CHAPTER 3. FLUVIAL PROCESSES AND CHANNEL FORM

3.1. INTRODUCTION

As introduced in Chapter 2, the natural characteristics of an alluvial river ecosystem are created and maintained by the interaction of water, sediment, underlying geology, and in some cases, large wood structures (ranging from individual logs to accumulations of logs and branches). Flow and sediment shape the channel, floodplain, and habitat for aquatic and terrestrial species (Figure 3-1). For example, high flows transport sediment, deposit sediment, cause channel migration, cause channel avulsion (rapid relocations of channels), distribute riparian seeds, and cause other large scale geomorphic and biotic processes.

The size, shape, and form of the San Joaquin River (channel morphology) changes in different reaches between Friant Dam and the Merced River. This diversity between the reaches is caused by different geologic factors and the corresponding changes in fluvial processes. For example, the San Joaquin River courses through steep confined canyons of the Sierra Nevada, and the steep gradient and confined valley walls result in a high energy environment that is efficient in transporting most size classes of sediment (up to large boulders). As a result, the channel morphology is typified by high gradient, dominated by large substrate and exposed bedrock (non-alluvial), and small amounts of sediment storage (bars). Riparian vegetation is limited to individual trees in hydraulically sheltered areas, such as behind large boulders and along channel margins at the base of the valley walls. As the river exits the Sierra Nevada foothills, valley confinement and gradient decreases. Resulting channel morphology in this region is mostly alluvial, with a low gradient meandering channel, gravel/cobble substrate, multiple channels, and more extensive riparian vegetation. Further downstream, gradient and confinement continues to decrease, resulting in a more sinuous, sand-bedded channel (Reaches 2 through 5). Riparian vegetation is more extensive, channel migration and avulsion is more pronounced, and sloughs become more common. In the downstream-most reaches along the axis of the San Joaquin River Valley, the low gradient and backwater effect from the Merced River alluvial fan creates a relatively unconfined flood basin several miles wide in some areas that was historically inundated over a prolonged portion of the year. Sediment supply from the upper watershed cumulatively settled out in upstream reaches, such that sediment supply in these lower reaches was low. This resulted in a channel morphology that was still sand-bedded, but had small riparian “levees” that dropped away into extensive tule marshes and sloughs away from the primary channel of the San Joaquin River. This diversity of channel morphology provided habitat for a wide range of aquatic and terrestrial species, making the San Joaquin River Valley one of the most diverse ecosystems in the western United States.

The longitudinal diversity of the San Joaquin River created a dynamic gradient of habitat types over the project reach. Salmonids, their habitats, and other aquatic flora and fauna were distributed in relatively predictable ways along that gradient, according to their specific life history requirements. Hence, describing the historic and contemporary fluvial geomorphic processes that form and maintain alluvial rivers is important for assessing related ecological impacts of human actions. Human “actions” include historic activity conducted as part of resource utilization, agriculture, and/or land development; actions also include future activity conducted as restoration. As with other chapters in this report, understanding how the river formed and functioned, and how historic human activities changed these functions, is important to provide insights on how to restore the San Joaquin River (Kondolf 1995).

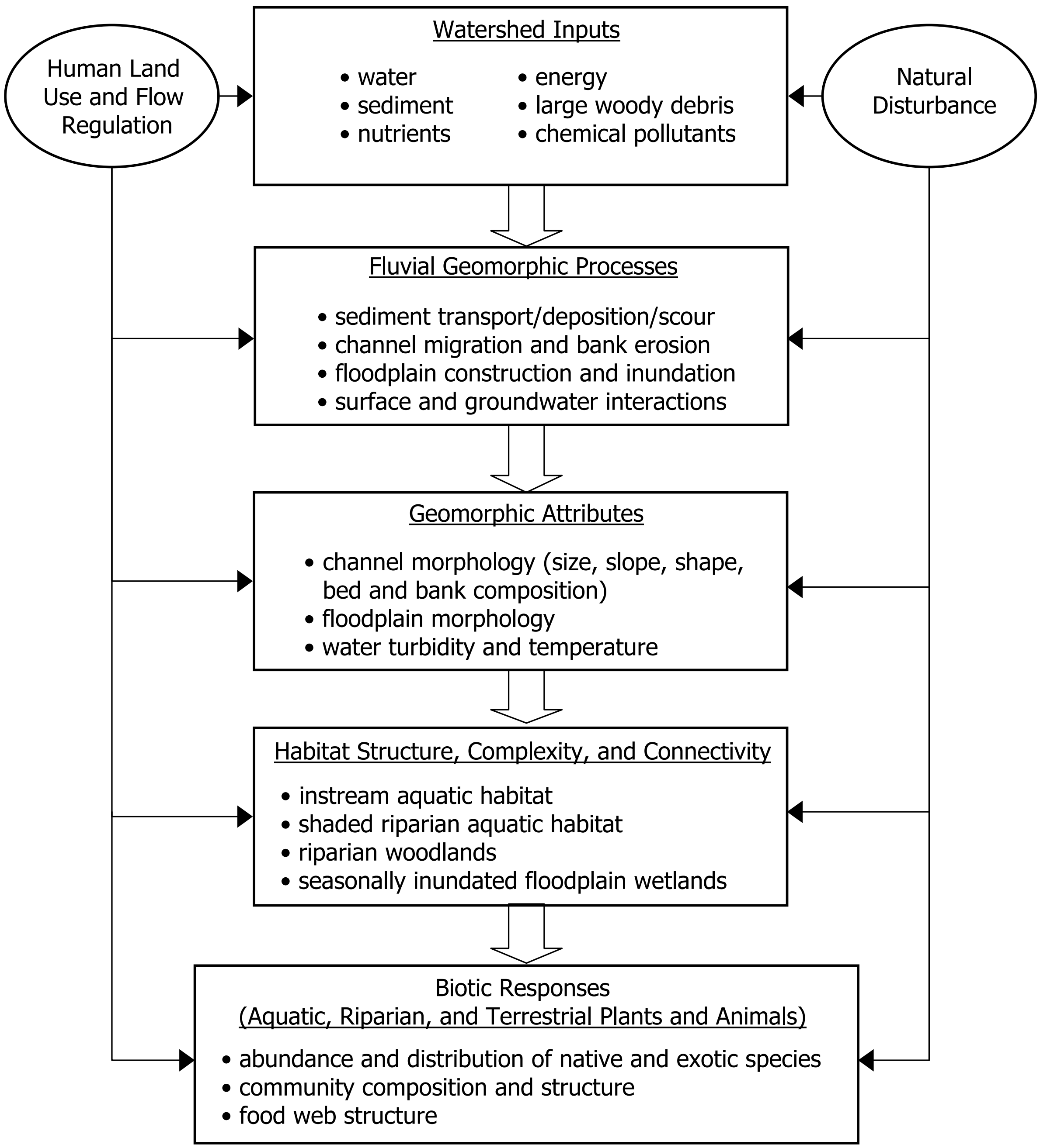


Figure 3-1. Conceptual physical framework of alluvial river ecosystems, showing how natural fluvial geomorphic components and human components cascade to changes in biota.

3.2. OBJECTIVES

The goal of this chapter is to describe and analyze the historical and existing geomorphic conditions to improve our understanding of the physical and environmental processes that have shaped the San Joaquin River ecosystem over time, and to gain insight into the kind of actions necessary to achieve the restoration goals and their subcomponents. As with the hydrology chapter, the products of this chapter are meant to provide insight into the potential benefits of certain geomorphic restoration actions, but not necessarily to provide the historical conditions per se as a restoration goal. Based on the April 2000 Scope of Work, the objectives of this chapter are to:

- Measure and summarize changes in primary, secondary, and high flow channels greater than 1,000 feet long (assess changes in channel length)
- Summarize available substrate composition for each reach
- Summarize sediment budget in all reaches based on results of sediment transport model
- Summarize bed mobility thresholds in Reach 1 based on sediment transport model
- Quantify and describe rates of channel migration and avulsion during the pre-dam, and post-dam period.
- Describe historic and contemporary channel conditions based on historical maps and early explorer accounts.

There have been several hydrologic and geomorphic studies previously conducted that provide information pertinent to these objectives, and information from historical sources and these previous studies is integrated to address these objectives. This chapter does not perform any unique analyses, with the exception of synthesizing information to develop conceptual models of historical channel processes and channel morphology. These conceptual models will be useful in developing and evaluating restoration strategies when developed by the Restoration Study.

3.3. STUDY AREA

As described in Chapter 1, The San Joaquin River is bounded by the Sierra Nevada on the east and Coast Ranges on the west; its southern boundary is on the divide with the Tulare Lake basin, and its northern boundary is the Delta near Stockton (Figure 3-2). Between Friant Dam and the Merced River confluence, the San Joaquin River passes through several reaches differentiated by their geomorphology and resulting channel morphology, and by their human-imposed infrastructure along the river. Therefore, the river has been subdivided into five primary reaches that exhibit similar flows, geomorphology, and channel morphology (Figure 3-2). Primary Reaches 1, 2, and 4 have been further divided into reaches based on distinct geomorphic and morphologic features (Table 3-1). Additionally, these reach delineations are further subdivided by the sediment transport modeling effort, which is discussed further in Section 3.9.2.

Table 3-1. Brief summary of reach and reach locations and general boundary descriptions.

Reach	*Subreach*	*Reach boundary (river mile)*	*General description*
1	1A	267.5 – 243.2	Friant Dam to State Route 99
	1B	243.2 – 229.0	State Route 99 and extends downstream to Gravelly Ford
2	2A	229.0 – 216.1	Gravelly Ford to the Chowchilla Bypass Bifurcation Structure
	2B	216.1 – 204.8	Chowchilla Bypass Bifurcation Structure to Mendota Dam
3	3	204.8 – 182.0	Mendota Dam to Sack Dam. Reach 3 has not been subdivided into subreaches.
4	4A	182.0 – 168.5	Sack Dam to the Sand Slough Control Structure.
	4B	168.5 – 135.8	Sand Slough Control Structure to the confluence with Bear Creek and the Eastside Bypass
5	5	135.8 – 118.0	Confluence with Bear Creek and the Eastside Bypass to the Merced River confluence. No unique reaches are delineated within Reach 5.

The drainage area of the San Joaquin River is 1,638 mi^2 at Friant (upstream end of study area) and 7,615 mi^2 at Fremont Ford (located just upstream of the confluence with the Merced River at the downstream end of the study area). Elevations of the watershed range from sea level at Stockton to over 13,000 feet at the crest of the Sierra Nevada. Within the study area, elevations range from 70 feet at the confluence with the Merced River to 320 feet at the base of Friant Dam.

3.4. INFORMATION SOURCES

This report draws on a number of previous reports, maps, surveys, data, and historical anecdotes to qualitatively and quantitatively describe historic and present geomorphic conditions in the study reach. Over the last 150 years, numerous government agencies surveyed and mapped the river for various purposes, including the Government Land Office (1854-55), the State Engineer (Hall 1870's), the Army Corps of Engineers (1914), the U.S. Bureau of Reclamation (1938), the State Lands Commission (1989), and the San Joaquin River Riparian Program (Ayres 1998). This report relies on information from this maps and surveys to characterize historical conditions and patterns of change throughout the study reach in the last 150 years. Additional quantitative data for present-day conditions are derived from several studies (e.g., MEI 2000a, MEI 2000b, Cain 1997) as well as unpublished data collected as part of the San Joaquin River Restoration Study.

3.4.1. Early Anecdotal Descriptions

Historical descriptions from early explorers were used to develop some insights of Central Valley channel morphology prior to European settlement. An extensive review of this material did not provide much useful information on historical channel morphology or processes; most descriptions focused on vegetation and soils because resource exploration was the primary purpose of many of the early expeditions. The primary historical descriptions are those of William Brewer (Brewer, 1949), George Derby (Derby 1850), and compilations of Phyllis Fox (Fox, 1987). These sources, coupled with historical maps, form the basis for discussing historical channel conditions in Section

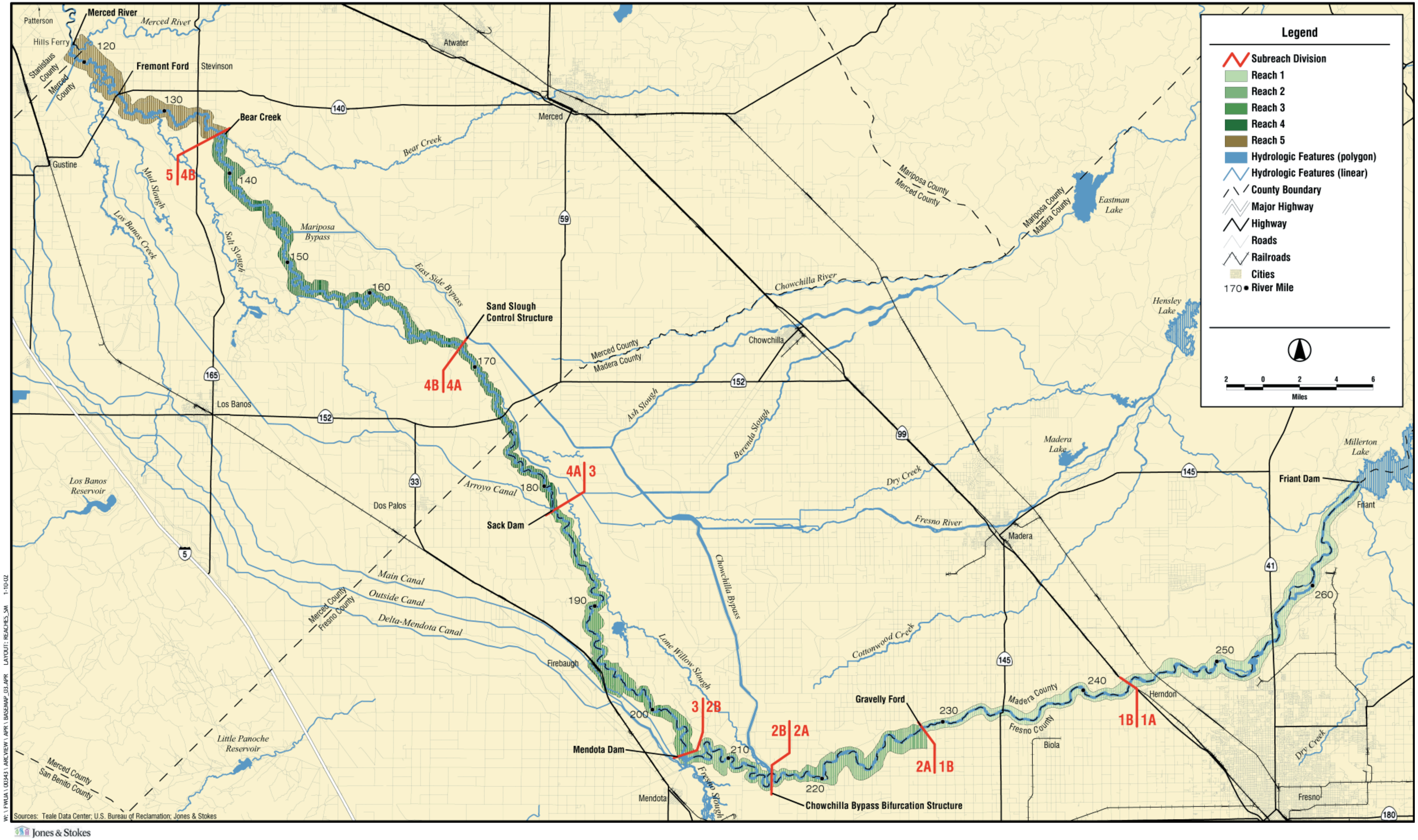


Figure 3-2. Study area for the San Joaquin River Restoration Plan, showing the reach and sub-reach boundaries.

3.6.6. The California Debris Commission (CDC) survey maps (ACOE 1917), which encompass the area from Herndon downstream to the confluence with the Merced River, are another useful source; however, these maps clearly reflect that effects on the riparian environment from relatively extensive land use changes must have already occurred. Maps from the William Hammond Hall surveys have been considered in this report, but extensive field notes and field books prepared during these surveys may contain additional details that could provide further insights to historical conditions on the San Joaquin River. These sources were not investigated in this report due to time constraints. Lastly, a collection of historical descriptions of the San Joaquin River were gathered from the Bancroft Library, Humboldt State University Library, and personal libraries; this compilation is available on CD from the Friant Water Users Authority.

3.4.2. Aerial Photographs

There are many sets of aerial photographs, but the most useful were those of 1937/1938 and 1998 because they best illustrate the historical to current conditions evolution. The 1937 photographs were obtained from the Exchange Contractors, Bureau of Reclamation, and Fairchild Aerial Photo Archives, contact prints have a scale of 1”=1,667’, and extend from the Ledger Island (RM 263) downstream to the end of Reach 4A (photos end at RM 170). The 1938 photographs were obtained from the Army Corp of Engineers, contact prints have a scale of 1”=833’, and extend from the Friant Dam site (RM 268) to Herndon (RM 261). The 1998 photographs were obtained from Bureau of Reclamation, contact prints have a scale of 1”= 333’, and extend from Friant Dam (RM 267.5) to the Merced River confluence (RM 118). The term “Historical” is meant to refer to the date of the data source, and does not infer an unimpaired condition. Because pre-1937 aerial photographs do not exist, unimpaired conditions cannot be documented from aerial photographs, and must be inferred from historical maps, anecdotal descriptions, and professional judgment based on observations of the 1937 and 1938 aerial photographs with appropriate acknowledgement of changes that had occurred between 1848 and 1937 (e.g., clearing of riparian vegetation for steamboats, construction of levees, Miller-Lux grazing, agricultural clearing).

