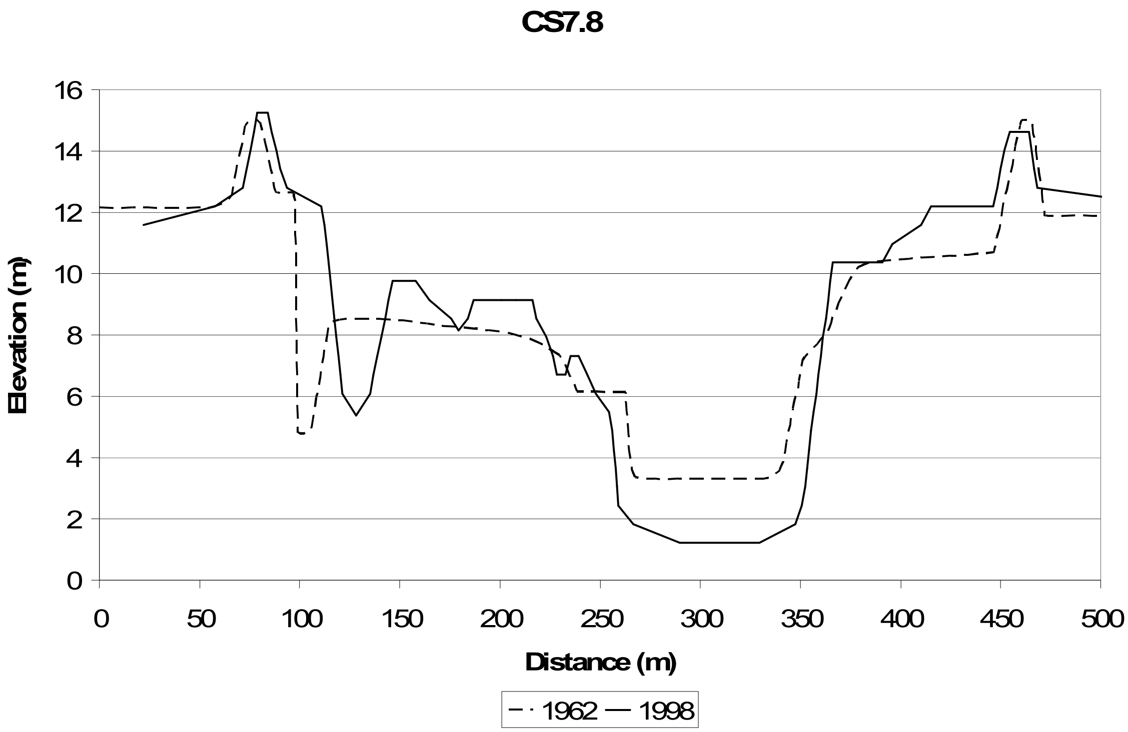


Figure 5-7 Cross-sections showing erosion between 1962 and 1998 in reach 2 at river kilometer 12.6 (USACE 1963; USACE 1998).

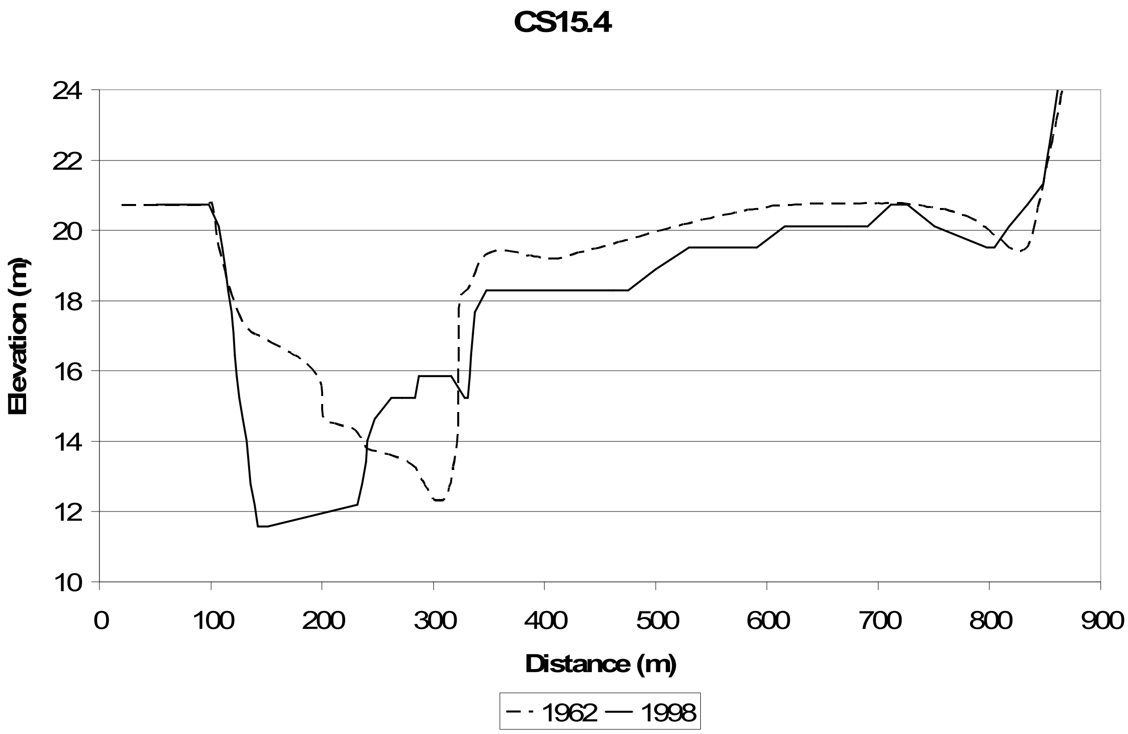


Figure 5-8 Cross-sections showing erosion between 1962 and 1998 in reach 3 at river kilometer 24.8 (USACE 1963; USACE 1998).

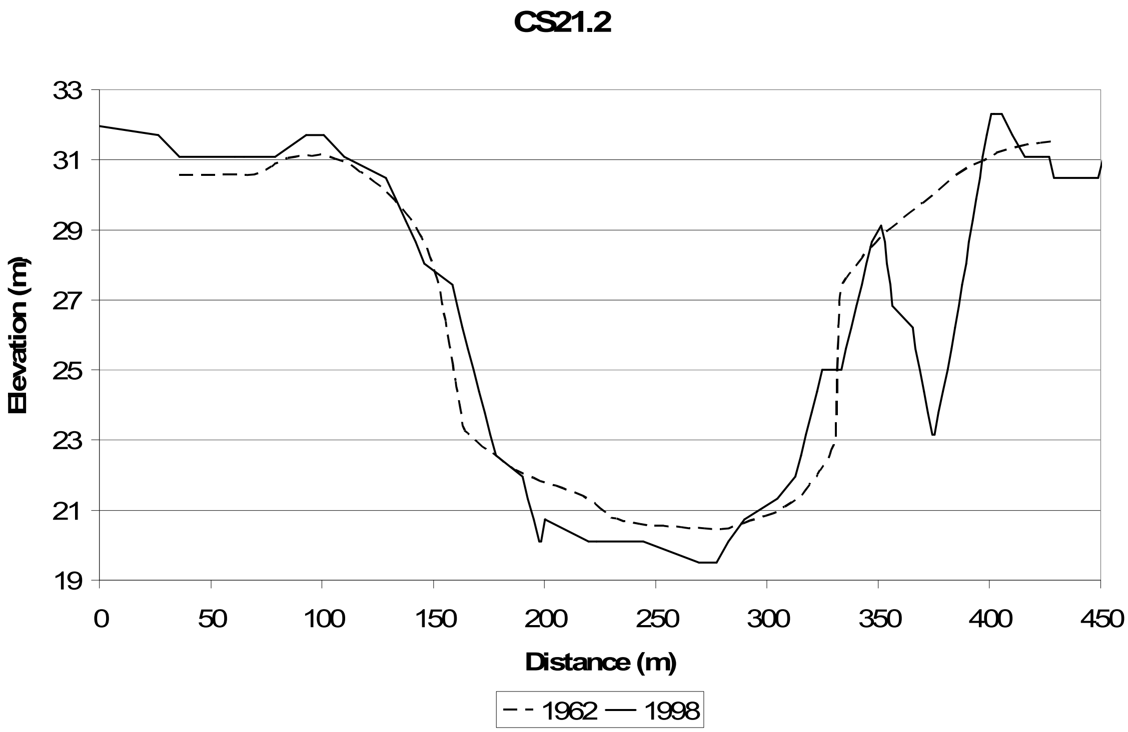


Figure 5-9 Cross-sections showing erosion between 1962 and 1998 in reach 4 at river kilometer 34.1 (USACE 1963; USACE 1998).