3.4.3. Maps and Surveys

Historical mapping pre-dates the aerial photographs; however, many of the maps are more qualitative and small-scale, and not appropriate for quantitative comparisons. Spanish and Mexican explorers produced the earliest maps in the early 1800’s, with the first maps produced by Americans in the late 1840’s and early 1850’s. The U.S. Government Land Office (GLO) produced the first large-scale quantitative maps in 1854-1855. The purpose of the GLO mapping effort was to subdivide lands in the new State of California, establish range, township, and section lines, and to establish U.S. Meander Lines along the rivers (these lands were subsequently deeded to the State of California to be reclaimed under the Swamp and Overflow Act).

Surveys conducted by William Hammond Hall in the 1870’s resulted in maps of the Sacramento and San Joaquin valleys (See Figure 4-6), but the scale is too large to use for detailed evaluation of channel location or morphology. In 1878, Hall surveyed over a dozen cross sections and a 2,000 ft long longitudinal profile in the upper portion of Reach 1. These are located in a 3-mile reach near Friant Dam and in a 1.25-mile reach near the Highway 99 bridge (Hall 1878 as cited in Cain 1997).

The Army Corps of Engineers (ACOE 1917) produced the next large-scale maps for the California Debris Commission (CDC). These maps were surveyed in 1914 and 1915, extended from Herndon (RM 261) downstream to the Merced River confluence (RM 118), contain channel locations, riparian vegetation, and section corners, and have a scale of 1”=400’. As part of the mapping effort to produce the 1914-1915 maps (ACOE 1917), longitudinal profiles and cross sections were produced. These cross sections and profiles represent the earliest elevational data upon which long-term trends could be compared. The 1914 longitudinal profile is shown in Figure 3-3; cross sections from the 1914 survey effort are shown as needed in subsequent sections.

The Bureau of Reclamation prepared better-scaled topographic maps in 1939, as well as 150 cross sections, between Friant Dam and Gravelly Ford (as cited in Cain 1997). In 1993, the State Lands Commission used these maps and conducted additional surveying in 1989 to develop topographic maps of the reach from Friant Dam to Herndon (RM 243.2). There are also cross sections available at State highway crossings from CalTrans from 1970 and 1997.

The USGS topographic maps provide early (1910's to 1920's) elevational information, but the precision of this topography is not very useful for historical comparisons. These USGS quadrangle maps were revised in the 1960's to 1980's.

The most recent topographic information was generated by Ayers and Associates as part of the Comprehensive Study (Ayers and Associates 1998). Topography was generated using 1998 photogrammetry and bathymetry. Digital Terrain Models were developed from these surveys, allowing cross sections to be generated at any location between Friant Dam and the Merced River confluence. This topography has a stated accuracy of 2' contour interval and thus provides much more precise topography than UGSG topographic maps. More recent field-based cross section surveys in Reach 1A (Cain 1997), in Reach 1B and Reach 2 as part of the San Joaquin River Riparian Habitat Restoration Program Pilot Project (JSA and MEI 2002, SAIC 2002), and in Reach 4B (MEI, 2000) provide more precise cross sections than the 1998 Ayers and Associates topography for those selected locations.

For planform comparisons, this chapter emphasizes the 1854 GLO plat maps, 1914 CDC maps, 1937 aerial photographs, and 1998 photographs. For cross section and longitudinal comparisons, this chapter emphasizes the 1914 cross sections and longitudinal profiles, the 1938 USBR cross sections, the 1998 Ayers and Associates topography, and Cain 1997 cross sections.

3.4.4. Previous Reports and Analyses

There are several reports that describe historical and/or existing channel processes and form on the San Joaquin River. Janda (1965) describes the hydrology and geology of the upper San Joaquin River during the Pleistocene (last 2,000,000 years). Cain (1997) provides a more recent comparison of changes in hydrology and channel morphology over the last 100 years in Reach 1, focusing on flow and sediment changes associated with Friant Dam, and reduction in coarse sediment budget due to aggregate extraction. JSA and MEA (1998) provide a summary of physical processes and channel morphology for the entire study area (Friant Dam to the Merced River confluence), assessing changes in cross section and longitudinal profiles by comparing data from the 1914 CDC maps (ACOE 1917) with 1998 topography. MEI (2000a) evaluates hydraulic and sediment transport continuity between Friant Dam (RM 267.5) and Mendota Dam (RM 205), and MEI (2000b) evaluates hydraulic and sediment transport continuity between Mendota Dam (RM 205) and the Merced River confluence (RM 118). These two reports estimate sediment transport capacity, sediment budget surpluses and deficits, hydraulic conveyance capacity, and particle size at select locations. Lastly, more recent data collected by Jones and Stokes Associates and Stillwater Sciences as part of the San Joaquin River Restoration Study are included in relevant sections of this chapter.

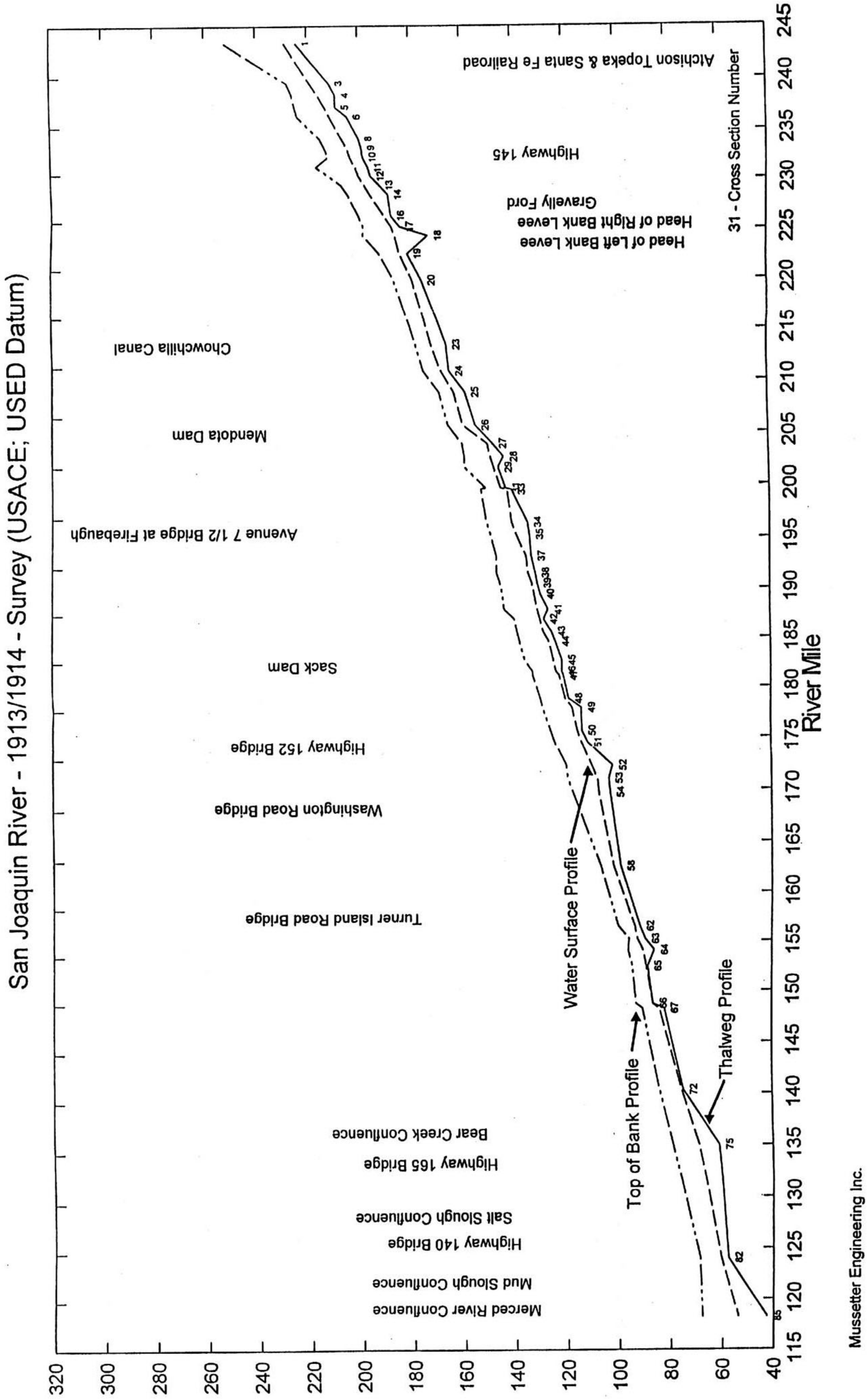


Figure 3-3. Longitudinal profiles from 1914 mapping effort (ACOE 1917) between Herndon and the Merced River confluence. The river mile markers begin at the Merced River confluence (RM 118.2), but the river mile markers and channel length from that point upstream are different than the mile markers used in this report.

3.5. DEFINITION OF TERMS

Geomorphology discussions are prone to terms that may be unfamiliar to many readers; thus, the following definition of terms has been developed to assist readers. To the greatest degree possible, the chapter attempts to minimize jargon and uses standardized terms.

Aggradation: The process of building up a surface by deposition (American Geological Institute 1984). In rivers, the process of the channel bed increasing in elevation by systematic net deposition.

Alluvium: Boulders, cobbles, sand, and silt moved and deposited by a stream or running water (American Geological Institute 1984).

Alluvial Rivers: Rivers whose bed and banks are formed from alluvium, and that have the ability to adjust their dimensions by erosion or deposition of alluvium.

Alluvial fan: An outspread, gently sloping mass of alluvium deposited by a stream, typically formed at the exit of a confined valley (American Geological Institute 1984).

Anastomosing channel: One of two or more channels that cut back and forth across a depositional area, but with the flow primarily concentrated in one dominant channel.

Anabranching channel: One of two or more channels that cuts parallel channels to the mainstem and rejoins the mainstem downstream. The difference between anabraching channels and anastomosing channels is the amount of sediment that the river is transporting. Avulsions are cause by excess sediment building up (aggrading) and creating another channel path (anastomosing channels) while an anabranching system results from sediment starved systems because there is a lack of coarse sediment to plug gaps that are scoured by seasonal flows that exceed channel capacity and scour a new channel in the floodplain.

Bankfull channel: Portion of the channel that conveys flows up to the point where flows begin to spill out of the bank and onto the floodplain. The outer extent of the bankfull channel marks the beginning of the floodplain, and is often correlated with a break in slope in the channel geometry where the width of the channel increases rapidly with increasing discharge (Leopold et al. 1964).

Bankfull discharge: Flow that is conveyed by the bankfull channel. The bankfull discharge often correlates with a flood recurrence of approximately 1.5-years (Leopold 1994), and the flow that transports the most sediment over time ("effective discharge)(Andrews, 1980).

Bedload: The part of a stream's load that is moved on or immediately above the stream bed, such as the larger or heavier particles rolled along the bottom; the part of the load that is not continuously in suspension or solution (Figure 3-4) (Einstein 1950).

Bed material load: The discharge of sediment particles transported by the flow that are predominately found in the stream bed (Figure 3-4) (Einstein 1950).

Cenozoic: The latest of the four eras into which geologic time is divided; it extends from the close of the Mesozoic era, about 65 million years ago, to the present. The Cenozoic Era is subdivided into Tertiary and Quaternary periods.

Channel morphology: The size, shape, and character of the channel (planform, particle size, etc.).

Channel geometry: The size, shape, and character of the channel cross section.

Channel Slope: Change in elevation between two points along the stream channel divided by the curved line distance along the channel between the two points.

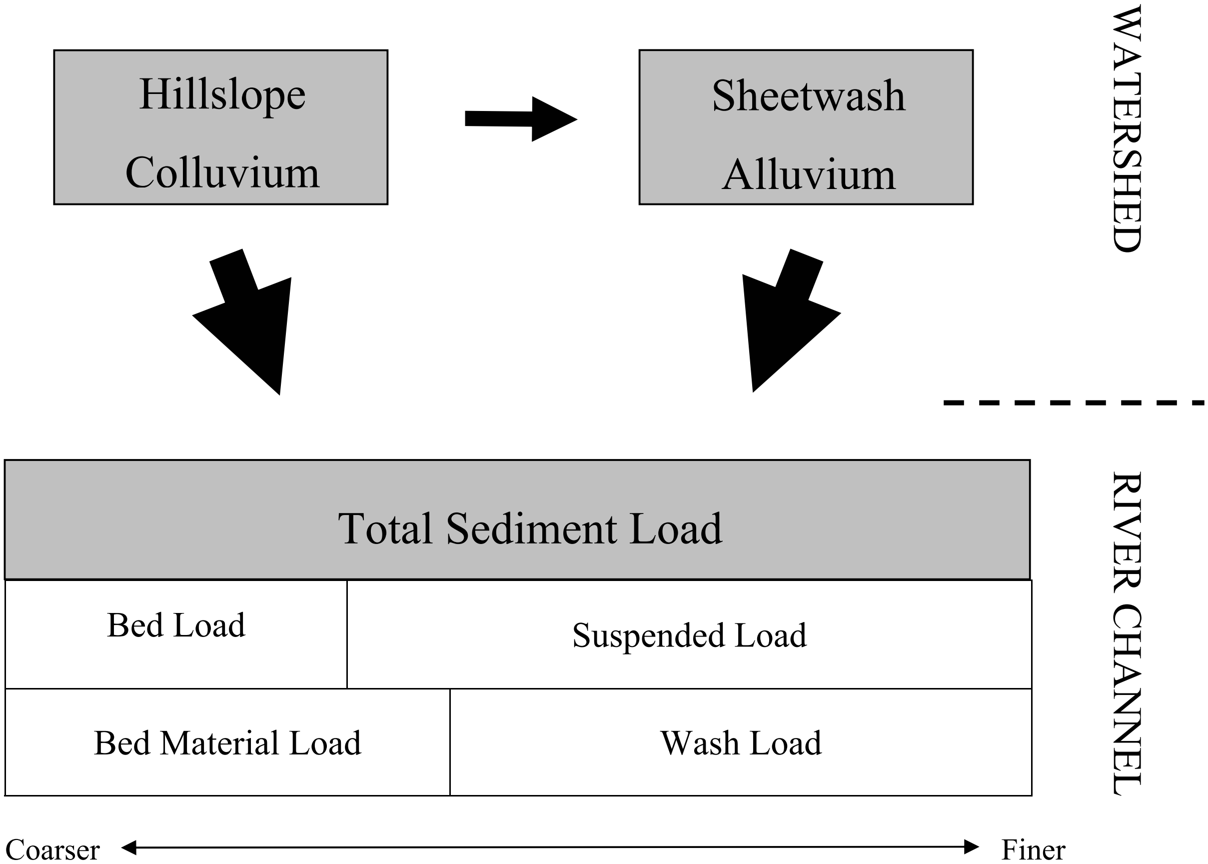


Figure 3-4. Conceptual flowchart showing sediment transfer from hillslope regime to fluvial regime, and subdivisions of total sediment supply.

Colluvium: Loose and incoherent deposits of sediment, usually at the foot of a slope and brought there chiefly by gravity (American Geological Institute 1984). Sediment originating from hillslopes and deposited by gravity rather than wind or water.

D_{84} particle size: Particle size diameter of a distribution of grain sizes in which 84% of the particles are finer. The D_{84} is a larger particle size of the distribution that provides a structural matrix of a gravel/cobble bar.

D_{50} particle size: Particle size diameter of a distribution of grain sizes in which 50% of the particles are finer (thus, the median grain size of a gravel/cobble bar).

Degradation: The process of lowering a surface by erosion (American Geological Institute 1984). In rivers, the process of the channel bed decreasing in elevation by systematic net incision.

Geomorphology: The study of landforms and the processes related to the formation of these landforms.

Holocene: An epoch of the Quaternary period, from the end of the Pleistocene, approximately 11 thousand years ago, to the present time. Also, the corresponding period of rocks and deposits

Fluvial geomorphology: The study of landforms created by fluvial (river) systems, including the study of the processes that create these landforms.

Meander wavelength: The length of a complete meander sequence. The distance between one meander bend and the next meander bend is one-half of a meander wavelength.

Planform: View of the channel looking vertically down from above (as if one was in a balloon).

Pleistocene: An epoch of the Quaternary period, after the Pliocene of the tertiary and before the Holocene; also, the corresponding series of rocks. The Pleistocene began about 2 million years ago and lasted until the start of the Holocene.

Quaternary: The second period of the Cenozoic era, following the Tertiary; also, the corresponding system of rocks. It began approximately 2 million years ago and extends to the present. It consists of two grossly unequal epochs: the Pleistocene, up to about 11 thousand years ago, and the Holocene since that time.

Sediment: Solid fragmental material transported and deposited by wind, water, ice, (or gravity) that forms in layers in loose unconsolidated form (American Geological Institute 1984).

Sinuosity: The degree of curvature in a stream, defined by the ratio of the channel length to the valley length. The higher the sinuosity, the more curved the stream channel.

Suspended load: The part of the total sediment load that is carried for a considerable time in suspension, free from contact with the stream bed; it consists mainly of clay, silt, and sand (Figure 3-4) (American Geological Institute 1984). The discharge of sediment particles that are suspended in the flow current turbulence (Einstein 1950).

Tertiary: The first period of the Cenozoic era (after the Cretaceous of the Mesozoic era and before the Quaternary), thought to have covered the span of time between 65 million and 2 million years ago; also, the corresponding system of rocks. It is divided into five epochs: the Paleocene, Eocene, Oligocene, Miocene, and Pliocene.

Thalweg: The line connecting the lowest (deepest) points along a streambed (American Geological Institute 1984).

Total sediment load: The mass rate of discharge of solid materials, usually referred to as sediment, transported by the water current (Figure 3-4) (Fairbridge 1968).

Valley Slope: Change in elevation between two points along the valley divided by the straight line distance between the two points.

Washload: The very small sediment particles transported by the flow that are not found in significant quantities in the stream bed (Figure 3-4) (Einstein 1950).

3.6. WATERSHED CONTEXT

While the study area of the San Joaquin River Restoration Study and Background Report focuses on the reach from Friant Dam to the Merced River confluence, the unimpaired San Joaquin River in this study reach was influenced by geomorphic processes in the watershed upstream of Friant Dam. Water supply, sediment supply, runoff processes, geology, and tectonics all contributed to channel processes and form in the study reach (Figure 3-1). A brief discussion of this upper watershed context, as well as the geologic foundation of the study reach, is provided in the following sections.

3.6.1. Drainage

The headwaters of the San Joaquin River are located at over 13,000 feet in the Sierra Nevada, near Mt. Davis, and the river descends over 360 miles to its confluence with the Sacramento River in the

Sacramento-San Joaquin Delta. The three largest tributaries to the San Joaquin River are the Merced, Tuolumne, and Stanislaus rivers; each originate in the Sierra Nevada and flow into the San Joaquin River from the east. Los Banos and Oristemba Creeks are the major west side tributaries that drain the east side of the Coast Mountain Ranges, and the Chowchilla River and Fresno River are east-side tributaries that drain the foothills of the Sierra Nevada. Unlike the San Joaquin River, Merced River, and Tuolumne River tributaries that are snow-fed, these tributaries have smaller drainage areas and runoff is nearly entirely driven by rainfall-generated storm events. The drainage area of the San Joaquin River is 1,676 mi^2 at Friant Dam (marking the upstream extent of the study area) and 7,615 mi^2 at Fremont Ford, located upstream of the confluence with the Merced River that forms the downstream project extent (Figure 3-2). Within the study area, elevations range from 320 feet at the base of Friant Dam to 70 feet at the confluence with the Merced River, with an average valley slope of 0.0003 (0.03 percent).

The San Joaquin River watershed drains a large portion of the San Joaquin Valley, except for the southernmost portion of the valley, which is drained by rivers such as the Kings River, Kern River, and others, all of which drain into the Tulare Basin. The Tulare Basin contained a series of terminal lakes (e.g., Tulare Lake, Buena Vista Lake, and Kern Lake), which were drained and reclaimed for agriculture in the late 1800s and early 1900s (Norris and Webb, 1990). Prior to drying up from diversions, Tulare Lake, was normally isolated from the San Joaquin River (Derby 1850). The potential exception of this condition may have been during exceptionally high regional runoff. During these periods, the lake likely overflowed and spilled into the San Joaquin River basin via Fresno Slough; however, the lake elevation would have had to rise from a typical summer low elevation of 176 feet to 205-210 feet for this to occur (DPW, 1931). Under present-day conditions, floods from the Kings River still periodically flow to the San Joaquin River via James Bypass and Fresno Slough during flood control releases from Pine Flat Dam. These flows enter the San Joaquin River via Fresno Slough at Mendota Pool (RM 205).

3.6.2. Climate

California has a Mediterranean climate that is characterized by dry summers and wet winters. Similar to all major rivers flowing out of the Sierra Nevada Mountain Range, the San Joaquin River is a snowmelt-dominated river. Winter storms carrying dense moist air from the Pacific Ocean cause precipitation in the Sierra Nevada in the form of snow, most of which melts and runs off in the spring and summer (see Chapter 2). Typically, the largest flow events are caused by rapid runoff during warm "rain-on snow" storm events. These warm storm events have a snow elevation as high as 10,000 ft, such that rain (and some melting snow) rapidly runs off from the wateshed and causes large magnitude floods downstream. Runoff from the valley floor portion of the watershed is minor, as the topographic relief is low, soils permeable, and rainfall low (5-12 inches/year).

The Mediterranean climate is reflected in the wide range of temperatures that occur within the watershed. On the valley floor, maximum summer temperatures frequently exceed 100ºF, while minimum winter temperatures can sometimes drop below 32ºF. Summer temperatures are more moderate in the upper watershed, typically 10ºF to 30ºF cooler than the valley floor. Winter temperatures are usually less than 32ºF above the 6,000 feet elevation, and temperatures are typically colder as elevation increases towards the crest of the Sierra Nevada.

3.6.3. Geology

The San Joaquin River is a dominant feature of the San Joaquin Valley, which stretches from near Bakersfield in the south to its confluence with the Sacramento River at the Sacramento-San Joaquin Delta to the north. The San Joaquin Valley is approximately 36 miles wide by 250 miles long, and is an asymmetrical, subsiding trough filled with Mesozoic- (~225 to 65 million years ago) and Cenozoic-age (~65 million years ago to present) alluvial sediments up to 5.6 miles thick. Structurally, the San Joaquin River sediment basin is separated from the Sacramento basin to the north by the Stockton fault and Stockton Arch, and is separated from the Maricopa-Tejon basin in the south by the White Wolf Fault and Bakersfield Arch (Bartow 1991). The San Joaquin Valley is bordered by the Sierra Nevada Mountain Range to the east and California Coast Ranges to the west. The Sierra Nevada is composed of crystalline igneous rocks, metamorphic rocks (rocks that have been physically changed by temperature or pressure), and volcanic and meta-volcanic ("meta" infers metamorphosis of the rocks after they were formed) rocks, while folded and faulted Jurassic- (~190 to ~135 million years ago) and Cretaceous-age (~135 to ~65 million years ago) sedimentary rocks typify the Coast Ranges. The west side of the valley is defined by a steep homocline (the bedrock is folded up to create a ridge) to the north that transitions to a belt of folds and faults toward the south (Bartow 1991). A broad and slightly inclined alluvial plain, consisting of a series of coalescing alluvial fans from rivers draining the Sierra Nevada, define the east side of the San Joaquin Valley (Janda 1965). The larger alluvial fans associated with the Merced, San Joaquin, and Kings rivers form local base level controls, which caused historical floods to backwater and thus were a major influence on geomorphic processes between the controls (Hall, 1887). Geologic evidence suggests that that valley has been deforming progressively since the Mesozoic period (Davis and Green 1962, Bull and Miller 1975) and contemporary subsidence is estimated at approximately 0.25 millimeters per year (Janda 1965, Ouchi 1983).

3.6.4. Pleistocene Changes in Channel Processes and Form

The channel morphology of the present-day San Joaquin River, particularly in Reach 1, exists within a framework of climatic changes occurring over the last several million years, and this morphology must be viewed in context with these longer time-scale changes. For example, the San Joaquin River in Reach 1 has recently (last few thousand years) incised within a large-scale alluvial fan exiting the San Joaquin River that was formed during periodic glacial periods with increased sediment yield. The incision has abandoned floodplains, which are now terraces used for agriculture and aggregate mining. In addition to this temporal (time) context, there is a spatial context that must be acknowledged as well that influences channel morphology. Differences in underlying geology, runoff conditions, and geologic controls throughout the San Joaquin River watershed cause differing sediment yields and channel morphologies between the study reach and in the watershed above Friant Dam (upstream of the study reach). This section provides some of this large-scale context.

The watershed of the lower San Joaquin River within the study area is composed of water-bearing Tertiary (~65 to ~2 million years ago) and Quaternary-age (~2 million years ago to present) alluvial sediments. The impermeable middle to late Pleistocene-age (~1.2 million years ago to ~10,000 years ago) Corcoran clay confines some of these water-bearing sediments; however, more recent alluvial deposits have buried the Corcoran clay (Norris and Webb 1990) (see Figure 4-4). Base-level control at the downstream end of the study area is provided by the Merced River alluvial fan. Conversely, the underlying rocks of the Sierra Nevada provide base level control for the San Joaquin River above Friant Dam. These rocks are composed of granitic rocks (75%), metamorphosed (physical change of rocks by temperature or pressure) sedimentary and volcanic rocks (15%) and discontinuous Cenozoic volcanic rocks such as basalt (10%) (Janda 1965). At Friant Dam, the San Joaquin River flows out of the bedrock foothills of the Sierra Nevada and cuts across the Pleistocene alluvial fan sediments of the San Joaquin Valley in a shallow, terraced trench for 35 miles downstream to Mendota (RM 205). Understanding the long-term sediment supply dynamics of the upper watershed in relation to the sediment transport character of the upper project reaches is critical in understanding the interactions between the flow, sediment, and habitat within the project reaches.

By examining rock units of different age that represent (1) a change from deposition, to erosion, and back to deposition again (unconformities), (2) the westward tilt of clay deposits, and (3) interglacial (times between glacial periods) marine beds, Janda (1965) concluded that the alluvial fan formations below the Friant Dam site are related primarily to sediment transport variations during glacial and interglacial periods, rather than to tectonics and eustatic sea level fluctuation (sea level change related to the creation and subsequent melting of continental glaciers). His evidence indicated the following sequence of events:

- *During glaciation*: extensive erosion of mountain slopes, leading to rapid aggradation of mountain canyons and alluvial fans;
- *During glacial waning (glacial retreat)*: reduction in sediment yield from mountain slopes, leading to incision in mountain canyons but continued aggradation of alluvial fans
- *Late glacial/early interglacial*: further reductions in sediment yield lead to major rivers incising into their alluvial fans. Upon reaching a stable gradient, lateral activity commenced.

This cyclic process repeated during different glacial periods, resulting in several depositional units derived from the Sierra Nevada sediments, including the older Turlock Lake Formation, the younger Turlock Formation, Riverbank Formation, Modesto Formation, and recent alluvium. Table 3-2 correlates the glacial history of the Sierra Nevada to the alluvial deposits in the San Joaquin Valley. Glacial deposits near the foothills form a sequence of nested terraces where successively younger deposits fill the canyons carved into the older deposits. A short discussion of the most recent valley fill and incision provides a frame of reference for present-day valley morphology in Reaches 1 and 2. Beginning approximately 100,000 years ago, period of glaciation filled the valley with sediments in Reach 1 to approximately the tops of the bluffs in the Herndon area (RM 261) and extended into the axis of the San Joaquin Valley as a large alluvial fan (Modesto Formation, Table 3-2). Subsequent interglacial periods of low sediment yield resulted in the San Joaquin River incising into the large-scale alluvial fan. Remnants of the Pleistocene fan remain in Reach 1, and terraces in Reach 1 and 2 are remnants of smaller fans created during subsequent glaciations (e.g., Tioga and Tahoe). Further incision of the smaller fans during the post-Tioga glaciation period has resulted in the present-day entrenchment of the San Joaquin River in the smaller Holocene-age alluvial fan. In other words, over the last several hundred thousand years, the San Joaquin River has filled and eroded its valley in Reach 1 and 2 two to three times, and the present-day condition is one of an incised river rather than an aggraded river. The river currently flows through bottomlands entrenched 50-100 feet below its Pleistocene fan surface and bounded on each side by bluffs, and within the bottomlands, flows between 15-30 high terraces of the Holocene fan (Figure 3-5). Gravelly Ford (RM 229) is the downstream extent of the confining terraces of the San Joaquin River.

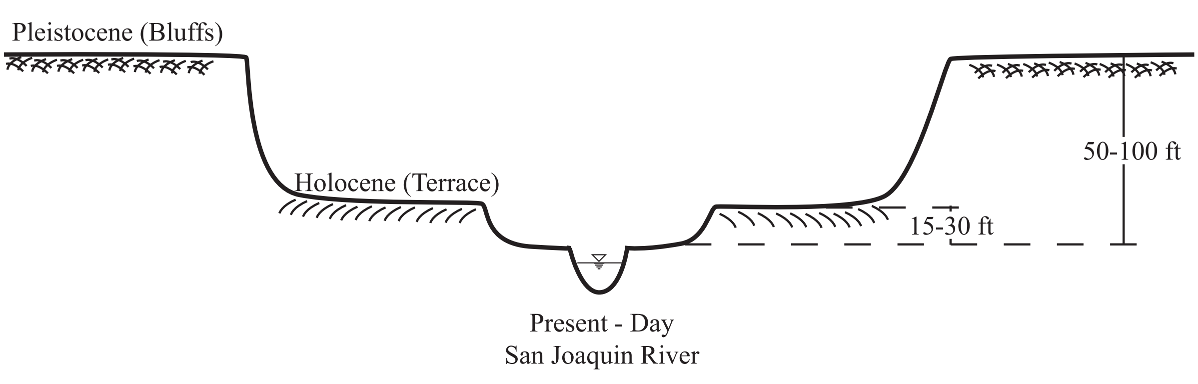


Figure 3-5. Conceptual cross section through Reach 1 illustrating different geomorphic surfaces within the San Joaquin River bottomlands.

Table 3-2. Correlation of glacial history to the alluvial deposits in the San Joaquin Valley (adapted from Janda 1965).

Sierra Nevada		San Joaquin Valley
Glacial Event	Generalized numerical age (years before present)	Alluvial [Volcanic] Deposits
Tioga, Tenaya, Tahoe, & Mono Basin Glaciations	0 – 100,000	Modesto Formation (2 – 3 phases)
Glaciation at Mammoth Mountain, Donner Lake Glaciation?	200,000	Riverbank Formation
Hobart Glaciation?	600,000	Turlock Lake Formation (younger phase) Friant Pumice Member & Corcoran Clay Member]
Sherwin Glaciation	> 700,000	Turlock Lake Formation (older phase)

The numerical ages of Sierra Nevada glacial stages are an active topic of research and debate. Recent work by Pinter et al (1994) summarizes more recent research of Sierra Nevada glacial event ages, and although some of the dates and nomenclature differ slightly from Janda's work, other elements are similar and have persisted through today's research. Because Janda's research focused on relating San Joaquin Valley sediments to the glacial stages listed in Table 3-2, and because the objective of this discussion is to describe the local geology as it relates to sediment production and erosional processes, we use the results of Janda's work (rather than the more recent glacial sequencing and age dating) to estimate sediment production and yield.

3.6.5. Sediment yield

Janda's hypothesis was that sediment yields were high during glacial periods, and low in interglacial periods, particularly in the modern interglacial period prior to the construction of upstream reservoirs. Based on Janda's hypothesis, it is reasonable to assume that the recent unimpaired (pre-dams) sediment yield from the upper watershed to the project reaches below the Friant Dam site is small relative to geologic averages over the last million year, and thus it is not unexpected that the river below the Friant Dam site would incise into its alluvial fan. This is consistent with the bluffs and terrace formations found in this location. Further, the base of the historic alluvial sequence is marked by bedrock outcrops consisting of intrusive granodiorite and, notably, the Friant Pumice resulting from a large rhyolitic (volcanic rock rich in silica) eruption approximately 600,000 years ago. The exposure of these outcrops, acting as base level control in Reach 1A, is assumed as proof that the present day river is as entrenched as at any time in the recent geologic past. Janda (1965) estimated that contemporary denudation (erosion of watershed) rates are only 25-40% of the rate averaged over the last 600,000 years, and only 10-15% of the last 27,000 years. In the absence of glacial erosion and a wetter climate, it is not surprising that the sediment yield from the erosion resistant granite characteristic of most of the upper watershed is low.

Janda (1965) estimated maximum denudation rates of 0.15 feet/1,000 years (0.0018 in/yr) and denudation rates of 0.08 ft/1,000 years (0.0010 in/yr) for snowmelt runoff portions of the watershed. Using the maximum rate as a conservatively high sediment yield, the corresponding total sediment yield would be approximately 260,000 yd^3/yr (Table 3-3). A small proportion of the total sediment load is coarse sediment, usually 5% (gravel bedded rivers) to 50% (sand bedded rivers) (Dunne and

Leopold, 1976). Collins and Dunne (1990) estimate that the coarse sediment component in lowland rivers typically ranges from 2% to 6% of the total sediment load (gradient from 0.0004 to 0.0023), and the coarse sediment proportion in mountainous rivers typically ranges from 8% to 16%. There are no data specifically for the San Joaquin River, so for comparative purposes, it is assumed that the coarse sediment component at a location where the San Joaquin River exits the Sierra Nevada is 10% of the total sediment yield. Using this adjustment value, the San Joaquin River watershed above the Friant Dam site (1,676 mi^2) would have delivered on average approximately 26,000 yd^3/yr of coarse sediment (58,000 tons/yr, or 34.6 tons/mi^2/yr) to the reach prior to Friant Dam and other upstream dams. Corresponding estimates for the Merced River and Tuolumne River using reservoir sedimentation from those rivers (Brown and Thorp 1947) are also computed at the location where the rivers exit the Sierra Nevada to compare with the San Joaquin River (Table 3-3).

Table 3-3. Summary of sediment yield estimates on the San Joaquin River and Tuolumne River.