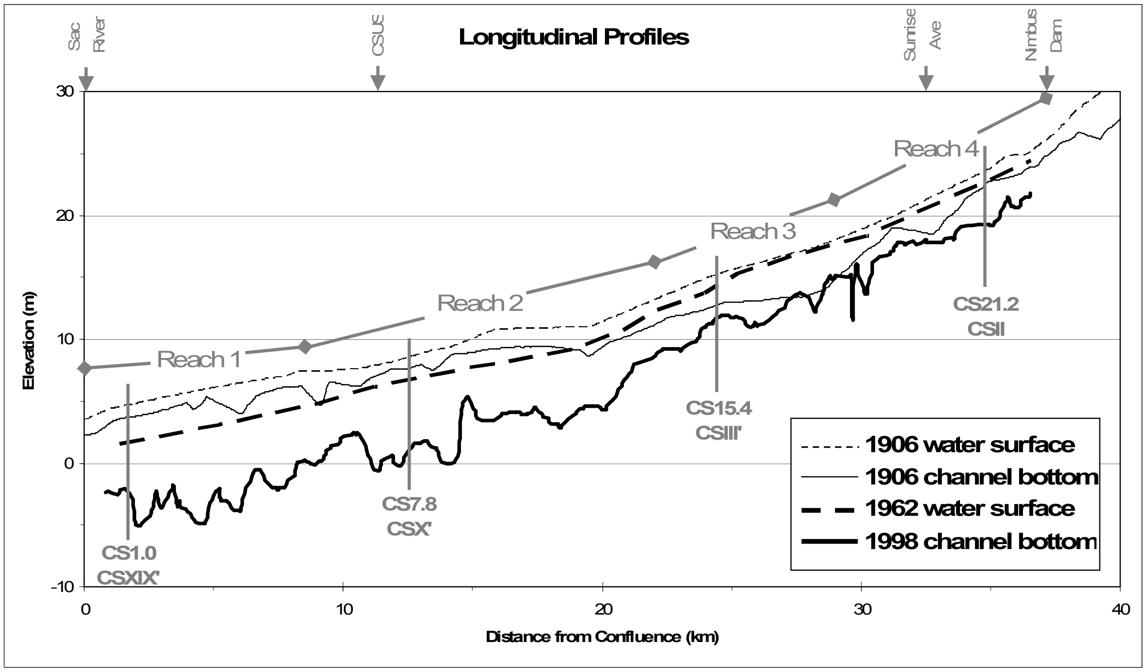


Figure 5-10 Longitudinal profiles used to correct the sediment volume eroded (CDC 1907; USACE 1963; USACE 1998).

Table 5-1

Net Gravel Volume Losses on the Lower American River

1906 to 1998

Reach	Cross Section	Cross Sectional Area (m^2)	Length of Reach (m)	Sediment Volume Eroded (m^3)	Incision at Cross Section (m)	Average Incision for Reach (m)	Adjusted Sediment Volume Eroded (m^3)	Percent Gravel	Gravel Volume Eroded (m^3)	Adjusted Gravel Volume Eroded (m^3)
1	CSXIX'	500	8,900	4,400,000	8.2	7.2	3,900,000	10%	440,000	390,000
2	CSX'	860	11,000	9,700,000	5.8	5.5	9,200,000	25%	2,400,000	2,300,000
3	CSIII'	260	8,900	2,300,000	1.4	1.3	2,200,000	75%	1,800,000	1,600,000
4	CSII	420	8,000	3,400,000	3.0	1.5	1,700,000	100%	3,400,000	1,700,000
Total (reaches 3&4)				5,700,000			3,900,000		5,100,000	3,400,000
Total (reaches 1-4)				20,000,000			17,000,000		8,000,000	6,100,000
1962 to 1998										
1	CS1.0	440	8,900	3,900,000	2.8	4.2	5,800,000	10%	390,000	580,000
2	CS7.8	230	11,000	2,600,000	2.1	3.5	4,300,000	25%	650,000	1,100,000
3	CS15.4	300	8,900	2,600,000	0.7	0.5	2,000,000	75%	2,000,000	1,500,000
4	CS21.2	15	8,000	120,000	0.9	0.8	100,000	100%	120,000	100,000
Total (reaches 3&4)				2,700,000			2,100,000		2,100,000	1,600,000
Total (reaches 1-4)				9,200,000			12,000,000		3,100,000	3,200,000

Table 5-2

Rates of Gravel Loss on the Lower American River

Reaches 1-4

Years	Gravel Volume Eroded (m^3)	Adjusted Gravel Volume Eroded (m^3)	Time (years)	Rate of Gravel Loss (m^3/yr)	Adjusted Rate of Gravel Loss[1] (m^3/yr)
1906-1998	8,000,000	6,100,000	92	87,000	66,000
1906-1962	4,900,000	2,800,000	56	88,000	51,000
1962-1998	3,100,000	3,200,000	36	87,000	90,000

Reaches 3&4

1906-1998	5,100,000	3,400,000	92	56,000	37,000
1906-1962	3,100,000	1,800,000	56	55,000	32,000
1962-1998	2,100,000	1,600,000	36	58,000	44,000

[1] The disparity in adjusted rates of gravel loss between 1906-1962 and 1962-1998 may be a result of increased scour after dam construction in 1955, but could also be explained by the different types of longitudinal profiles used in the adjustment process (see Figure 5-10).

Chapter 6: Estimating bedrock depths

6.1 Introduction

The purpose of this part of the study is to determine the range of gravel depths on the Lower American River (LAR), which will help constrain the significance of gravel losses on the LAR. This depends to some degree on how close the river comes to degrading down to bedrock.

Bedrock outcrops in and near the channel can be observed in various places throughout reaches 3 and 4 (upper 15 km) of the LAR (Figure 6-1). Most of these outcrops are on the banks where the channel is eroding laterally. Clearly the range of gravel depths starts at zero, but how deep is it in other areas? Is the channel bottom on the LAR simply a thin veneer of gravel overlying bedrock, or are there areas where the gravel is many meters deep? Seismic refraction was used to address this question.

6.2 Method

Seismic refraction surveys were performed at various locations along the LAR by installing an array of 12 geophones at 3m intervals along the gravel surface (Figure 6-2). Iron rods were pounded into the ground and secured to each geophone with zip ties in order to ensure good coupling between the geophone and the gravel. As a result, geophone measurements were essentially being made 0.3m (the length of the rods) below the surface. This length was added to all depth measurements.

Seismic waves were generated (using a sledge hammer and metal plate) 1.5 – 7.6m from each end of the array and the travel time for the first wave to arrive at each geophone was recorded (Figure 6-3). Interpretations were made using either a two or three layer model, which assumes that the layers are horizontal and that the seismic velocity increases with depth (Figure 6-4). Therefore, the bedrock is assumed to have a significantly higher seismic velocity than the unconsolidated sediments that overlie it. Changes in seismic velocity within two meters of the surface were interpreted as the location of the water table. This assumption is reasonable given that all surveys were located within a few meters (laterally) of the shoreline. In cases where three layers were observed, they were assumed to be dry gravel, wet gravel, and bedrock. Lillie (1999) indicates that unconsolidated sediments have seismic velocities of 100 – 2000m/s. Expected velocities for dry gravel (which contain a high fraction of void space) would be close to that for air (approximately 320m/s) and wet gravel (with water filling the voids) close to that for water (1500m/s). Lillie (1999) also indicates that clastic sedimentary rocks have velocities of 1500 – 5500m/s. The bedrock in the area (Fair Oaks and Mehrten Formations) is poorly consolidated sandstone and siltstone with some conglomerate (Shlemon 1967), so bedrock velocities are expected to be in the lower part of this range. The overlap in typical seismic velocities for the unconsolidated sediments and clastic sedimentary rocks introduces the possibility that the velocity of the bedrock is less than or does not differ significantly from the overlying sediment (which would contradict one of the premises of the interpretation models). However, because seismic velocities of about 2700m/s were observed at NB2, it is assumed that the bedrock velocities in the area are generally greater than 2000m/s.

Figure 6-4 shows the interpretation model and equations used to determine depths to bedrock. Surveys were done in both directions (i.e. with seismic waves generated from each end of the array), calculations were performed for each, and depth values averaged from both directions.

6.3 Results

Seismic surveys were performed at 4 locations in the upper 7km of the LAR (Figure 6-1). Surveys were done parallel to the river at all locations with additional surveys perpendicular to the river in two locations (Nimbus Basin and Lower Sunrise).

Nimbus Basin is located at river kilometer 37.0, just downstream from Nimbus Dam (Figure 6-5). The area has been highly modified for construction of the dam, fish hatchery, and Hazel Avenue bridge. The exposure of bedrock near NB1 and the armoring of the streambed provide evidence that the area has degraded since the dam was constructed in 1955. Two seismic surveys were performed at this location, one perpendicular to the river on the upstream end of the bar closest to the dam (NB1) and one parallel to the river on the downstream end of the bar close to Hazel Avenue (NB2). Both surveys were performed in early August of 2006 during flows of 3300cfs. Results from NB1 were inconsistent with a simple horizontal layer model (Figure 6-6). The shot locations on the north end of the array show seismic waves arriving at more distant geophones sooner than at closer ones. This indicates that the bedrock surface is likely to be undulating, perhaps shallow at either end of the array and deep in the middle. NB2 was the only location on the LAR to produce results indicating a horizontally-oriented bedrock surface within the depth range of the method (Figure 6-6). Seismic velocities for layer 1 averaged 450m/s, consistent with dry gravel. Velocities for layer 2 averaged 1600m/s, consistent with wet gravel. Finally, velocities for layer 3 averaged 2700m/s which is interpreted as the velocity of underlying bedrock. Using equations for a three layer model, depth to the water table is 1.1m and depth to bedrock is 6.8m.

Sailor Bar is located at river km 36.0, downstream of the fish hatchery (Figure 6-7). The survey (SB) was done on a bar feature parallel to the channel on the north bank in early August of 2006 during flows of 3300cfs. Results from SB indicate a change in seismic velocity (410m/s to 1800m/s) at a depth of about 1.1m which is consistent with the water table at that depth (Figure 6-8). No other changes in velocity are apparent. If we assume that the bedrock was slightly deeper than the depth of the survey and that the bedrock in this location has a velocity close to that measured at NB2 (2700m/s), we can calculate a minimum gravel depth of 8.5m.

The Upper Upper Sunrise site (UUS) is located at river km 34.5, between Sailor Bar and the Upper Sunrise island (Figure 6-9). The survey was done parallel to the channel on the south bank in mid-April of 2007 during flows of 1800cfs. Results from UUS indicate no changes in seismic velocity (Figure 6-10). If we assume that the bedrock was slightly deeper than the depth of the survey and that the bedrock in this location has a velocity close to that measured at NB2 (2700m/s), we can calculate a minimum gravel depth of 9.2m.

Lower Sunrise is located at river km 31.7, downstream of Sunrise Boulevard (Figure 6-11). Two seismic surveys were performed at this location, one perpendicular to the channel (LS1) and one parallel (LS2). The survey at LS1 was performed in early August of 2006 during flows of 3300cfs and LS2 was performed in early April 2007 during flows of 2000cfs. Results from LS1 showed changes in seismic velocity, but were inconsistent with a simple horizontal layer model and perhaps indicate an undulating surface in the NW-SE direction (Figure 6-12). However, the results from LS2, which was oriented NE-SW, did not indicate any change in seismic velocity (Figure 6-12). Applying the same algorithm as for SB and UUS, the minimum depth to bedrock is 8.3m.

6.4 Discussion

Minimum or absolute depths could be determined for four of the six seismic refraction surveys (Table 6-1). Of these four, only one showed an absolute depth to bedrock (6.8 m) at the Nimbus Basin Site, NB2. The rest indicate that the bedrock is at least 8.3m deep. Using these values, gravel depths on the LAR span the range of 0m to greater than 9m. It is worth noting that the two surveys where depths could not be determined were done perpendicular to the direction of the channel. This may indicate that bedrock elevations are less variable parallel to the channel and more variable perpendicular to it.

How deep are the gravel deposits on the LAR? The depth of gravel appears to vary greatly. At the sites of the four seismic surveys, the gravel is not a thin veneer, however, all of the surveys were done on or near gravel bars where one expects the gravel to be deep. There are also areas where the river has already reached bedrock (Figure 6-1). If shallow bedrock is limited to the channel margins shown in Figure 6-1, then the gravel in the channel of the LAR may be many meters deep, but if shallow bedrock areas extend well into the channel, the river may be close to a gravel deficit. Because we have little evidence of this extent, the degree of vertical bedrock control on the LAR remains largely an open question.

6.5 Figures and Tables

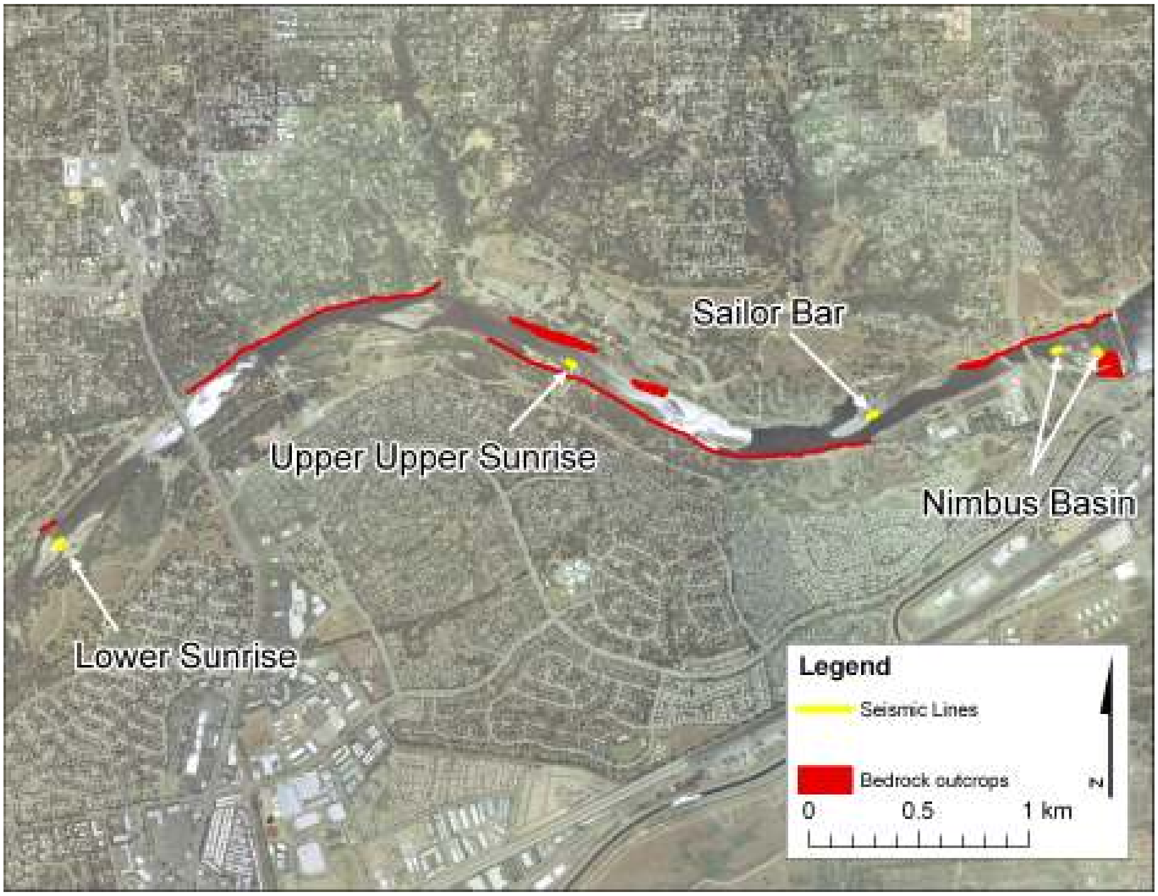
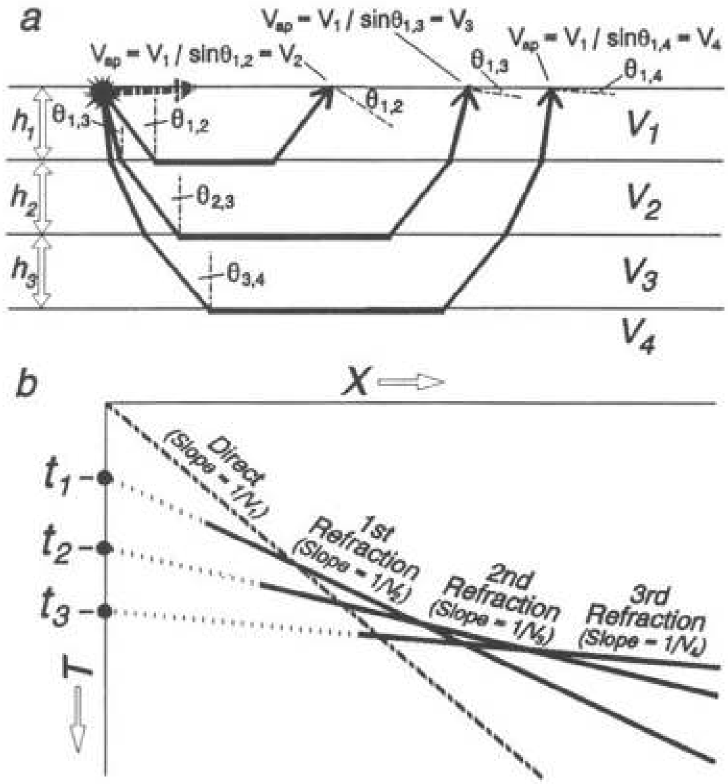