Location	Unit sedimentation rate used (units below)	Drainage Area (mi^2)	Total sediment yield (yd^3/yr)	Coarse sediment yield assuming 10% of total sediment yield (yd^3/yr)	Sources/method
San Joaquin River at Friant Dam location	0.0015 in/year	1,676	260,000	26,000	Janda (1965) from watershed denudation rate estimates
San Joaquin River at Friant Dam location	0.18 ac-ft/yr	1,676	486,000	48,600	Cain (1997), using a higher value of reservoir sedimentation rates from Brown and Thorpe (1947)
Merced River at Merced Falls, near Snelling	0.17 ac-ft/yr	1,061	291,000	29,100	Brown and Thorpe (1947) from reservoir sedimentation rates
Tuolumne River at LaGrange	0.21 ac-ft/yr	1,538	521,000	52,100	Brown and Thorpe (1947) from reservoir sedimentation rates

All estimates in Table 3-3 assume that coarse sediment is 10% of the total sediment yield. The low values of bedload delivery for the San Joaquin River are much lower than that estimated from the Tuolumne River, even though the San Joaquin River has a larger drainage area. The naturally low sediment yield from the upper San Joaquin River watershed, combined with the very low gradient of the reach immediately below Friant Dam, suggests that the coarse sediment in the study area was characterized by low supply and low transport rates, even before the supply was disconnected by the construction of Friant Dam. Janda (1965) also argued that rates of transport are low, and that sediment sources for alluvial gravel were primarily local (lateral erosion of terraces) on the basis that:

- Little gravel is accumulating as deltas at the head of upstream reservoirs.
- Present day gravel occurs adjacent to gravel-bearing river bluffs.
- Recent gravels are lithologically similar to Pleistocene gravel with the exception of granite (weathered and eroded).

While the point has been made that gravel deposits are found well away from the Pleistocene bluffs (Cain 1997), the balance of evidence, including sediment transport calculations, appears still to favor a low supply-low transport basis for the reach below Friant Dam.

3.6.6. Historical Channel Form and Processes in Study Area

Quantitative data on pre-settlement channel form and processes are virtually non-existent; however, there are several sources of historical information (as described in Section 3.4). Of these historical sources, the 1854 Government Land Office maps are the only source that may reasonably reflect unimpaired channel morphology conditions because more extensive land conversion, levees, and clearing occurred after the mid 1850's. However, the detail of these maps is not extensive, such that the primary use of these maps is to estimate channel location and planform morphology. The latter maps and photographs provide valuable insights to unimpaired channel processes and morphology, but their use to infer unimpaired conditions must be tempered by the fact that substantial land use changes had occurred prior to the dates of the maps and photos (canals, diversions, grazing, land clearing, etc.). Anecdotal information from historical surveys and explorations is also limited; most descriptions focus on soils, water, and riparian vegetation (also see Chapter 8). This anecdotal information is summarized in Section 3.6.6.1, and more quantitative information from the historical mapping sources is provided in the reach descriptions (Section 3.7). Post-Friant Dam information is more readily available, and typically more quantitative. This information is summarized in Section 3.4.

3.6.6.1. Reach-wide Historical Perspective

The first explorers to document conditions along the San Joaquin River were the Spanish, beginning in the 1770s. As the Spanish established missions along the Pacific Coast, several expeditions into the San Joaquin River and Tulare Lake regions provided the first descriptions and maps of these regions. Numerous expeditions by Gabriel Moraga between 1806 and 1810 covered most of the San Joaquin Valley and Tulare Valley; however, descriptions of the river focused mostly on the tule marshes and other types of vegetation, and did not discuss any details about the channel morphology of the San Joaquin River. Jedediah Smith was the first American explorer to travel along the San Joaquin River in 1827, trapping beaver along Tulare Lake, the San Joaquin River, Kings River, and others on his way north through the valley (Brooks 1977). As with Moraga's expeditions, Jedediah Smith did not provide much description of the San Joaquin River channel morphology. The most useful description of the channel is a comparison of the river upstream and downstream of the bend at present-day Mendota:

> *above the bend, the banks were high and the current rapid, but below [the bend] the river had been divided into many small sloughs and channels, the banks low, and the current sluggish. In many places, rushes and mud a mile in width made it impassible for horses.*

C.D. Gibbs, in a letter to the *Stockton Times* in 1850 (as cited in Fox 1987), provides a small description of the natural levees along the San Joaquin River in the flood basin (assumed to characterize Reach 3 through 5):

> *As near as I can judge, the tule land in the upper part of this tract is from 2 to 5 feet lower than the banks of the river*

Later military (e.g., George Derby in 1850), geology (e.g., William Brewer in 1862-1864), and engineering (e.g., William Hammond Hall in the 1880's) expeditions made more observations, but again focused on vegetation, as well as water and soils. These limited descriptions of the channel morphology, combined with our review and interpretation of historical maps and aerial photographs, allows for a general description of channel processes and morphology within the study area. The general descriptions below are supported more in the reach descriptions in Section 3.7.

3.6.6.2. Effect of Slope and Control on Sediment Transport and Routing

As described in Section 3.6.5, unimpaired levels sediment supply from the upper San Joaquin River watershed to the study area appears to be extremely low. Additionally, valley slopes in Reach 1 are very low (0.001 to 0.00063) compared to adjacent tributaries (e.g., comparable Tuolumne River slopes are 0.0015), resulting in historically low sediment transport rates. Although the sediment supply rates from the upper watershed were probably low, the river had a supply of coarse sediment (cobbles and gravels) and fine sediment (sand and silts). Longitudinally, the coarser sediments deposited in Reach 1A and the upper portion of Reach 1B. The lower portion of Reach 1B was a transition zone from gravel-bedded to sand-bedded channel, with Reach 2 through Reach 5 being entirely sand bedded. Because east-side tributaries emptied into the floodbasins in Reach 3 through Reach 5 rather than directly connecting to the San Joaquin River (Carson 1852, as cited in Fox 1987), they deposited their sediment supply well before entering the San Joaquin River. Therefore, as sediment was deposited longitudinally in the channel and on floodplains, the supply of sediment decreased in the downstream direction because there were no tributaries to supply the river with sediment. This decreasing sediment supply and sediment transport capacity (lower slope) in downstream reaches resulted in a changing channel geometry in the downstream direction. The channel is extremely flat in the lower reaches and the river remains within 5 feet of sea level 50 miles upstream of the confluence with the Sacramento River. The low slopes suggest that the channel is slowly aggrading as a result of base level rise from the rising sea level after the end of the last glacial period.

3.6.6.3. Channel Migration and Avulsion

Review of sequences of historical maps and aerial photographs suggests that channel migration rates were small and channel avulsion was infrequent; however, the observations of scroll bars, oxbows, sloughs, and scour channels in various reaches confirm that migration and avulsion did occur. To date, a comprehensive historical channel analysis has not been conducted for the entire study reach, so quantitative estimates of migration rates and avulsion frequency has not been made. Review of historical channel overlays in representative portions of Reach 1 through Reach 3 show that the baseflow channel moves considerably within the bankfull channel, but the meander pattern of the bankfull channel appears to moderately stable. In Reach 4 and 5, the channel location appears to be much more stable, likely a result of the decreasing sediment supply in these downstream reaches. Again, there are oxbows and side channels, so channel migration and avulsion does occur, perhaps just during extreme flood events.

3.6.6.4. Planform Morphology

The San Joaquin river is a moderately sinuous gravel bed river similar to other gravel bed rivers which originate in the Sierra Nevada and flow into the Central Valley. Meanders were poorly defined from Friant Dam downstream to RM 250, then the meander pattern becomes more sinusoidal and begins having a more consistent planform dimension tendency. Numerous split channels (e.g., Cobb Island at RM 258-260), side channels, and high flow scour channels (e.g., Ledger Island at RM 262-263) occurred in Reach 1, with some of the side channels being more than a mile long (Figure 3-6). With the transition of the river into the sand-bedded channel in Reach 2, the planform morphology transitioned into a purely meandering morphology (Figure 3-7). Sinuosity was large, and the river had a single primary channel. The notable exception was at Lone Willow Slough, which may have conveyed baseflows, but was smaller than the mainstem San Joaquin River. High flow scour channels at the downstream end of Reach 2 conveyed overbank flows south to Fresno Slough, which then apparently conveyed flows back to the San Joaquin River at Mendota (Derby 1850). Both Reach

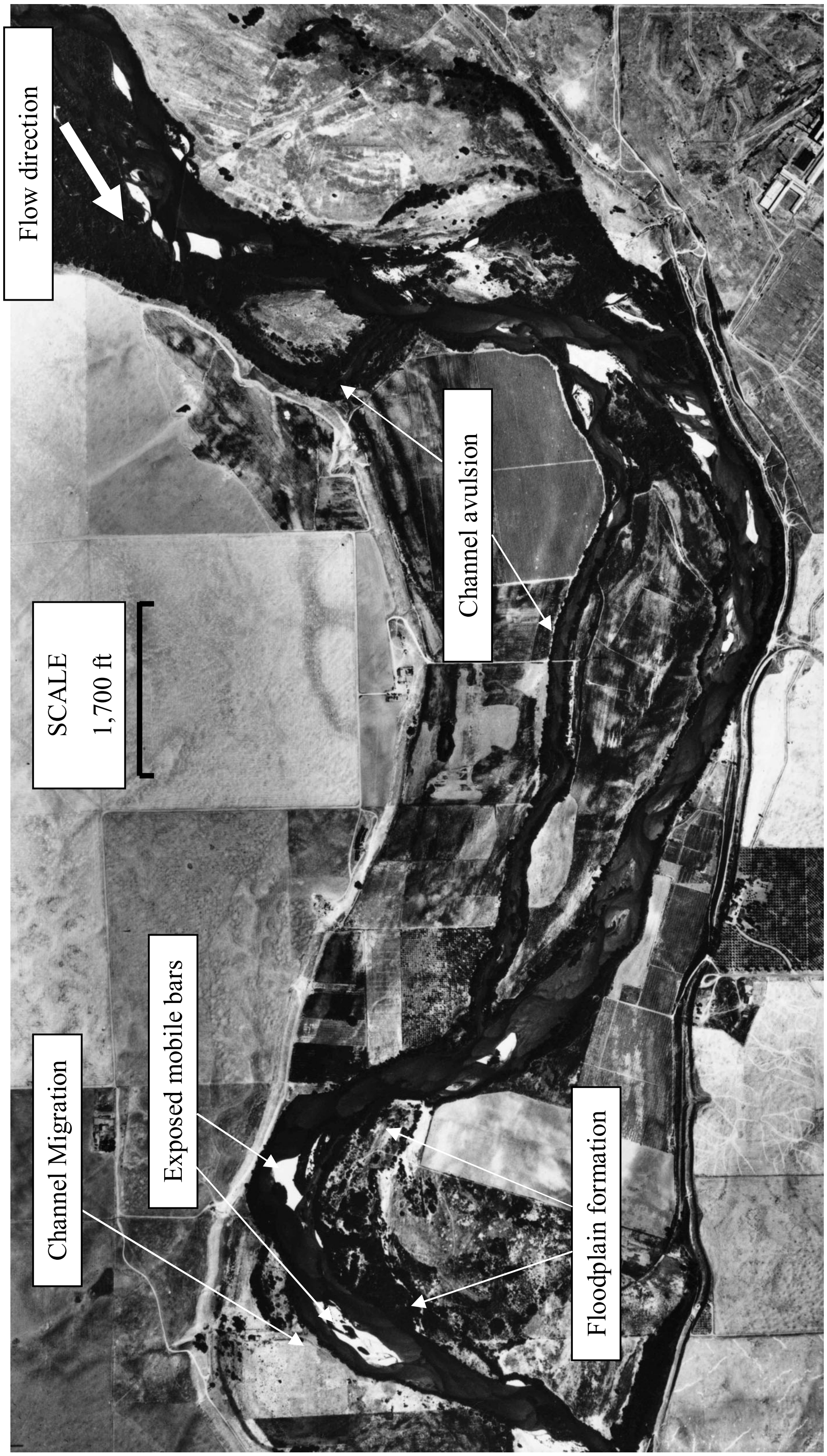


Figure 3-6. 1937 aerial photo of a portion of Reach 1 from RM 249.3 to 254.5 illustrating evidence of fluvial processes under the pre-Friant Dam flow regime.

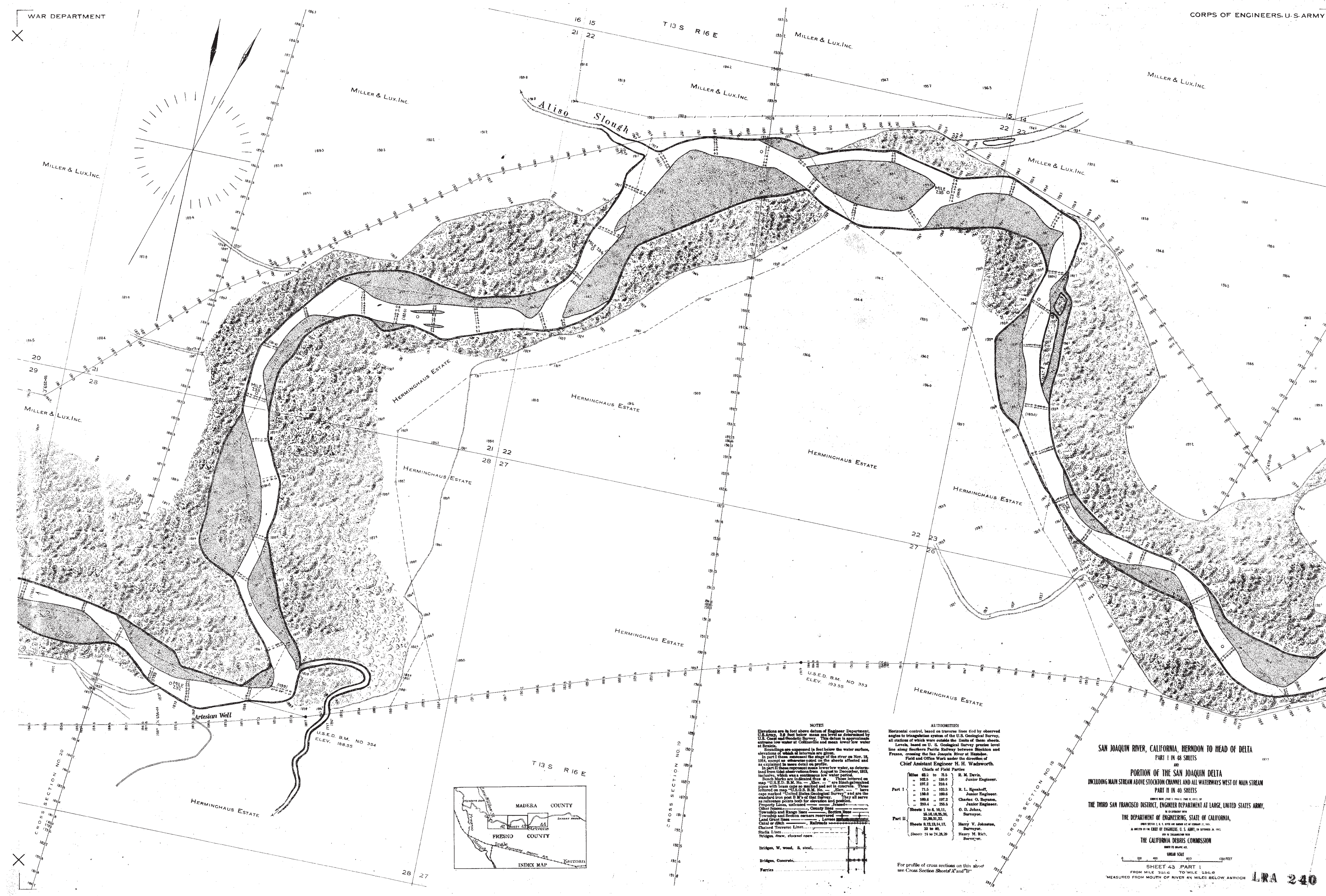


Figure 3-7. 1914 planform maps of Reach 2 from RM 214.7 to 219.5, illustrating meander pattern, bar features, and other morphological features of interest (ACOE 1917).

Figure 3-8. 1914 planform maps of Reach 3 from RM 193.3 to 197.8, illustrating meander pattern, bar features, and other morphological features of interest (ACOE 1917).

1 and Reach 2 are on the prograding alluvial fan of the San Joaquin River; the alluvial fan ends at Mendota, which marks the upstream end of Reach 3.

The 1914 maps (ACOE 1917) and 1937 aerial photographs does not show distinct changes in planform morphology between Reach 2 and Reach 3 despite the slightly lower slope and decreasing sediment supply in Reach 3 (Figure 3-8). The 1914 maps imply that there are more oxbows in Reach 3 than Reach 2, but the aerial photos do not provide the same evidence, suggesting that the additional oxbows are a relic of mapping differences between the reaches. Reach 3 still has high flow scour channels that indicate frequent overbank flows, but does not have numerous anabranching slough channels.

Reach 4 and Reach 5 all have anabranching slough channels, with many of the sloughs originating in Reach 4 (e.g., Pick Anderson Slough, Santa Margarita Slough) and converging back to the mainstem San Joaquin River in Reach 5 (e.g., Salt Slough, Mud Slough). These anabranching channels had a meandering planform morphology and small bar forms, but appeared to migrate at a low rate. Additionally, the 1914 maps and 1937 aerial photographs do show exposed sand bars in both Reach 4 and Reach 5, but they are much less pronounced than the exposed sand bars in Reach 2 and Reach 3 (Figure 3-9 and Figure 3-10).

3.6.6.5. Channel Geometry and Slope

Channel geometry in Reach 1 reflected the meandering gravel-bed channel morphology, having a primary bankfull channel and floodplain, but also contained side channels that conveyed baseflows, as well as higher elevation scour channels that conveyed high flows (Figure 3-6). The river is moderately confined between bluffs downstream to Skaggs Bridge (RM 234.1), then the confining bluffs begin to fall away from the river to the point where they disappear at the downstream end of Reach 1B. Channel geometry in Reach 2 was typified by a single primary channel and perhaps small natural riparian levees along the banks (Figure 3-7). Because Reach 2 is on the San Joaquin River alluvial fan, and has no confining bluffs or high terraces, large flood flows spilled towards the south via scour channels, as well as north through Lone Willow Slough. Reach 3 is moderately confined on the left (west) bank by a terrace, which falls away at the downstream end of the reach. Channel geometry in Reach 3 was similar to Reach 2, having large exposed sand point bars and riparian vegetation at the top of the point bars and on the floodplains (Figure 3-8). The extensive flood basin in Reach 4 through 5 was the dominant feature in channel geometry in these reaches, and marsh delineations are evident on the 1914 maps (Figure 3-9 and Figure 3-10). This flood basin was several miles wide, confined by a terrace on the west side of the valley and by prograding alluvial fans on the east side of the valley, and influenced by the backwater from the Merced River alluvial fan (JSA and MEI 1998). Another prominent feature of channel geometry in these downstream reaches was the natural riparian levees along the channel margins. During high flows that suspended fine sediments, vegetation along the channel margins slowed water velocities, allowing sediments to deposit. Over time, these sediments accumulated to create levees. Katibah (1984) hypothesizes that these levees decreased in size as they progressed downstream due to decreasing energy, decreasing peak flows (due to flood peak attenuation in the flood basin), and decreasing sediment supply.

3.6.6.5.1. 1914 Cross Section, Profile, and Slope Summary

The 1914 survey of the study area by the ACOE (1917) provides a reasonable baseline condition for San Joaquin River channel geometry between the Merced River confluence at RM 118 and Herndon at RM 243 (the results of this data are presented for all reaches for simplicity). Cross sections surveyed by the Bureau of Reclamation in 1939 can be used to document channel geometry for the reach upstream of Herndon. Between 1914 and 1915, the ACOE surveyed 85 cross sections within the study area, and used these to construct longitudinal profiles of the river thalweg (minimum elevation at the cross section), water-surface elevation at the time of the surveys, and the top of bank elevation (Figure 3-3). The top-of-bank profile represents the elevation of the bank at each cross section that defines the bankfull stage of the channel. JSA and MEI (1998) measured the width and depth of the channel at the bankfull stage from the cross sections, and plotted widths and depths against the river mile to show their spatial distribution (Figure 3-11 and Figure 3-12). The channel widths and depths tend to be largest in Reaches 1 and 3, and lowest in Reaches 2, 4, and 5. The combination of low width and low depth indicates areas where overbank flooding frequently occurred; Reach 2 aerial photographs show frequent flooding to the south into Fresno Slough, and Reaches 4 and 5 are the flood basins that were inundated for long periods of time in most years. The width-depth ratio at the bankfull stage was computed for each cross section and plotted against river mile (Figure 3-13). The bankfull stage is estimated from morphological features on each cross section, and not from a computed water surface elevation for a consistent estimate of bankfull discharge. Average values for the valley slope (top of bank), channel slope, bankfull width, bankfull depth, width-depth ratio, and sinuosity were computed for each of the reaches (Table 3-4).

Table 3-4. Channel and planform characteristics for Reaches and sloughs of the San Joaquin River based on the 1914 maps (ACOE 1917).

Subreach	Valley Slope (feet/feet)	Channel Slope (feet/ feet)	Average Bankfull Width (feet)	Average Bankfull Depth (feet)	Width-Depth Ratio	Sinuosity
1A	0.0008	0.0007	N/A[a]	N/A[a]	N/A[a]	1.14[b]
1B	0.00077	0.00063	875	18	49	1.22
2	0.00057	0.00031	744	14	53	1.83
3	0.00033	0.00022	564	14	40	1.44
4A	0.00037	0.00028	277	14	20	1.33
Sand/Salt Slough	0.00037	0.0005	150	7	21	
4B	0.00037	0.00022	311	9	35	1.67
Salt Slough	0.00037	0.00033	258	9	29	
5	0.00036	0.00021	386	13	30	1.71
Salt Slough	.00036	0.0002	394	10	39	

[a] 1914 maps did not extend into Reach 1A, no data available.

[b] 1914 maps did not extend into Reach 1A, 1937 aerial photography used.

Previous studies (JSA and MEI 1998, Cain 1997) compared thirteen cross sections from 1914 and 1939 with contemporary cross sections to evaluate changes in channel elevation and shape (Table 3-5). Approximate cross section locations used for this comparison are shown on Figure 3-14. The topographic precision shown on the tables is often greater than the precision of the surveys they are based on (bathymetric surveys in 1914 and 1998), so the results shown in Tables 3-5 and Table 3-6 should be considered approximate. This inherent imprecision of the surveys, combined with complicating factors like ground subsidence and the small sample number of cross sections used, result in there being substantial uncertainty in these estimated changes shown in the tables.

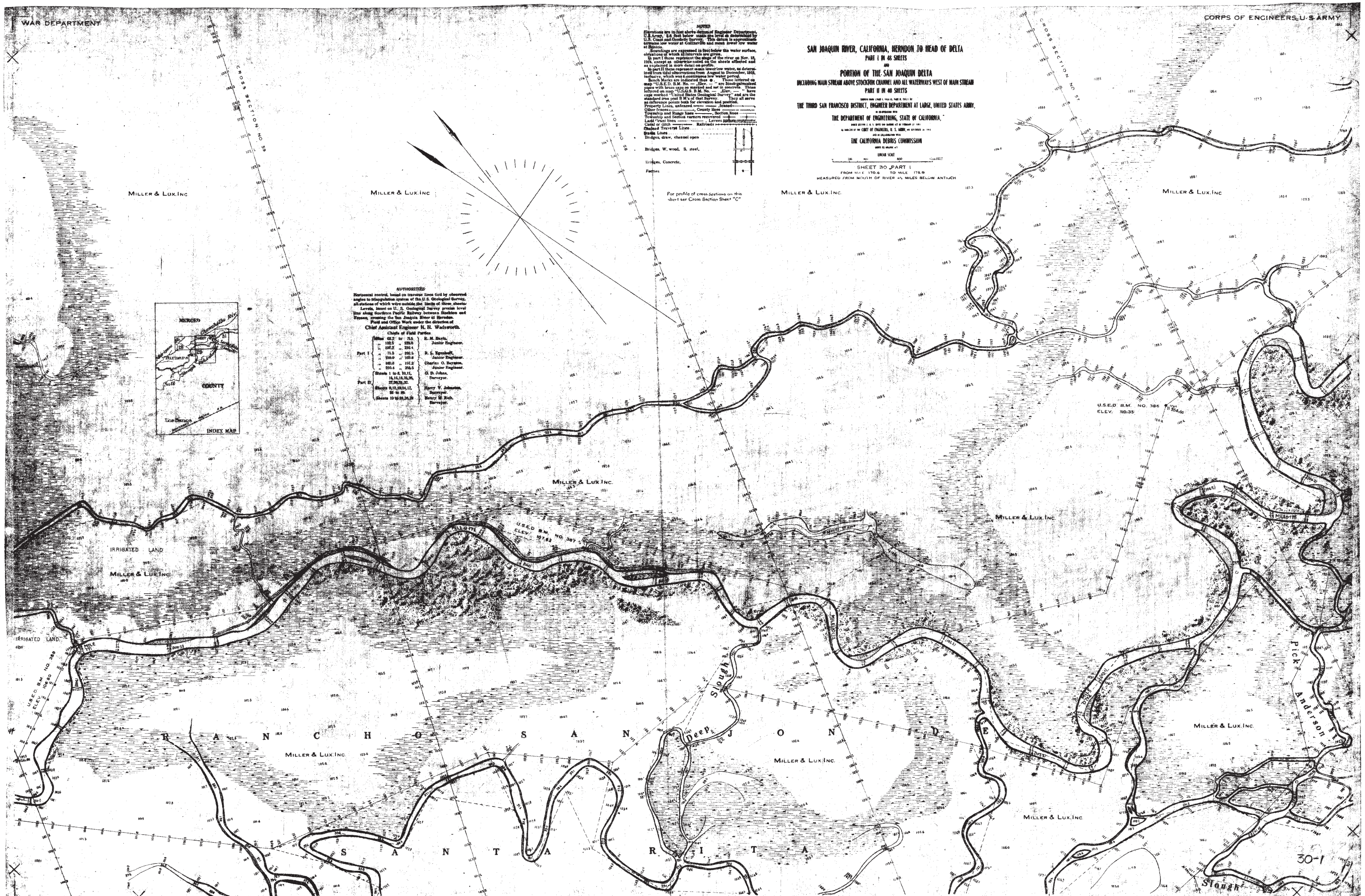


Figure 3-9. 1914 planform maps of Reach 4 from RM 161 to 166, illustrating meander pattern, bar features, and other morphological features of interest (ACOE 1917).

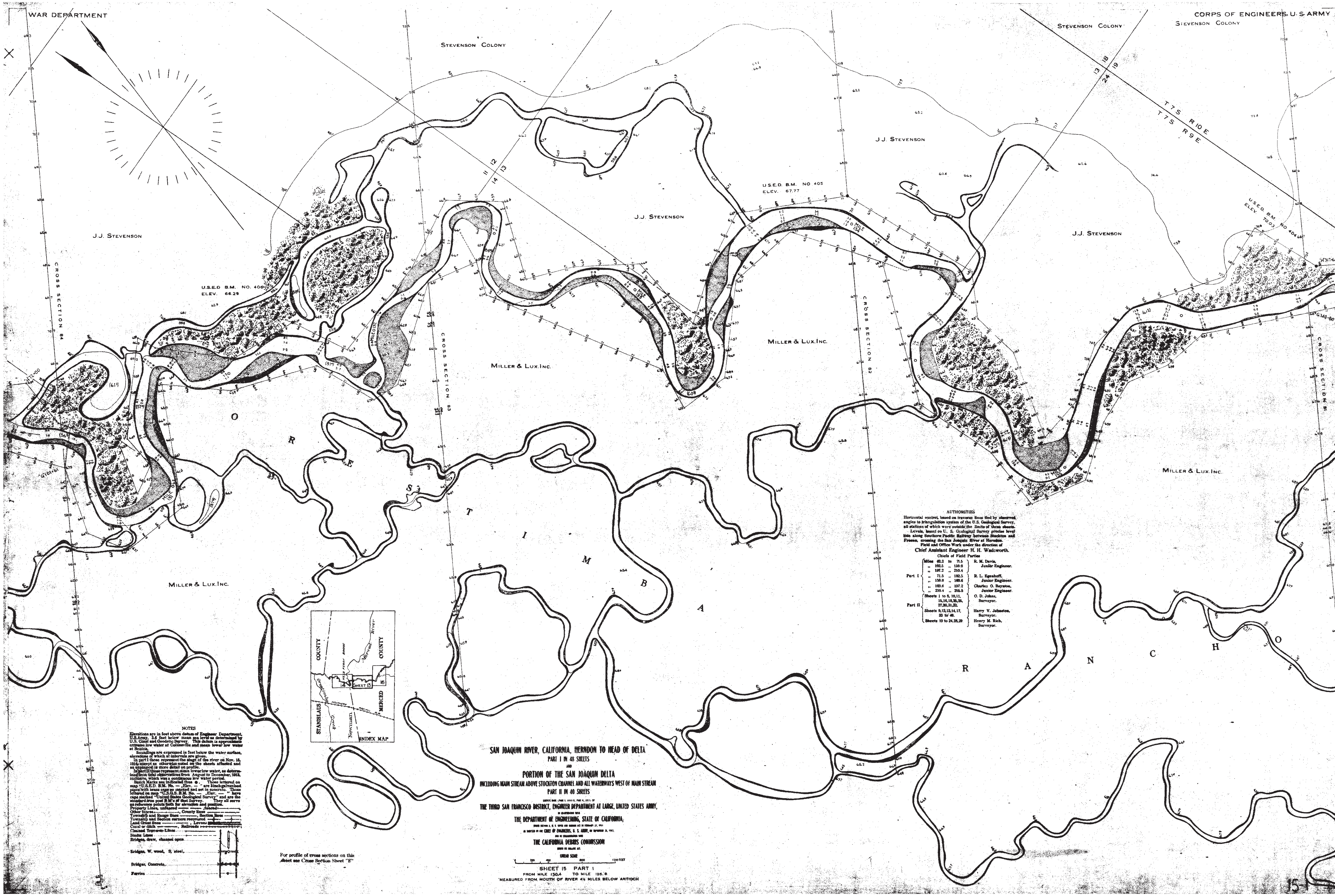


Figure 3-10. 1914 planform maps of Reach 5 from RM 120 to 125.3, illustrating meander pattern, bar features, and other morphological features of interest (ACOE 1917).

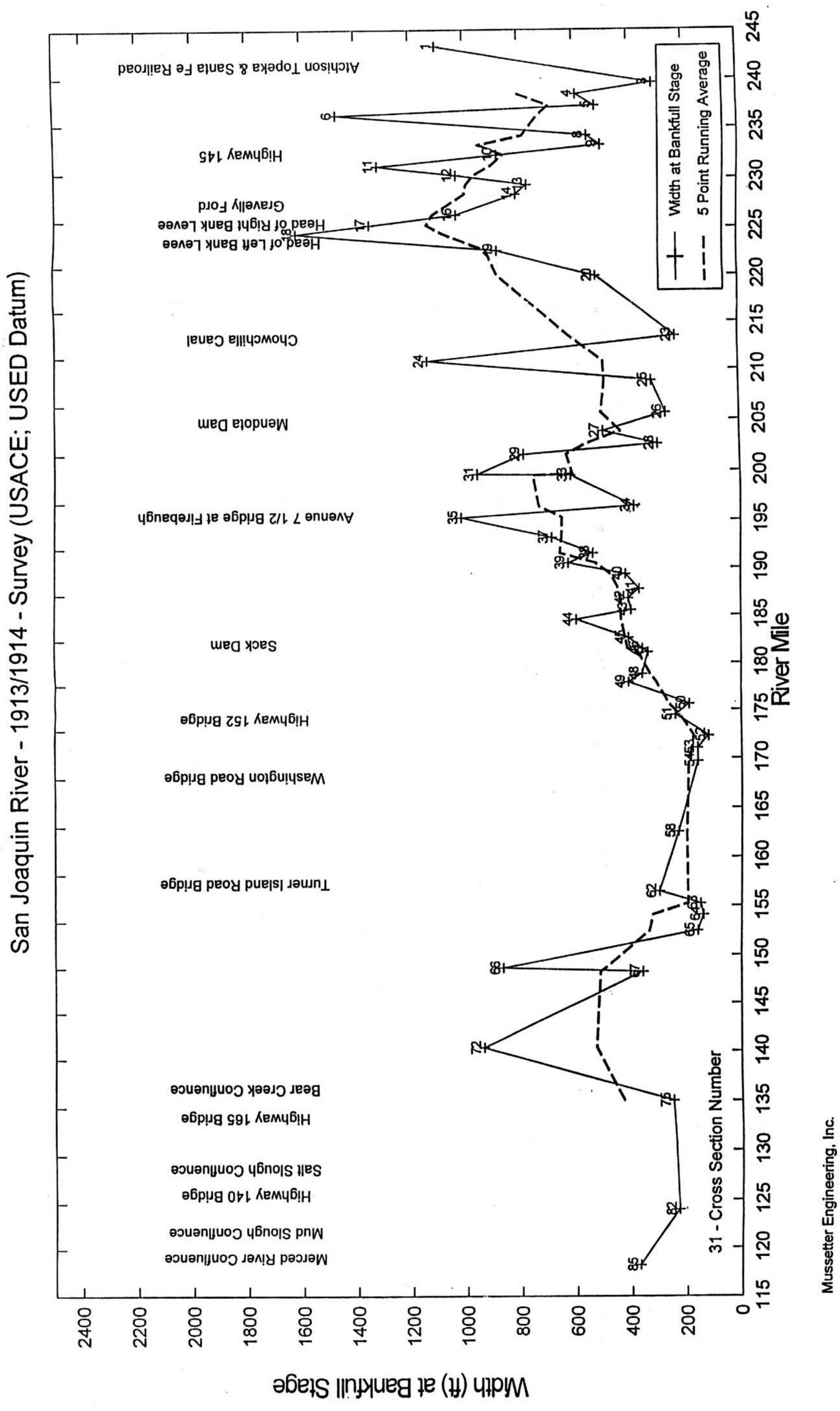


Figure 3-11. Longitudinal changes in channel width from 1914 mapping effort (ACOE 1917) between Herndon and the Merced River confluence. The river mile markers begin at the Merced River confluence (RM 118.2), but the river mile markers and channel length from that point upstream are different than the mile markers used in this report. Bankfull stage is based on field indicators, not a consistent bankfull discharge estimate.