Figure 6-1 Location map of the seismic surveys on the upper 7 km of the LAR.

Figure 6-2 Installation of the geophone array. The geophones were secured to 0.3m long rebar pounded into the gravel to ensure good coupling between the geophone and gravel.

Figure 6-3 Seismic wave generation. The plate was struck many times and the results stacked to minimize ambient noise.



$$\theta_{a,b} = \sin^{-1}\left(\frac{v_a}{v_b}\right)$$

$$h_1 = \frac{t_1 v_1}{2\cos\theta_{1,2}}$$

$$h_2 = \frac{v_2}{2\cos\theta_{2,3}}\left(t_2 - \frac{2h_1\cos\theta_{1,3}}{v_1}\right)$$

where

- h_n = thickness of layer n
- v_n = seismic velocity of layer n
- $\theta_{a,b}$ = critical angle between layers a and b ($v_a < v_b$)
- t_n = t-axis intercept of refraction n

Figure 6-4 Interpretation model for horizontal layers with seismic velocities that increase with depth ($v_1 < v_2 < v_3 < v_4$) (from Lillie 1999)

Figure 6-5 Location map for seismic surveys at Nimbus Basin

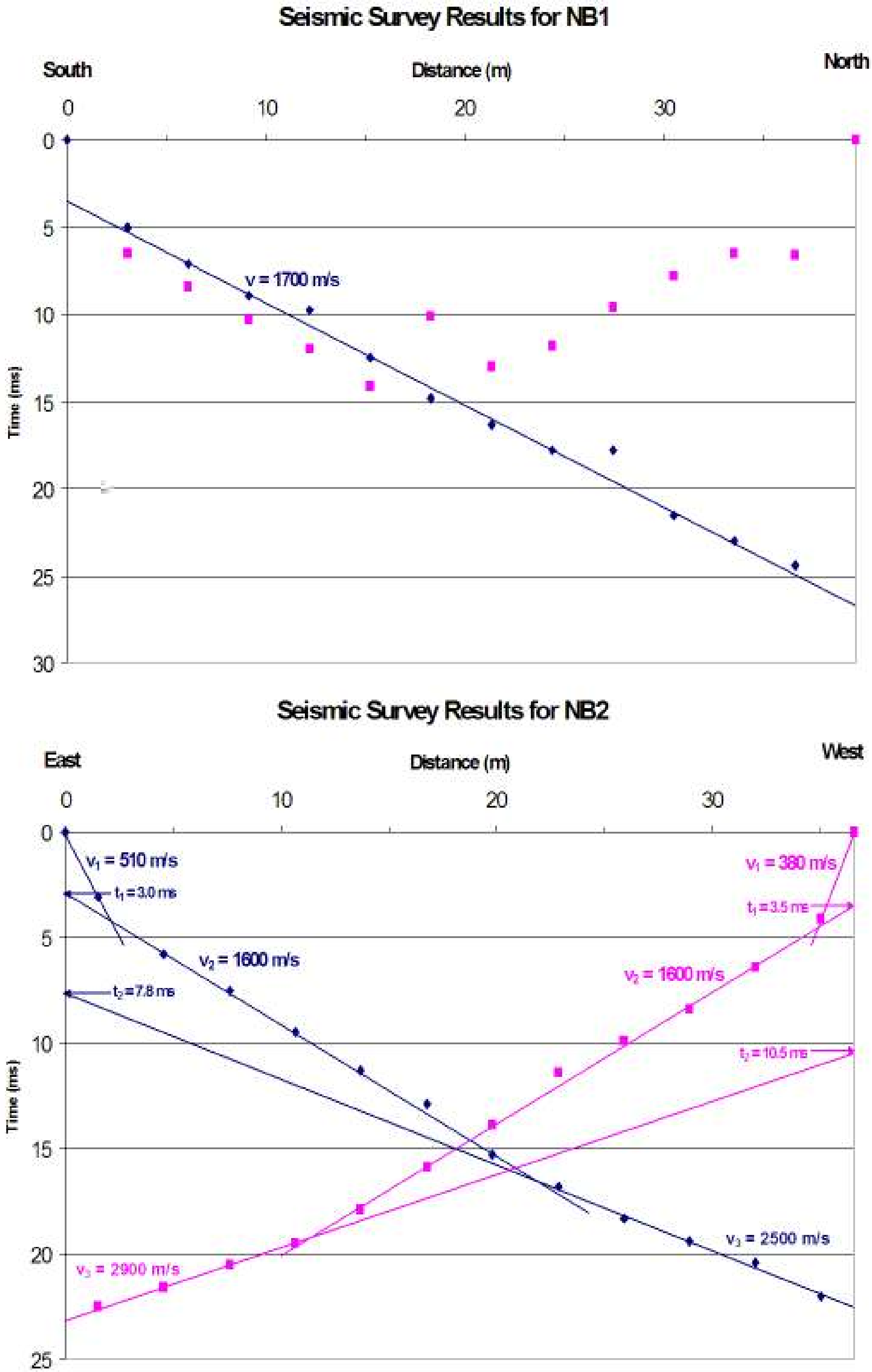


Figure 6-6 Seismic survey results for Nimbus Basin

Figure 6-7 Location map for seismic survey at Sailor Bar

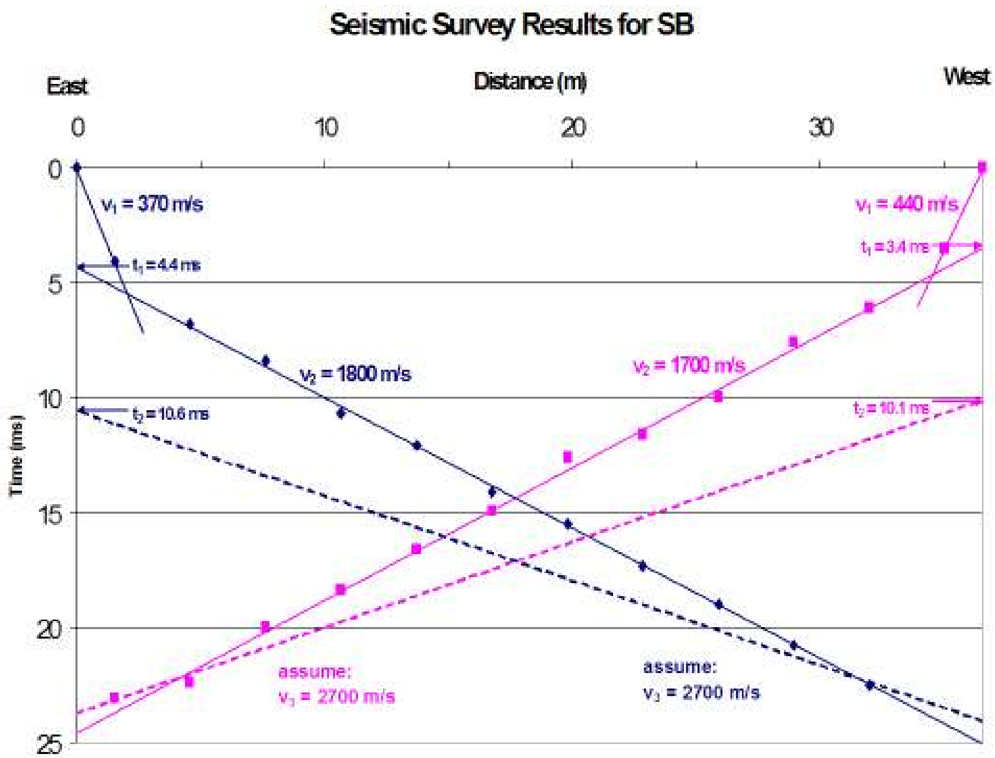


Figure 6-8 Seismic survey results for Sailor Bar

Figure 6-9 Location map for seismic survey at Upper Upper Sunrise

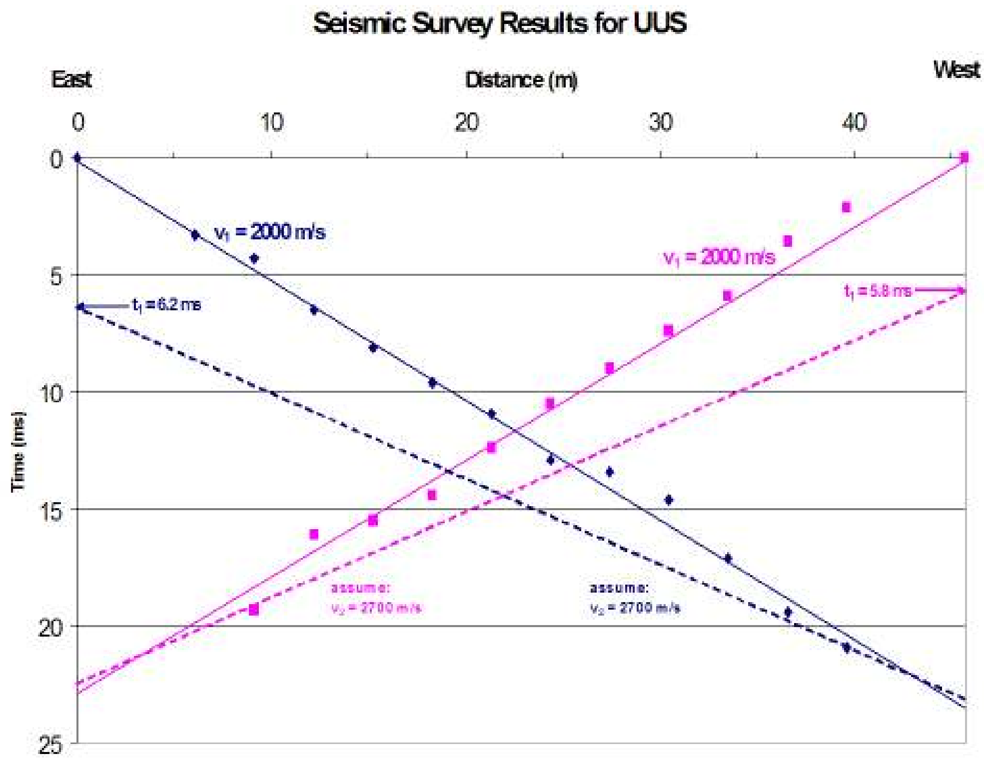


Figure 6-10 Seismic survey results for Upper Upper Sunrise

Figure 6-11 Location map for seismic surveys at Lower Sunrise

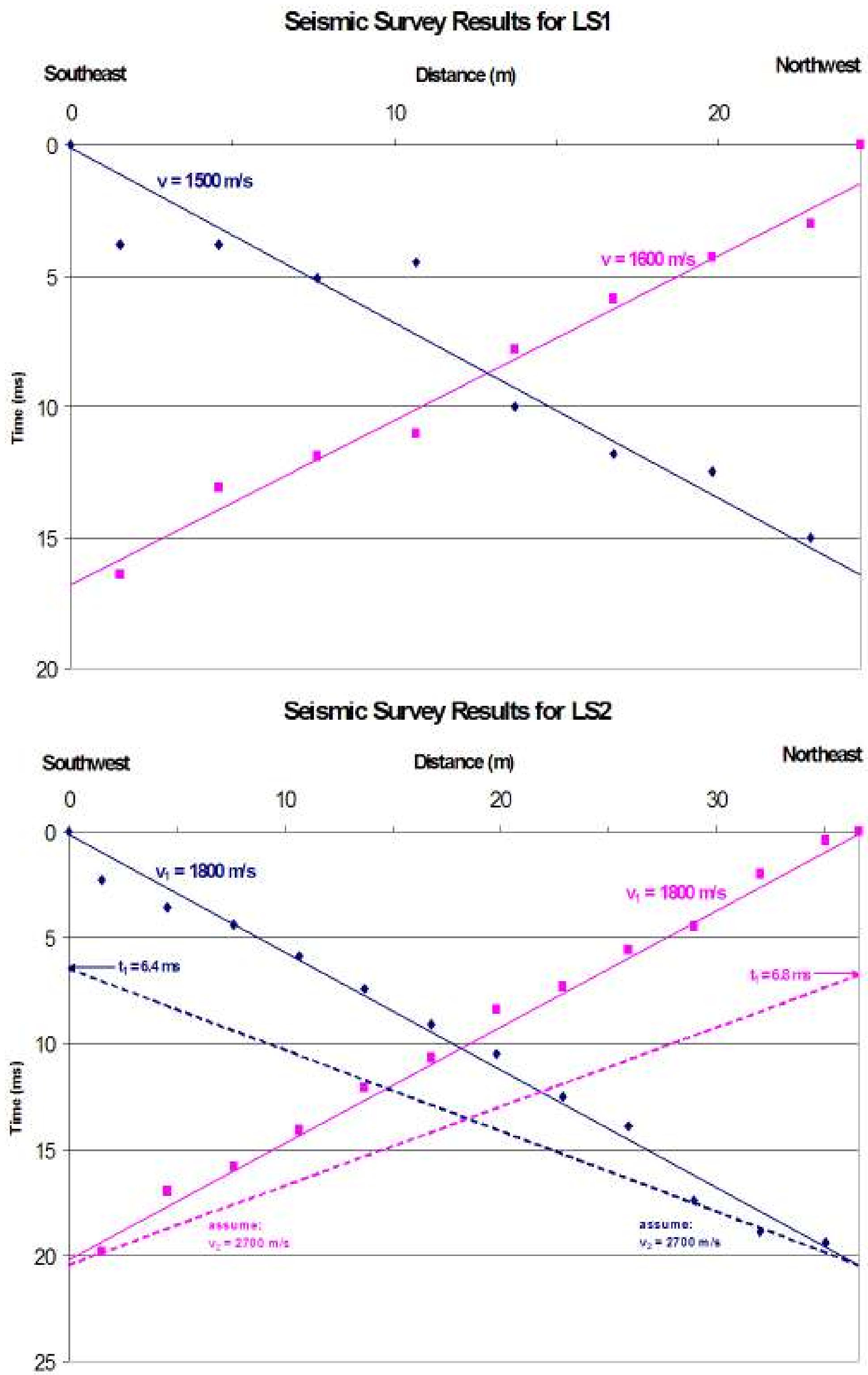


Figure 6-12 Seismic survey results for Lower Sunrise

Table 6-1 Results of Seismic Surveys

Location	Survey ID	River kilometer	Depth to water table (m)	Depth to bedrock (m)	Elevation of gravel surface (m above sea level)	Elevation of bedrock (m above sea level)
Nimbus Basin	NB1	37.0	----	----	25.6	----
Nimbus Basin	NB2	37.0	1.1	6.8	25.0	18.2
Sailor Bar	SB	36.0	1.1	>8.5	23.5	<15.0
U. Upper Sunrise	UUS	34.5	<0.3	>9.2	21.3	<12.1
Lower Sunrise	LS1	31.7	----	----	19.2	----
Lower Sunrise	LS2	31.7	<0.3	>8.3	19.2	<10.9

---- could not be determined

Chapter 7: Analysis and Conclusions

7.1 Summary of Results

The planform of the LAR has remained largely unchanged since 1906 (Figure 2-2). The LAR is primarily a single-channel, meandering, gravel-bed river. However, longitudinal profiles show a knickpoint (rapid drop in river elevation) near Goethe Park (Figure 2-10). The high gradient at this location has caused drastic localized planform changes, including sudden meander cutoffs and an increase in the number of channels from a single channel to two or three (Figures 2-3 to 2-9). The longitudinal profiles also indicate large amounts of incision throughout the LAR, with the channel bottom being lowered by up to 9m in reaches 1 and 2 and up to 4m in reaches 3 and 4 (Figure 2-10).