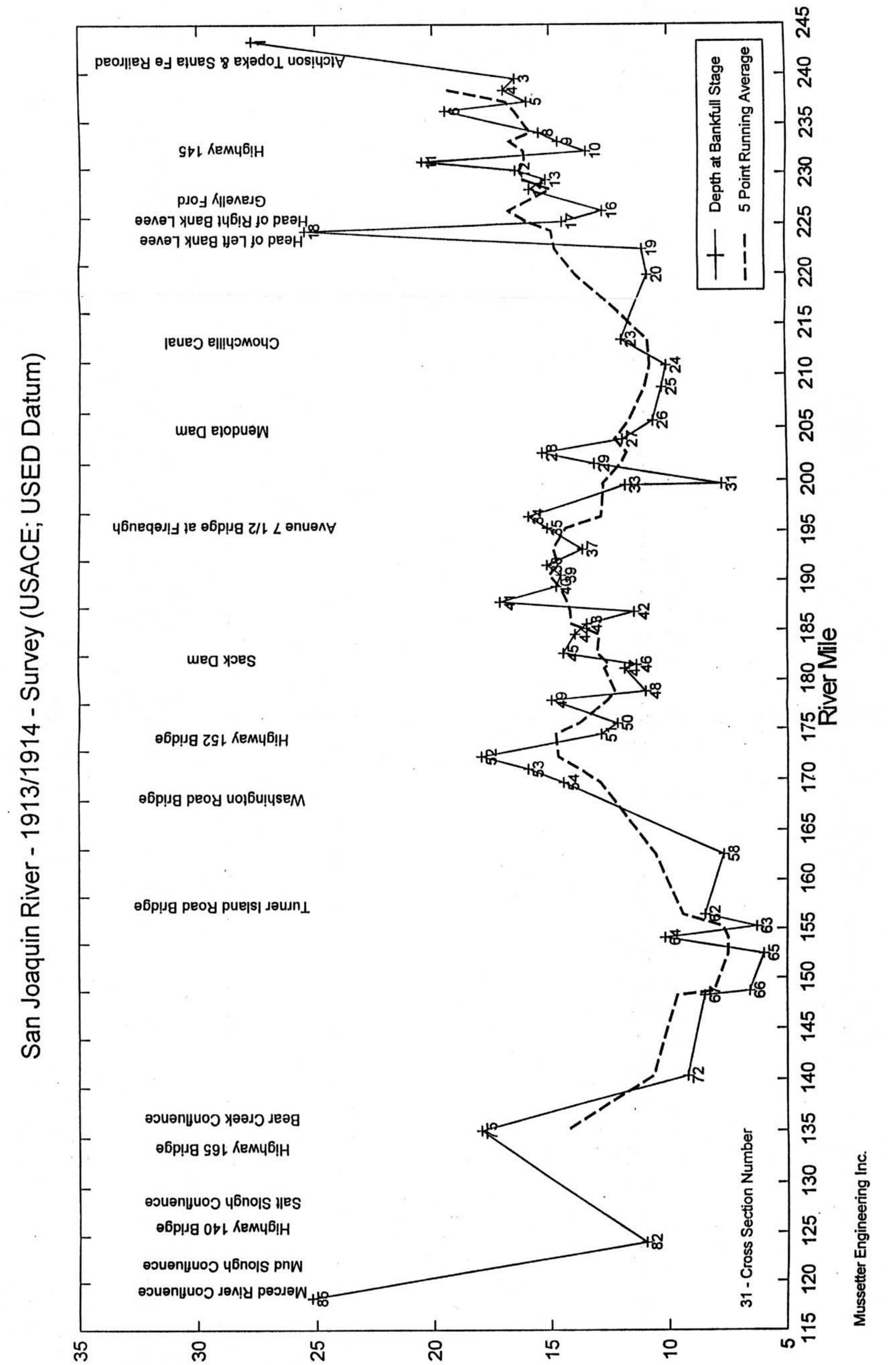


Figure 3-12. Longitudinal changes in channel depth from 1914 mapping effort (ACOE 1917) between Herndon and the Merced River confluence. The river mile markers begin at the Merced River confluence (RM 118.2), but the river mile markers and channel length from that point upstream are different than the mile markers used in this report. Bankfull stage is based on field indicators, not a consistent bankfull discharge estimate.

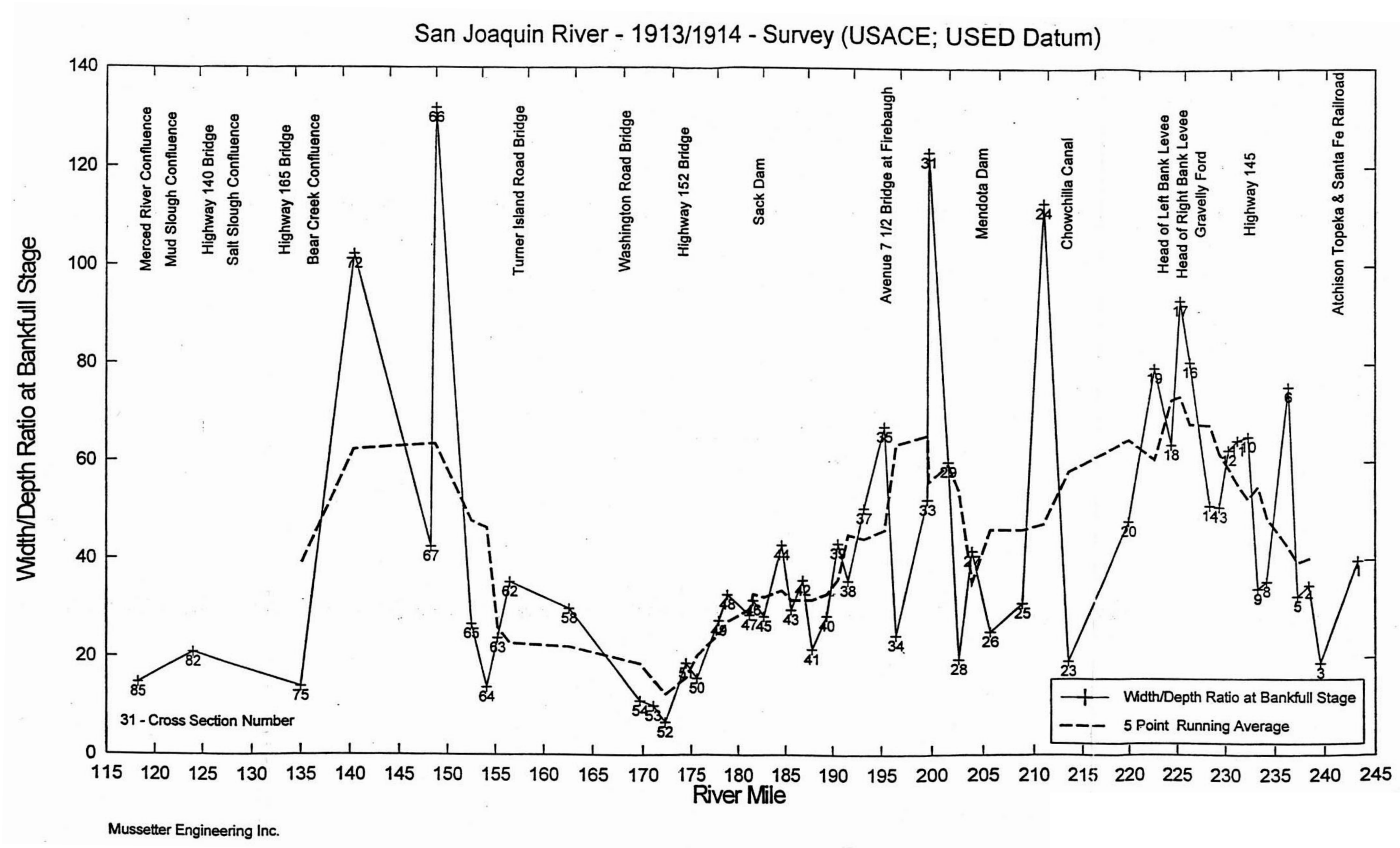


Figure 3-13. Longitudinal changes in width-to-depth (W/D) ratios from 1914 mapping effort (ACOE 1917) between Herndon and the Merced River confluence. The river mile markers begin at the Merced River confluence (RM 118.2), but the river mile markers and channel length from that point upstream are different than the mile markers used in this report. Bankfull stage is based on field indicators, not a consistent bankfull discharge estimate.

Table 3-5. Changes in thalweg elevation at resurveyed representative cross sections in the San Joaquin River study area.

Reach	Cross section	River mile	Period of record	Change in thalweg elevation (feet)
1A	C1[a]	266.6	1939–1996	-6.9
	C2[a]	266.5	1939–1996	-7.0
	C3[a]	265.8	1939–1996	+2.9
	C4[a]	265.4	1939–1996	+3.2
	C5[a]	260.6	1939–1996	+0.8
	C6[a]	259.3	1939–1996	-4.5
	C7[a]	255.3	1939–1996	-5.2
1B	C8[a]	243.7	1939–1996	-18.7[b]
	C9[a]	234.4	1939–1996	-3.0
	2	241.5	1914–1998	0.0
	9	233.3	1914–1998	-16.0[b]
2	14	228.4	1914–1998	-2.1
	19	222.6	1914–1998	-2.1
3	29	201.6	1914–1998	-10.8
	36	193.7	1914–1995	-1.5
4A	48	178.8	1914–1998	-3.9
	53	171.0	1914–1998	-2.2
4B	58	162.6	1914–1998	-1.0
	70	142.7	1914–1998	+6.7
5	78	130.1	1914–1998	-8.5
	81	125.8	1914–1998	+2.0
	85	118.2	1914–1998	0.0

[a] Cross Sections C1 through C9 obtained from Cain (1997)

[b] At instream aggregate mining pit

3.6.6.5.2. Changes in Width and Depth

Twelve cross sections that were originally surveyed in 1914 were resurveyed in 1998 (JSA and MEI 1998). Topographic data were extracted from the 1998 cross sections so that these could be compared with the values established from the 1914 survey (Table 3-6). Because the 1914 surveys did not extend to Reach 1A, Cain (1997) used the 1938 USBR topographic maps and the 1989 State Lands Commission maps to compare changes in channel width at 100 ft increments through Reach 1A. Assuming that the active channel delineated by the State Lands Commission on the 1938 topographic maps was equivalent to the bankfull or dominant discharge channel (Leopold et al. 1964) at that time, Cain (1997) showed that the 1939 average active channel width ranged from 630 feet between Friant Dam and Little Dry Creek to 1,400 feet between Little Dry Creek and Lanes Bridge. The average low flow channel width in the reach in 1939 was more variable, ranging from 220 feet between Friant Dam and Little Dry Creek to 425 feet just upstream of Lanes Bridge (Cain 1997). These "average low flow channel width" estimates are based on the delineation of the State Lands Commission on the 1939 topographic maps.

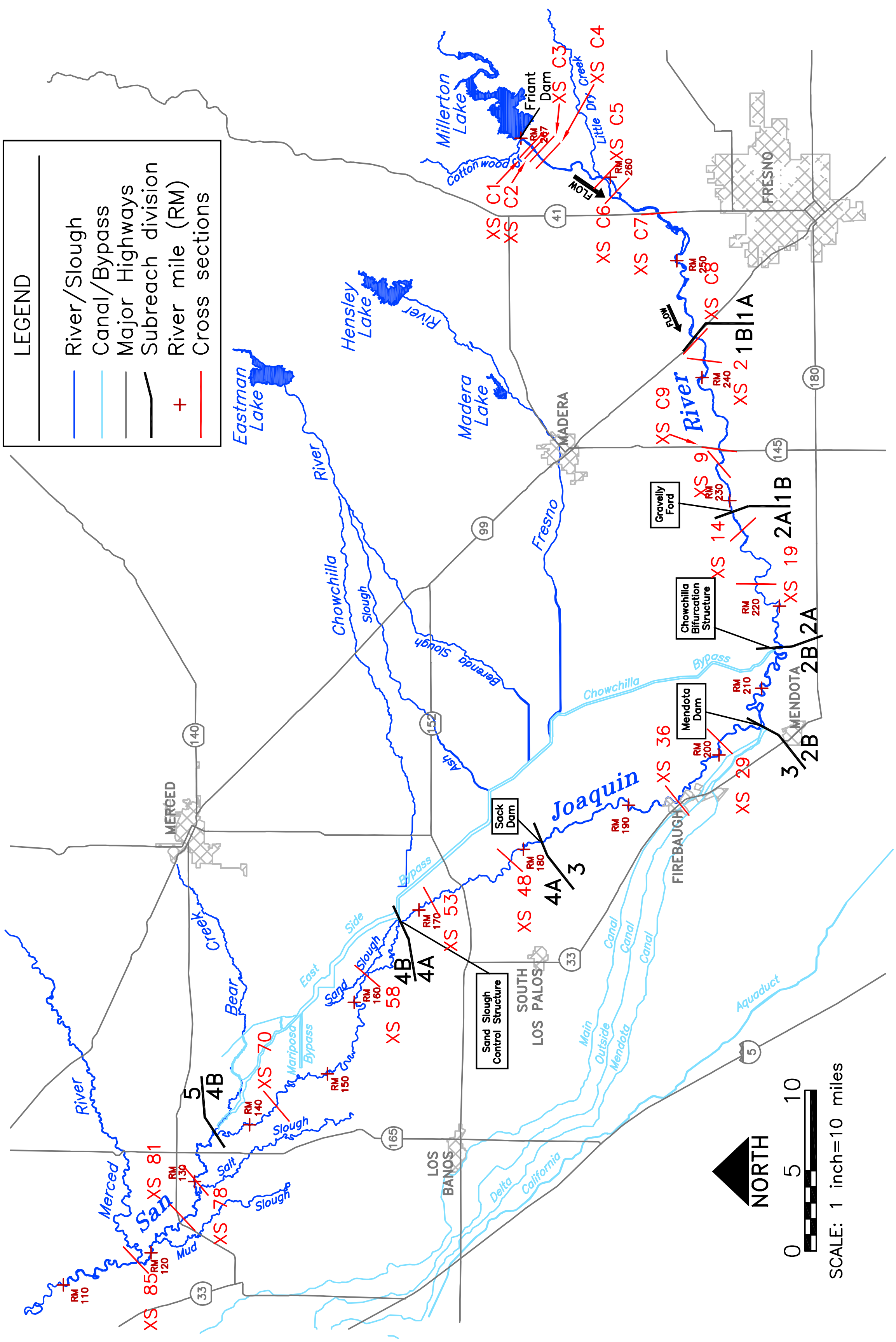


Figure 3-14. Approximate locations of 1914 cross sections (ACOE 1917) and 1939 cross sections (Cain 1997) re-occupied to evaluate changes in bed elevation.

Present-day bankfull channel widths were more problematic because of the riparian encroachment and the limited ability of the post-Friant Dam channel morphology to adjust its dimensions in response to the changed flow and sediment regime. Therefore, Cain used the aerial extent of the 1983 flood extent as captured on aerial photographs. The 1983 flood peak was 12,300 cfs, which was a 1.7-year flood event using the pre-Friant Dam flow regime. Therefore, the 1939 widths should be comparable with the 1983 bankfull widths. Cain (1997) compared the ratios of the low-flow channel widths in 1939 and 1989 to the 1939 active channel widths and the ratio of the 1980 high-flow channel width to the 1939 active channel width and concluded that the channel in Reach 1A had narrowed over time. Results for downstream reaches are solely based on individual cross section comparisons (1914-1998) rather than 100 ft increments as done in Reach 1A, thus results may not be as conclusive as in Reach 1A (Table 3-6).

Table 3-6. Comparison of channel morphology characteristics between 1914 and 1998.

Reach	Cross Section	1913–1914			1998		
		Bankfull Width (feet)	Bankfull Depth (feet)	Width-Depth Ratio	Bankfull Width (feet)	Bankfull Depth (feet)	Width-Depth Ratio
1B	2	1,327	25.0	53	800	15.7	51
	9	500	14.7	34	680	14.4	47
2	14	810	15.9	51	531	21.4	26
	19	880	11.1	79	1,011	11.4	89
3	29	790	13.2	60	384	14	27
	36	460	19.0	24	307	12.9	24
4A	48	360	11.0	33	279	9.8	29
	53	160	16.0	10	234	18.0	13
4B	58	230	7.7	30	143	8.5	17
	70	210	13.0	16	259	7.6	34
5	78	200	9.6	21	295	15.5	19
	85	370	25.2	15	374	25.0	15

Table 3-6 also illustrates longitudinal changes in bankfull width; bankfull width in 1914 decreases from Reach 1B (875 feet) to Reach 4A (277 feet), where the multichanneled anabranching system commences. Channel widths increase slightly in Reaches 4B (311 feet) and 5 (386 feet) (Figure 3-11). Average channel depths at bankfull stage are remarkably constant from Reach 2 to Reach 4A (14 feet) (Figure 3-12). Depth is highest in Reach 1B (18 feet) and lowest in Reach 4B (9 feet). Channel depth increases to 13 feet in Reach 5. Width-depth ratios show a general decrease in the downstream direction from about 50 in Reach 1B to 20 in Reach 4A (Table 3-6, Figure 3-13). Width-depth ratios increase again in Reaches 4B and 5 to 35 and 30, respectively. The width-depth ratio trends can be correlated with the resistance to erosion of the channel banks (Schumm 1963). The reaches with a higher width-depth ratio have more erodible banks, whereas those with lower values have more erosion resistant banks. The lower values of width-depth ratio in Reaches 4A, 4B, and 5 are also consistent with the required channel adjustments to maintain the continuity of sediment and water through the lower reaches, where there is a rising base level (Nanson and Huang 1997).