Discharge on the LAR has been altered by the regulation of flow by Folsom and Nimbus Dams since 1955. Minimum yearly flows have increased from about 350 to 2300cfs (over 600% increase) (Figure 1-9) while yearly peak flows have decreased from an average of 54,000 to 30,000cfs (less than 50% decrease) since impoundment (Figure 1-7). Of these peak flows, the largest events (with greater than an eight year recurrence interval) have seen the least change with only a 20% reduction in discharge magnitude (Figure 1-8).

The incipient motion of gravel on the LAR has been studied by various researchers, including Ayres Associates (2001) who determined that gravel beds are generally immobile below 50,000cfs. However, the relationship between discharge and the volume of gravel loss from the LAR remains largely unknown. In this study, yearly cross-sectional changes at the Fair Oaks Gauge were used to determine when major scour and gravel loss occurs. Flows below 100,000cfs caused little loss of gravel at the gauge, while the five events since 1945 with magnitudes over 100,000cfs all caused deepening and/or widening of the channel. Assuming that this cross-section is representative of changes throughout the LAR, 100,000cfs may be the threshold for major gravel loss (Figures 3-13 to 3-18).

Bank erosion (widening of the channel) is the only major gravel input to the LAR, because upstream recruitment is blocked by Nimbus Dam, and no tributaries contribute significant amounts of coarse sediment. Nine locations of significant bank erosion were identified in reaches 3 and 4 (upper 12.5km) using aerial photographs from 1957 and 2002 (Figures 4-1 and 4-2). Approximately 440,000m^3 of gravel has been eroded from the banks and introduced to the LAR in this timeframe (Table 4-2).

Loss of gravel from the active channel was also measured using changes in area between historic and modern cross-sections and longitudinal profiles (Table 5-1). An estimated 1,600,000m^3 of gravel has been eroded from the active channel in reaches 3 and 4 between 1962 and 1998. The gravel transported out of reaches 3 and 4 includes the gravel eroded from both the channel and the banks, totaling 2,000,000m^3 from about 1960 to 2000 (Figure 7-1).

The significance of gravel loss on the LAR depends to some degree on the depth of the gravel deposits. Results from mapping of the channel bottom and seismic refraction surveys indicate that gravel depths range from 0m (bedrock outcrops on the channel bottom) to greater than 9m (Table 6-1). This wide range of depths precludes definitive statements about the extent of bedrock control and the volume of gravel remaining in the channel.

7.2 Discussion

The reasons for the net loss of gravel on the LAR are twofold. The LAR is responding to the influx of mining sediment in the late nineteenth century and the cessation of upstream gravel supply by the construction of Nimbus and Folsom Dams in 1955. The degree to which each of these is responsible for the gravel loss over the last 50 years is unknown, but both are likely contributors.

Analysis of channel erosion rates for time frames before and after dam construction (Table 5-2) indicate that gravel was being eroded from the channel before the emplacement of Folsom and Nimbus Dams (32,000m^3/yr from 1906-1962) as a response to the influx of mining debris. The rate of gravel loss estimated in this study since 1962 may have increased (44,000m^3/yr), but the low precision of these estimates precludes making this statement with certainty. If the mining debris were the only cause, the rate of depletion would be expected to decrease over time (Gilbert 1917). The volume estimates in this study show no such decrease, owing to the effects of Folsom and Nimbus Dams.

Based on patterns observed in other studies, channel incision (deepening) from the effects of the dams should be most prominent just below Nimbus and decrease downstream. The length and depth of degradation should increase over time until equilibrium is reached either by the armoring of the channel below the dam or flattening of the profile to a point where significant transport ceases (Williams and Wolman 1984).

The LAR channel currently has a significant layer of armor below the dam (Vyverberg et al. 1997; Horner 2005) which may indicate a low potential for further incision directly below the dam. The cross-sections at the Fair Oaks Gauge support this claim because no channel deepening has occurred at that location since 1986 (Figure 3-18). However, unless gravel is replaced, the length of the armored section may continue to lengthen downstream. The incised section may also continue to propagate downstream. Currently it appears to extend to San Juan Rapid (Figure 2-10) where the elevation may be controlled by bedrock and the reduction of stream power at a pair of sharp meander bends (Figure 2-7). However, this does not preclude further incision in the areas between San Juan Rapid and Nimbus Dam.

Incision below San Juan Rapid may have propagated upstream from the confluence of the Sacramento River. The Sacramento River aggraded by about 3.3m (10.8ft) during the peak of hydraulic mining (Gilbert 1917), and the subsequent lowering of the base elevation may have caused a knickpoint to migrate upstream. This knickpoint appears to be currently located near Goethe Park (Figure 2-10), although there is no evidence that it was further downstream at an earlier time. It is possible that the knickpoint has been in that location for the last 100 years and that the degration throughout reaches 1 and 2 was simultaneous. However, the knick point could progress further upstream from its current location, but bedrock outcrops (Figure 2-6) may limit the rate of progression.

The degree to which bedrock imposes geomorphic control on the LAR is largely an open question. Certainly the existence of outcrops on the channel bottom (Figures 2-6 to 2-19) indicates that bedrock is a factor in some locations, but the lateral extent of these outcrops underneath more recent deposits is uncertain. The results of seismic surveys in this study indicate wide variation in depths and possibly a wildly undulating bedrock surface. Perhaps these variations can be explained by ancient channels within the bedrock that were subsequently refilled with recent sediment. However, with seismic depths measured at only four locations, this remains speculation.

Although large amounts of gravel have been lost from the LAR, the consequences for salmonid spawning are not clear. The volume of gravel remaining in the LAR channel remains unknown and consequently there is insufficient evidence to say if the reduction in gravel volume is limiting spawning habitat, especially due to the important role of other physical factors such as substrate particle size and localized flow characteristics. The channel features that seem to promote the most spawning use are riffles. Riffles are created by in-channel features such as gravel bars, and the reduction of gravel supply from upstream may cause these bars to deteriorate and be replaced by plane-beds over time (Brandt 2000). Therefore any habitat enhancement effort should focus not only on the replacement of gravel volume, but on doing so in a way that maintains and enhances bed features that promote riffles and in-stream diversity of features.

7.3 Recommendations for future habitat enhancements

The discussion that follows will look at relationships between channel geometry (that produces riffles) and the distribution of spawning on the LAR, speculating about possible opportunities for habitat enhancement. It should be emphasized, however, that this discussion is primarily based on information from aerial photography and does not include the kinds of detailed hydrologic and habitat assessments needed to implement these ideas.

The Sunrise Boulevard area (river km 32) has some of the most highly used spawning habitat on the LAR (Hannon and Deason 2005; Horner 2005) (Figure 7-2). This habitat is associated with transverse bars (extending across the river at an acute angle) anchored by lateral bars (parallel to flow on either side of the channel). These features create riffles and cause river flow to switch from one bank to the other. High density spawning occurs near the lateral change in flow, perhaps due to the induction of subsurface flow (Thibodeaux and Boyle 1987) by the transverse bar.

Like Sunrise, Sailor Bar has a geometry that causes flow to shift from the left bank to the right bank (Figure 7-3), but the habitat is scarcely used for spawning. Its location just below Nimbus Dam heightens the effects of reduced gravel supply, and the bed material has become armored and too coarse for redd construction (Vyverberg et al. 1997; Horner 2005). This is in contrast to most other locations in reaches 3 and 4 which have a more appropriate range of sizes for spawning (Vyverberg et al. 1997). This site, therefore, provides an opportunity for rehabilitation. Efforts in this location should be focused on reinforcing this feature with sediment of appropriate sizes (gravel and cobbles, but not boulders). Others (Vyverberg et al. 1997) have noted that the high velocities here prevent these finer grains from staying in place. Rehabilitation may need to involve a change in the geometry of the channel as well. The flow is focused into a narrow width just upstream of the transverse bar, so perhaps widening this section would reduce velocities and transport of finer grains. One advantage of adding gravel at this location is that even if sediment is transported it may end up enhancing habitat downstream and reducing the potential for further armoring.

The area between Lower Sunrise and Sacramento Bar (Figure 7-4) has no significant bars that would induce riffles. The flow is relatively straight and homogeneous. Figure 7-4 shows how bars could be constructed to induce the flow to switch sides of the channel and possibly create new habitat and/or enhance existing habitat. The proposed location of the lateral bar on the north bank just below the Lower Sunrise Island already seems to be a location of sediment deposition, with water depths around 0.6m (2ft) at about 2700cfs. The creation of a bar at this location may simply involve enhancing the existing feature. The proposed location of the bar on the south bank currently has water depths around 1.2-1.8m (4-6ft) at about 2700cfs. However, this bar would be the key to rehabilitation at this site, as it would cause the flow to switch from south to north bank below Lower Sunrise and then switch back to the south again near Sacramento Bar. The amount of hydraulic head between the Lower Sunrise island (river km 31.5) and Sacramento Bar (river km 30.6) required to produce riffles in these locations may determine the viability of the proposed restoration projects.

There are several locations where salmonids engage in spawning, often with such a high density that redds are superimposed on one-another (Hannon and Deason 2005). The hydraulic characteristics in the channel may be what limit the quality of habitat. Further investigations should focus on analyzing the flow (both surface and subsurface) at high density spawning locations such as Lower Sunrise so that future habitat enhancements can be designed to mimic conditions at currently successful locations.

7.4 Figures and Tables

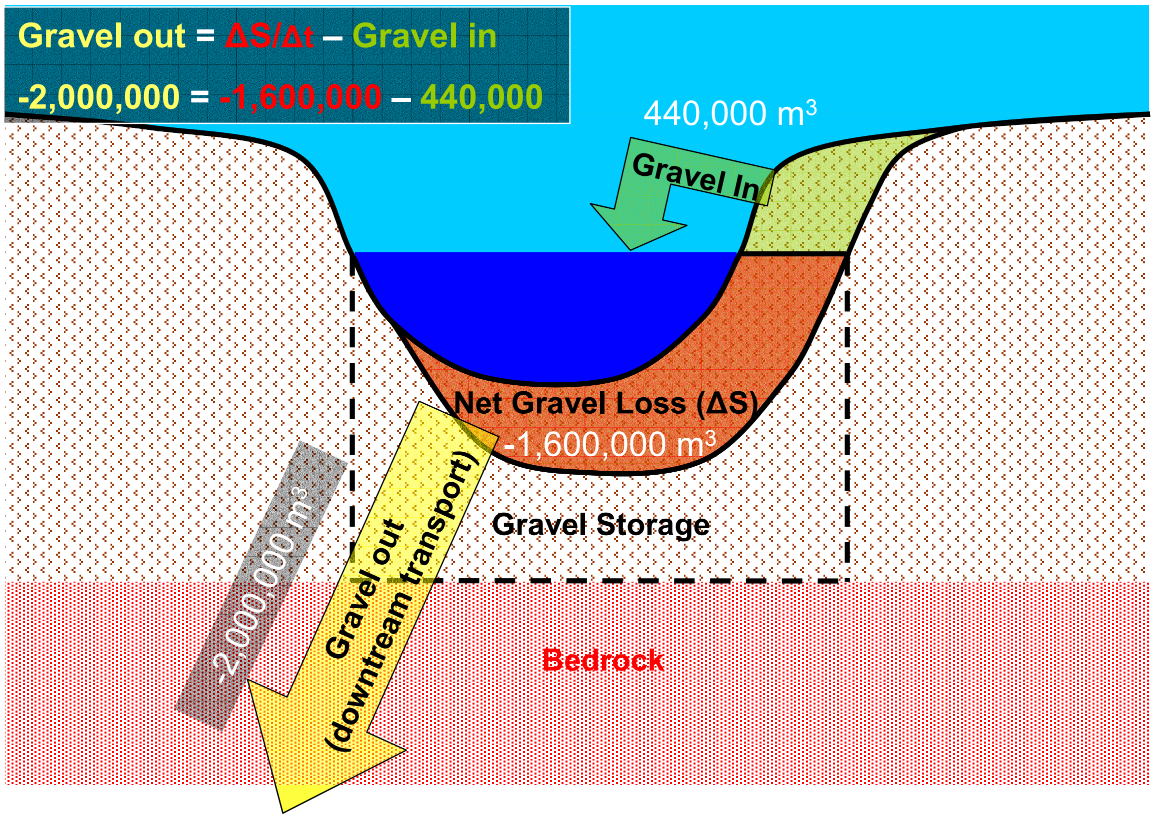


Figure 7-1 Completed gravel budget for reaches 3 and 4 from about 1960 to 2000 showing the estimated volume of gravel that has been transported out of the upper two reaches

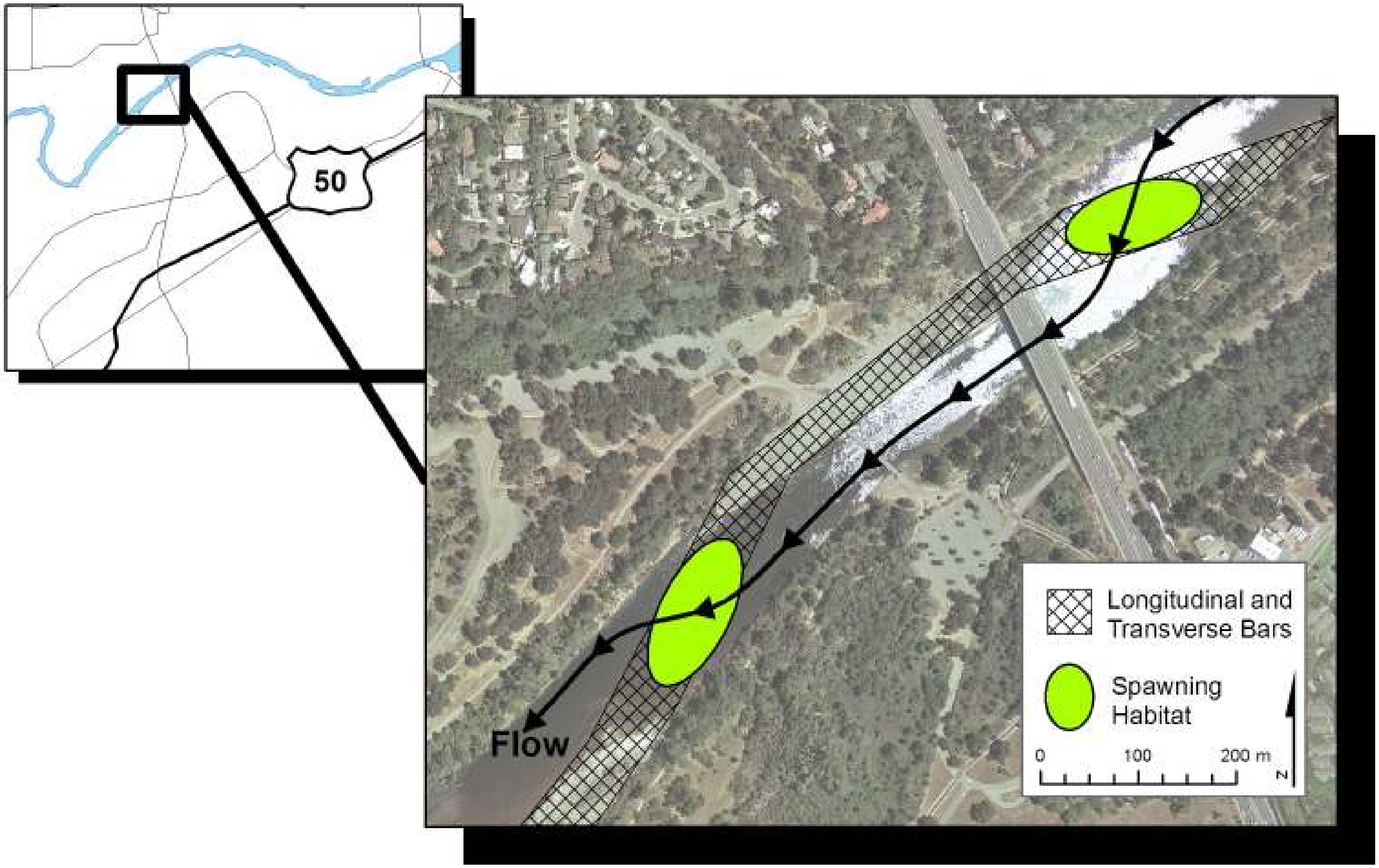


Figure 7-2 Geometry of gravel bars and highly used spawning habitat at Lower Sunrise (near river km 32). Bars on left and right banks are connected by transverse bars