3.6.6.6. Particle Size

The total sediment load delivered to the study area by the upper watershed (Figure 3-4) differentially deposited as the river exited the Sierra Nevada and traversed the alluvial fan of the San Joaquin River. Reach 1 is the first reach downstream of the San Joaquin River exit from the Sierra Nevada, and has the highest gradient of all reaches. The dominant particle sizes in Reach 1A are cobbles and gravels (Table 3-7), although a large volume of sand is stored in the reach based on field observations. The low slope of Reach 1A and Reach 1B causes a rapid decrease in particle size across Reach 1B, such that Reach 1B marks the beginning of the transition zone between the gravel-bedded and sand-bedded reach (Table 3-8). There are still gravel patches in Reach 1B (Table 3-8), but a greater proportion of the channelbed becomes predominantly sand downstream of Skaggs Bridge. Gravelly Ford marks the upstream end of Reach 2, and all downstream reaches are sand bedded.

Table 3-7. Summary of D_{16}, D_{50}, and D_{84} particle sizes from surface pebble counts collected in 2002 by Stillwater Sciences in Reach 1.

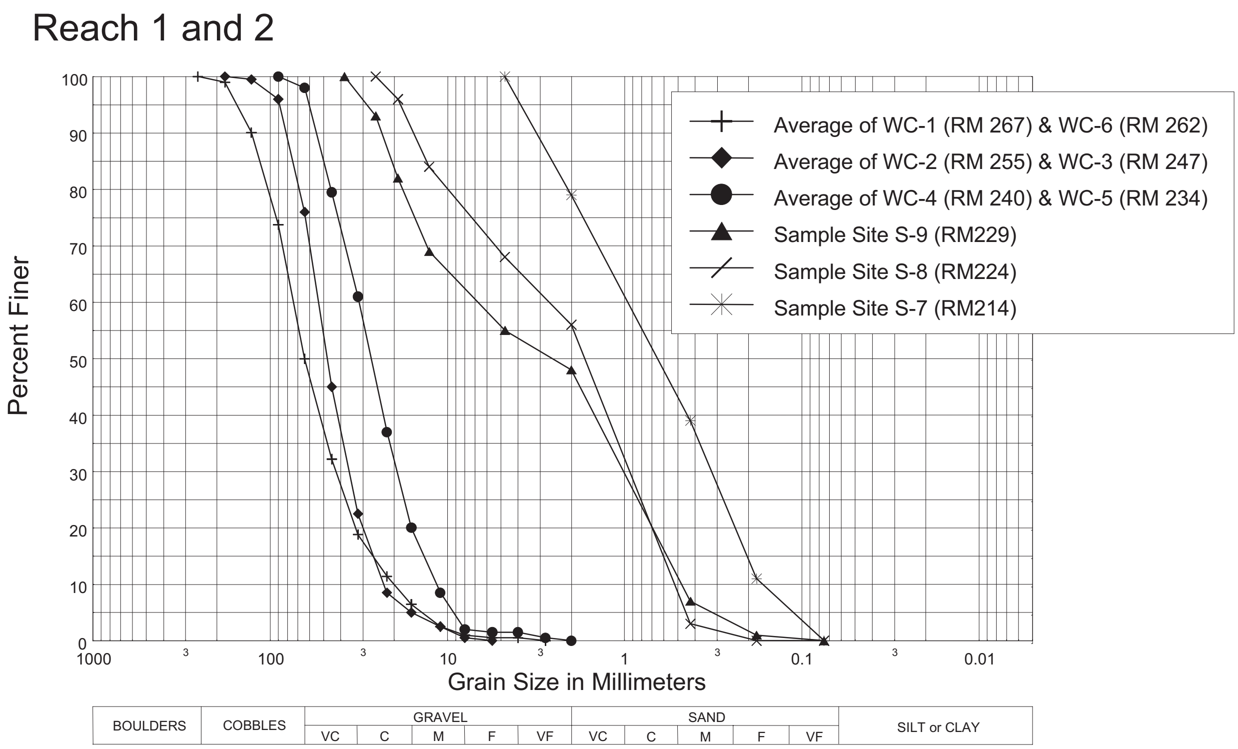
Sample Location	Sediment Size			Geomorphic unit sampled
	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	
RM 267.07	3	19	65	Point bar (out of the wetted channel)
RM 266.76	72	136	168	Head of riffle
RM 266.67	18	64	108	Riffle
RM 265.51	1	4	23	Shallow area of large pool
RM 265.41	12	26	42	Shallow area of large pool
RM 264.62	9	53	129	Riffle
RM 263.38	7	24	39	Head of riffle
RM 263.36	3	43	120	Riffle
RM 262.96	3	31	85	Shallow portion of a large pool
RM 262.32	2	11	95	Tail of a pool that shallows before a constriction
RM 262.23	11	40	97	Riffle
RM 262.11	19	52	84	Shallow portion of a larger pool
RM 260.65	16	47	73	Head of riffle
RM 260.60	18	60	111	Lower portion of the same riffle
RM 260.19	1	2	33	Depositional zone between the mainstem and secondary channel
RM 259.35	16	40	88	Riffle
RM 259.13	2	23	107	Shallow portion of a large pool
RM 258.87	19	75	116	Head of point bar (out of the wetted channel)
RM 258.36	20	73	101	Riffle
RM 257.96	19	45	109	Run at head of a captured pit
RM 257.33	28	55	97	Shallow pool between two riffles
RM 256.87	12	25	43	Run
RM 256.81	11	19	28	Run
RM 256.52	19	32	66	Shallow portion of a large pool/run
RM 256.17	5	30	74	Shallow portion of a large pool

Grain size data for the San Joaquin River is limited to recent data collection efforts, with most data located in Reach 1. Data collected by MEI (2000a) and MEI (2000b) provide grain size data in all reaches, as well as a few locations in the flood control bypass system (Table 3-8). In hydraulic modeling segments in Reach 1 and Reach 2 where the bed materials are coarser grained, the modificed Wolman pebble count procedure (Wolman 1954, Leopold 1970) was used to determine grain size gradations. For the remainder of the river, bulk samples of the bed material were collected for subsequent laboratory analysis. Representative bed material gradations for the hydraulic modeling segments between Friant Dam and the Merced River are shown in Figure 3-15. The bed materials in Reach 1A and the upstream portion of Reach 1B are primarily composed of gravel- and cobble-size materials, whereas the bed material in downstream reaches are composed primarily of finer gravels and sands.

Table 3-8. Summary of D16, D50, and D84 of bed material sediment samples collected along in the study area by Mussetter Engineering (MEI 2000a and MEI 2000b). "S" denotes bulk sample, and "WC" denotes a Wolman pebble count.

	Sediment Size		
Sample Number (Location)	**D_{16} (mm)**	**D_{50} (mm)**	**D_{84} (mm)**
WC-1 (RM 266.8)	45	90.5	138
WC-6 (RM 262)	27	52	80
WC-2 (RM 255)	27	44	64
WC-7 (RM 251)	23	40	57
WC-3 (RM 247)	11.2	19	30
WC-4 (RM 240)	19.5	46	74
WC-5 (RM 234)	9.6	18	29
S-9 (RM 229)	0.6	2.6	20
S-8 (RM 223.5)	0.62	1.7	12.7
S-7 (RM 215)	0.21	0.65	2.5
S-6 (RM 199)	0.54	1.56	6.2
S-5 (RM 197)	0.53	0.96	1.77
S-4 (RM 174)	0.32	0.73	1.49
S-1 (RM 133)	0.25	0.6	1.38
S-2 (Bravel Slough/Eastside Bypass)	0.24	0.5	1.31
S-3 (Eastside Bypass at Sand Slough)	0.53	1.3	3.36

In the summer of 2002, Stillwater Sciences collected additional grain size data in Reach 1 (Table 3-7, Figure 3-16). All samples were surface samples collected using the modified Wolman pebble count method (Wolman 1954, Leopold 1970), and type of geomorphic unit sampled was recorded to help explain the grain size variability in the samples.



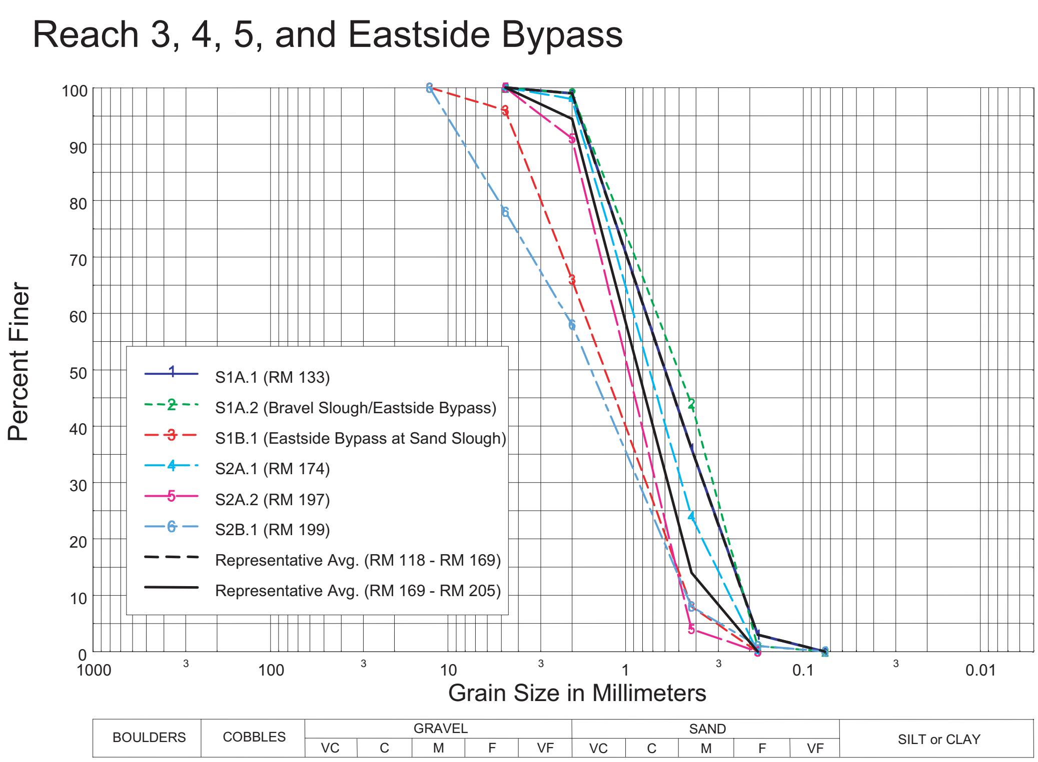


Figure 3-15. Bed material grain size gradations for samples collected between Friant Dam and the Merced River confluence (MEI 2000a and MEI 2000b).

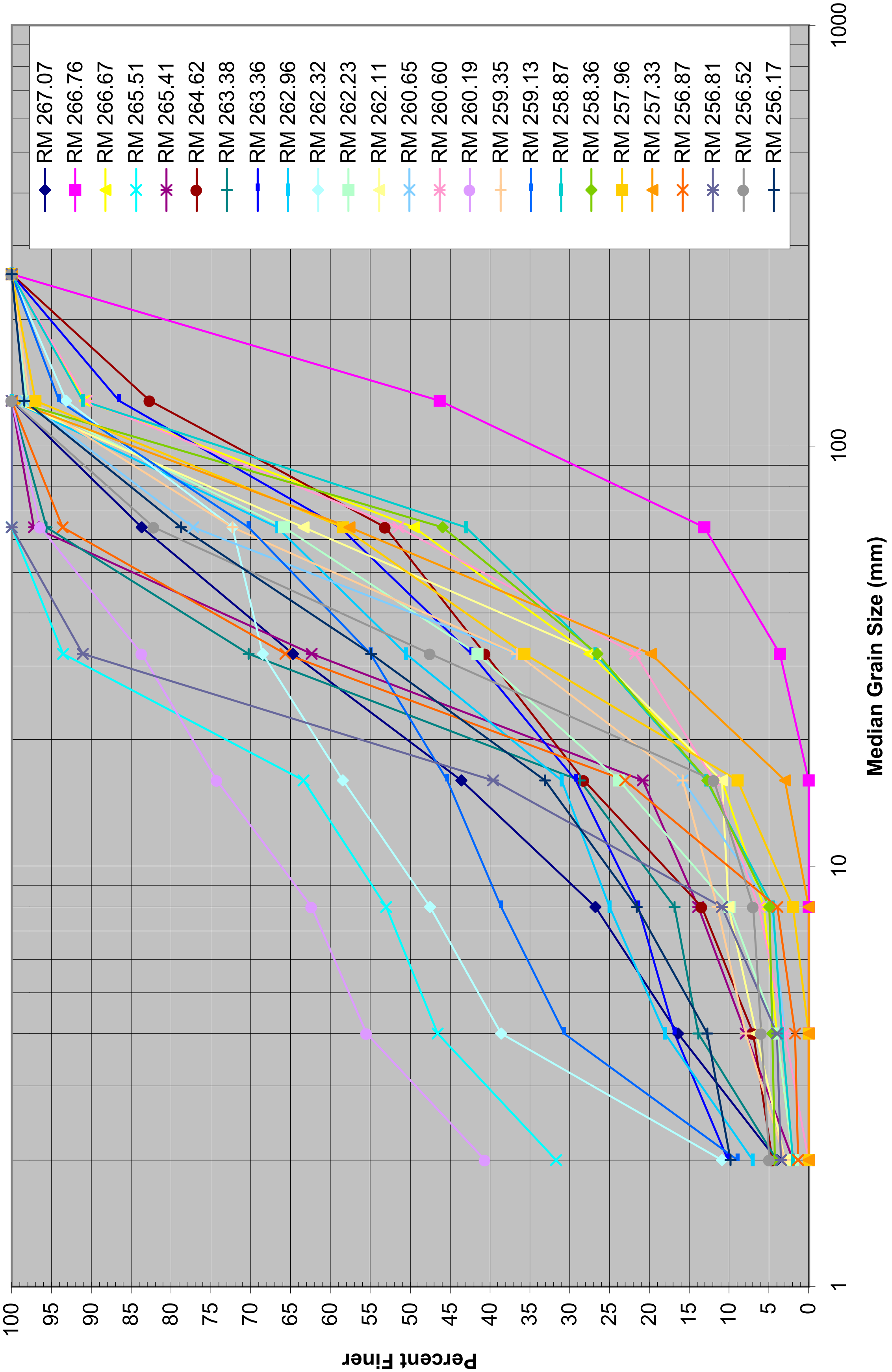


Figure 3-16. Bed material grain size gradations for samples collected between Friant Dam and the Lanes Bridge (HWY 41) collected by Stillwater Sciences in 2002.

3.7. HISTORICAL AND EXISTING CONDITIONS

The following sections synthesize much of the historical information and recent studies to describe reach-specific conditions within the San Joaquin River study area. These sections describe: (1) the high flow regime largely responsible for initiating fluvial processes and creating and maintaining channel form, (2) changes in the sediment regime as a function of dams, diversions, bypasses, and aggregate extraction, (3) changes in fluvial processes, channel morphology and planform morphology as a function of changes in flow regime, sediment regime, aggregate extraction, and infrastructure, (4) present-day bed mobility thresholds in Reach 1, and (5) inundation patterns based on the changes in flow regime and channel geometry.

3.7.1. Reach 1

Reach 1 is subdivided into two reaches: Reach 1A extends from Friant Dam (RM 267.5) to the Highway 99 Bridge (RM 243.2), and Reach 1B extends from the Highway 99 Bridge to Gravelly Ford (RM 229.0) (Figure 3-2). Reach 1 has the steepest slopes in the study area and would contain the most likely area for salmonid spawning if they were re-introduced. The river channel is moderately confined by terraces and bluffs throughout this reach. The gravel/sand transition begins in Reach 1B, and is sand-bedded by Gravelly Ford. Reach 1 is the only reach that provides spawning gravels for anadromous salmonids; thus, Reach 1 is a critical reach for efforts to restore anadromous salmonid production on the San Joaquin River.

3.7.1.1. High Flow Regime

The unimpaired flow regime is presented in Chapter 2; changes to the high flow regime have had the greatest impact to channel form and processes. The winter storm events and snowmelt peak hydrograph components were responsible for most fluvial geomorphic work on the San Joaquin River. Flood frequency curves are often used to characterize the high flow regime, as well as to evaluate changes to the high flow regime. A common conceptual model for alluvial river processes is that the common flood having a recurrence interval of approximately 1.5 to 2.0 years is responsible for (1) transporting the most sediment over time (e.g., Andrews 1980), (2) defining trends in channel geometry (e.g., channel width, meander wavelength) (Leopold et al. 1964), and (3) maintaining the channel morphology (Rosgen 1986). Less frequent floods (e.g., 10-yr flood) were also important in creating and maintaining channel features in the floodway. Thus, changes to the high flow regime would have an impact on channel processes, channel form, and channel scale. The pre-Friant Dam 1.5-year flood was 11,400 cfs, and the post-Friant Dam 1.5-yr flood was 400 cfs, reflecting a 96% reduction (See Table 2-2). The corresponding pre-Friant Dam 10-year flood was 34,400 cfs, and the post-Friant Dam 10-year flood was 8,950 cfs, reflecting a 74% reduction. In addition, the duration of high flows that are large enough to initiate large-scale geomorphic processes has been greatly reduced; in the 35 years from 1908-1942 representing pre-Friant Dam conditions, there were 391 days (3.06% of all days) over 10,000 cfs, whereas in the 51 years from 1950-2000 representing post-Friant Dam conditions, there were only 31 days (0.166% of all days) over 10,000 cfs. More detailed information on changes to surface water hydrology can be found in Chapter 2.