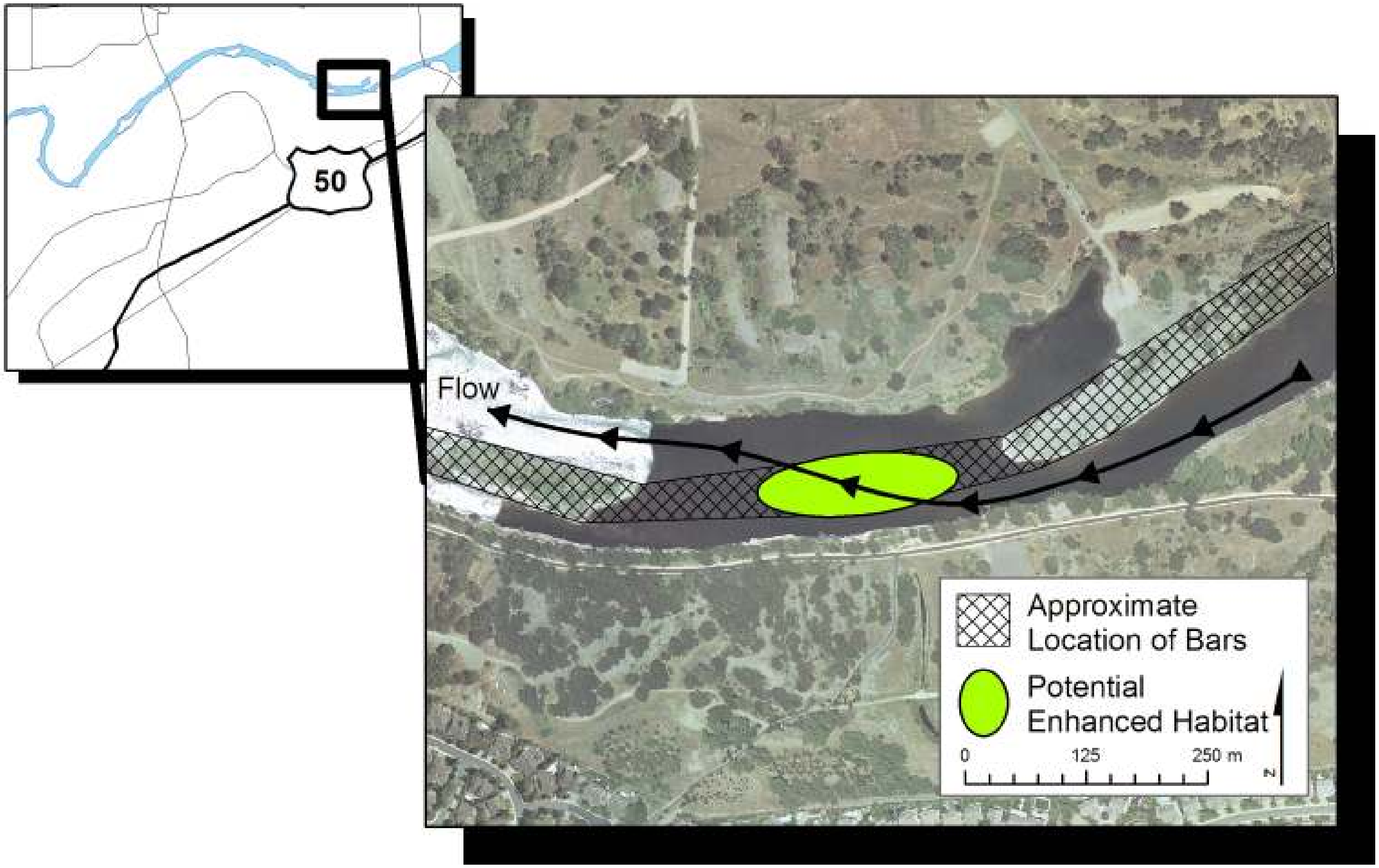


Figure 7-3 Site for potential habitat enhancement at Sailor Bar (river km 35). The gravel in this location is too coarse for redd construction, so efforts should concentrate on enhancing the bar with grains of appropriate sizes.

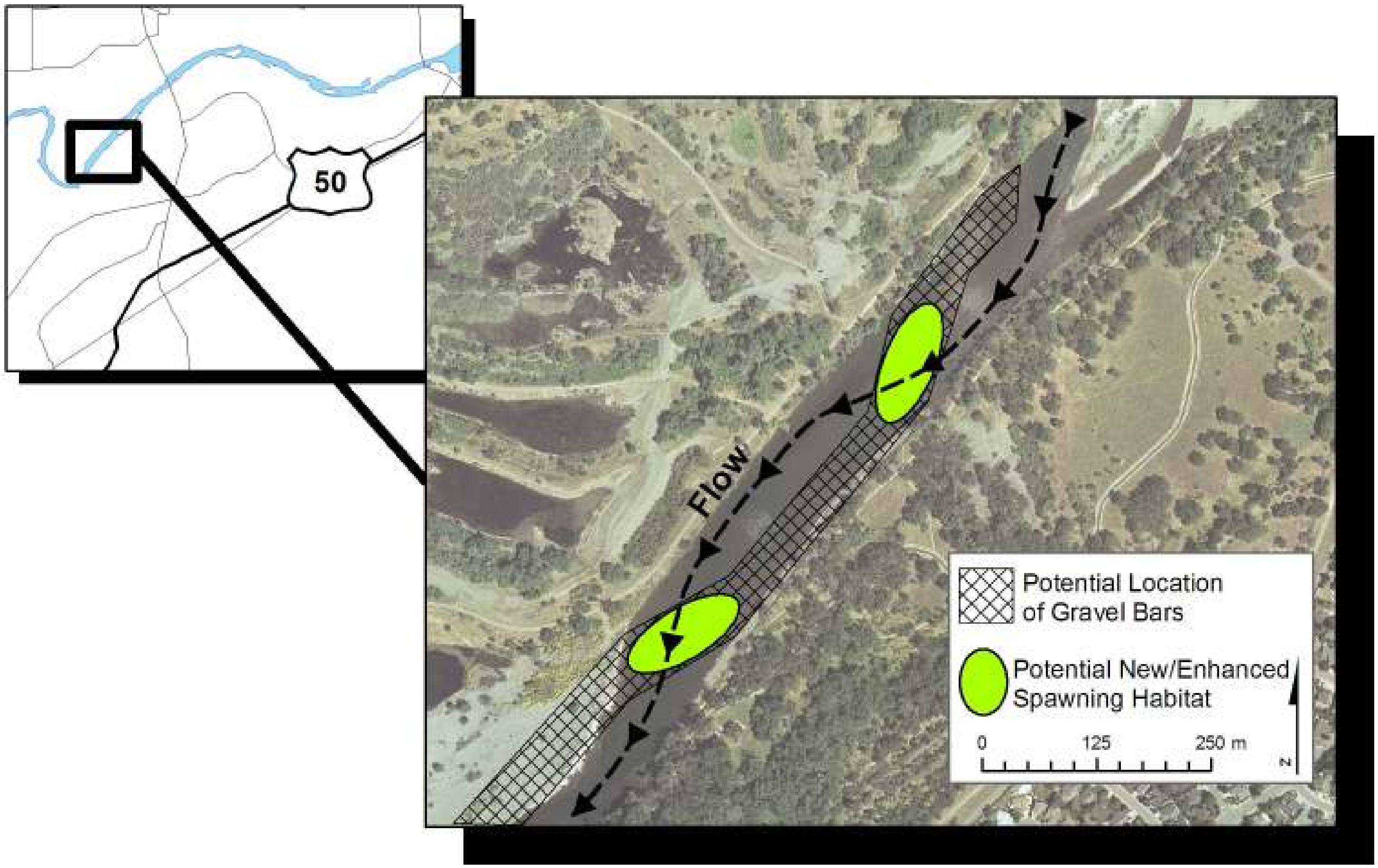


Figure 7-4 Site for potential habitat enhancement near Sacramento Bar (river km 31). Currently there is no bar on the south side of the channel, but construction of such a bar would cause streamflow to switch from the south bank, to the north bank, and back again.

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