3.7.1.2. Sediment Regime

The sediment regime for the San Joaquin River strongly influences channel morphology, fluvial processes, aquatic habitat, and terrestrial habitat. The coarse sediment supply (gravels and cobbles) form bars, riffles, pool tails, side channels, and other important geomorphic features critical for salmonid habitat. As shown in Figure 3-1, changes to the sediment regime propagate to salmonid habitat and other aquatic and terrestrial habitats. While the most common example of dam induced changes to the sediment regime is loss of spawning habitat, perhaps the most important impact is the cumulative impact of reduced coarse sediment supply to channel morphology. Reduced coarse sediment supply, combined with impaired ability to move the remaining coarse sediment due to reduced high flow regime, typically causes: (1) riparian vegetation to encroach into the low flow channel (see Section 3.10.6), (2) simplification of channel morphology, (3) reduced rates of channel migration, and (4) reduced storage of coarse sediment in the channel.

The predominant pre-Friant Dam sediment source was the upstream watershed and erosion of Pleistocene terraces in Reach 1 and 2 (Janda 1965). Unimpaired estimates of coarse sediment yield based on watershed denudation rates from Janda (1965) are a maximum of 26,000 yd^3/year assuming coarse sediment is 10% of the total sediment load. Corresponding fine sediment yield would have been approximately 234,000 yd^3/year. Watershed denudation rates are not necessarily the most accurate way to estimate sediment yield for recent climatic conditions, and recent reservoir sedimentation surveys provide a better estimate of yield.

Based on sedimentation rates from regional reservoirs, Cain (1997) estimated an average unimpaired coarse supply estimate (assuming 10% of total sediment yield is coarse sediment) of approximately 48,600 yd^3/year. This volume of average annual sediment supply is smaller by a factor of nearly 2 compared to estimates by Janda (1965) (Table 3-3). Tributary streams downstream of Friant Dam (e.g., Cottonwood Creek and Little Dry Creek) provided sediment to the San Joaquin River, but the magnitude of sediment delivery was most likely small compared to that delivered by the upper watershed. Cain (1997) estimates average annual unimpaired coarse sediment yield for Cottonwood Creek as 55 yd^3/year, and 335 yd^3/year for Little Dry Creek, assuming coarse sediment is 10% of total sediment yield. Corresponding fine sediment estimates for Cottonwood Creek is 495 yd^3/year and 3,015 yd^3/year for Little Dry Creek. Assuming reasonable accuracy of these estimates, Cottonwood Creek would have delivered approximately 0.113% of the coarse sediment contributed by the upper San Joaquin River watershed (55/48,600), and Little Dry Creek would have delivered approximately 0.69% of the coarse sediment contributed by the upper San Joaquin River watershed (335/48,600). The sediment yield estimate from the watershed upstream of Friant Dam in Cain (1997) are derived from NRCS measurements and estimates of numerous Central Valley reservoirs including Millerton Reservoir (Brown and Thorp, 1947). Brown and Thorps' measurements and estimates were for the purpose of predicting how fast reservoirs would fill under modern reservoir conditions. Sedimentation estimates for Millerton Reservoir were based on other San Joaquin watersheds where mining activity and other watershed disturbances may have been far greater. Cain's estimate using Brown and Thorps (1947) regional sedimentation estimates results in a value (48,600 yd^3/yr) is almost twice as large higher than Janda's unimpaired estimate (26,000 yd^3/yr). This difference may likely be a result of the Brown and Thorp data being derived from more disturbed watersheds than the upper San Joaquin River watershed, and application of this data to the San Joaquin River may over-estimate sediment yield from the upper San Joaquin River watershed.

Lateral erosion of terraces after Friant Dam was completed may have also augmented sediment supply in Reach 1, but qualitative review of channel migration from historical maps and photos suggests that migration rates were low, thus sediment contribution from terrace erosion was also likely low. A careful quantitative analysis has not been performed, and performing this analysis would better document the potential contribution of sediment by terrace erosion. As previously stated, the unimpaired sediment regime appears to have been small based on Janda (1965) and Brown and Thorp (1947). Elimination of this sediment supply from the upper watershed was combined with a reduction in high flow regime, which may have also reduced recruitment of sediment from terrace erosion. While these two sediment sources were small compared to other Central Valley rivers, their reduction still represents a substantial change from impaired conditions. The low gradient and low sediment transport capacity of downstream reaches has likely reduced the impact to coarse sediment storage in the reach. Remaining sediment sources downstream of Friant Dam include the following:

- Cottonwood Creek (confluence at RM 267.4)
- Little Dry Creek (confluence at RM 261)
- Lateral erosion of terraces
- Vertical incision of the bed surface

Cottonwood Creek is unregulated and continues to deliver sediment to the San Joaquin River, and because upstream sediment supply has been eliminated, the small amount of sediment that Cottonwood Creek delivers to the San Joaquin River has become the primary sediment source (other than the bed itself). As presented above, Little Dry Creek should have historically contributed more sediment to the San Joaquin River than Cottonwood Creek based on its larger drainage area and unit sediment yield; however, gravel mining in the lower portions of Little Dry Creek since at least the 1930's has likely greatly reduced sediment delivered to the San Joaquin River (Figure 3-17). Recent reconnaissance by JSA and MEI (2001) has suggested that these gravel pits trap sediment transported by Little Dry Creek; however, during large floods (e.g., 1995), there were field observations of evidence suggesting high rates of coarse sediment transport, and some coarse sediment may still be delivered to the San Joaquin River during high flows on Little Dry Creek (Cain, personal communication).

Compared to the loss of sediment supply from the upper San Joaquin River watershed and Little Dry Creek, the impact of instream aggregate extraction on coarse sediment storage is many times larger than the impact of upstream dams and reductions from Little Dry Creek (Figure 3-18). For Reach 1A, Cain (1997) estimated that 1,562,000 yd^3 were removed from the active channel of the San Joaquin River between 1939 and 1989 (3,124 yd^3/yr), and 3,103,000 yd^3 were removed from the floodplain and terraces. Reach 1B does not have nearly the level of aggregate extraction, with 107,000 yd^3 removed from the active channel, and 72,000 yd^3 removed from floodplains and terraces. When comparing the volume of aggregate removed from the active channel with the unimpaired volume of coarse sediment supplied from the upper San Joaquin River watershed, gravel extraction between 1939 and 1989 in the active channel of Reach 1A alone has removed two-thirds of the predicted volume of unimpaired coarse sediment yield to the lower river if upstream dams were not in place (31,240 yd^3/yr compared to 48,600 yd^3/yr). Because the sources from the upstream watershed have been blocked by Friant Dam and other dams, there is a substantial deficit in the coarse sediment budget.

Discussion of changed sediment regime in Reach 1 has focused on the reduction in coarse sediment. However, upstream dams have also impacted the fine sediment budget. First, these dams have trapped the washload component of the sediment regime, which consist of very fine sands and silts. The loss of washload to downstream reaches of gravel-bedded rivers is usually ignored because of the desire to reduce fine sediment (primarily sands) in salmonid spawning areas. However, these finer sediments typically transport as washload (Figure 3-4) and do not tend to deposit in the active channel, but do deposit on floodplains due to riparian vegetation roughness and a wide floodplain. These finer sediments are very important for riparian vegetation regeneration (both woody and herbaceous) on floodplains and high flow scour channels. Loss of this finer sediment source by blockage from upstream dams reduces or eliminates fine sediment deposition on floodplains, impairing natural regeneration processes of woody and herbaceous riparian vegetation.

The second impact to the fine sediment budget is that while upstream dams trap all fine sediments, downstream tributaries continue to deliver fine sediment, particularly coarse sand eroded from the sandy loam watershed. Review of 1937 aerial photos show large sand dunes within the low

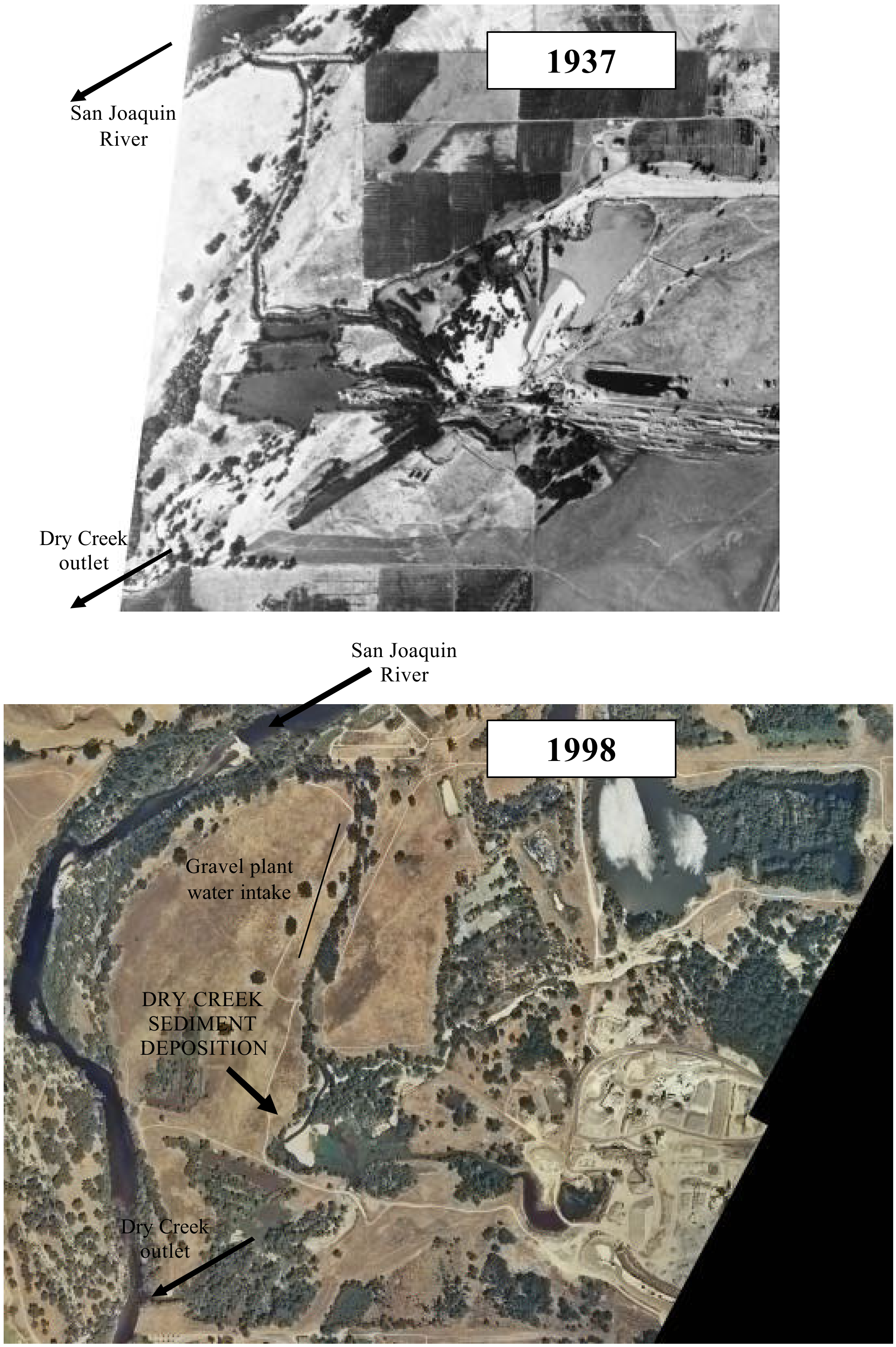


Figure 3-17. 1937 and 1998 aerial photography of lower Little Dry Creek, showing long-term gravel mining impacts on potential sediment delivery to the San Joaquin River.

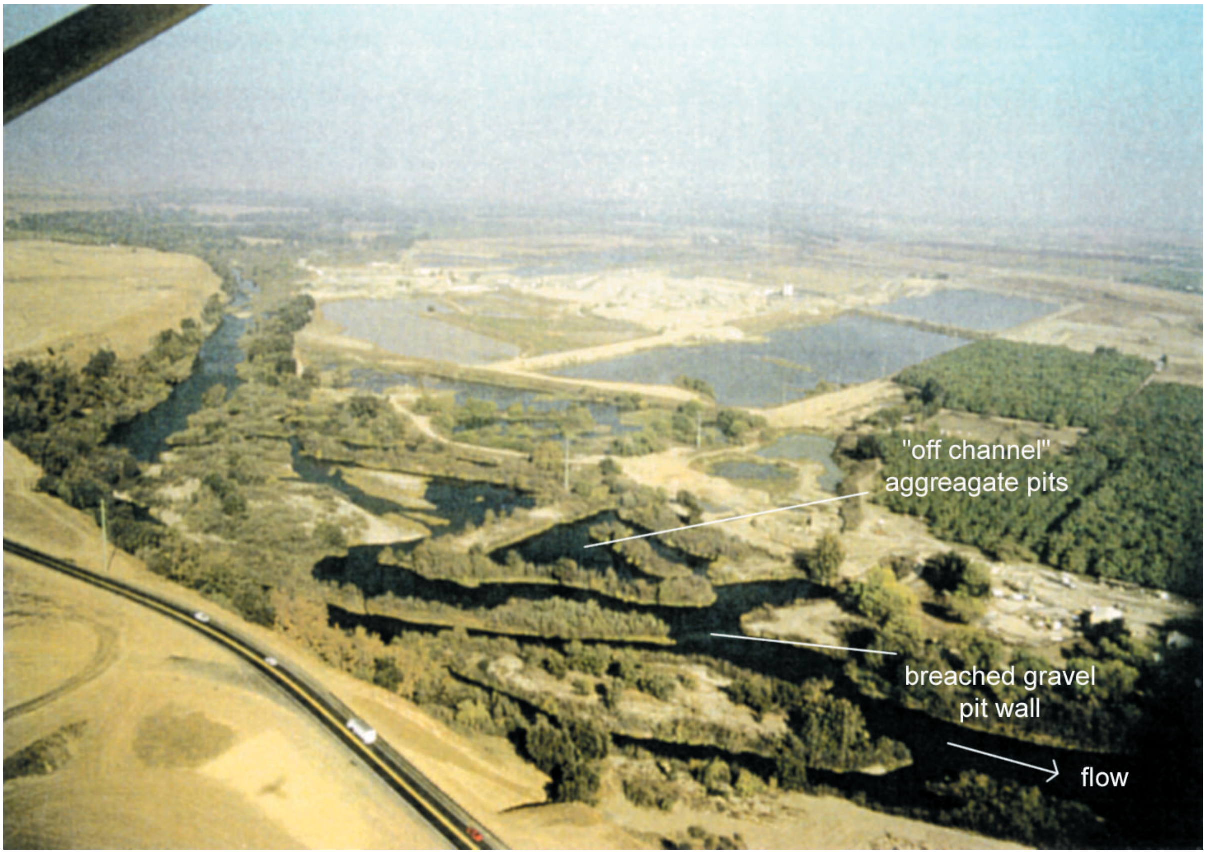


Figure 3-18. View upstream of the effects of historical in-channel sand and gravel mining at RM 257. Breaching of pit walls has led to the formation of a multi-channeled reach of the river. Active mining of the two lower terraces can be seen in the background. The highest terrace confines the channel along the right bank (looking downstream). From JSA and MEI (1998).

flow channel, and field observations by William Hammond Hall (1887) suggests that even under unimpaired conditions, sand storage in Reach 1 (partially due to the low gradient) was substantial. Reduction of the sand transport capacity occurred when the high flow regime was impaired by upstream dams, such that sands in the channel had low transport rates (thus high residency times) and sand contributed by tributaries was slow routing through the system. Field observations under current conditions illustrate a channel with substantial but unquantified volumes of sand storage within the low flow channel, even in the upstream-most portions of Reach 1 near the base of Friant Dam. Cottonwood Creek is a likely source of this sand, as it delivers its sediment load virtually at the base of Friant Dam. This sand storage may be a impediment to salmonid reproduction because: (1) it impairs gravel quality in habitats needed by spawning and rearing salmonids, and (2) future gravel cleaning or introduction efforts may have a short life-span as the in-channel sands are transported downstream and infiltrate into the cleaned gravels.

3.7.1.3. Fluvial Processes

Several conceptual models have been developed for fluvial processes on gravel-bedded reaches of San Joaquin River tributaries: the Merced River (Stillwater Sciences 2002) and the Tuolumne River (McBain and Trush, 1998). McBain and Trush summarize a list of “attributes of alluvial river integrity" for the Tuolumne River that summarizes important fluvial processes that are appropriate for both gravel-bedded reaches and sand-bedded (although the frequency differs between the two reaches). They include the following:

ATTRIBUTE No. 3. Frequently mobilized channel bed surface.

In gravel-bedded reaches, channel bed framework particles of coarse alluvial surfaces are mobilized by the bankfull discharge, which on average occurs every 1-2 years. In sand-bedded reaches, bed particles are in transport much of the year, creating migrating channel-bed "dunes" and shifting sand bars.

ATTRIBUTE No. 4. Periodic channel bed scour and fill.

Alternate bars are scoured deeper than their coarse surface layers by floods exceeding 3- to 5-year annual maximum flood recurrences. This scour is typically accompanied by re-deposition, such that net change in channel bed topography following a scouring flood usually is minimal. In gravel-bedded reaches, scour was most likely common in reaches where high flows were confined by valley walls.

ATTRIBUTE No. 5. Balanced fine and coarse sediment budget.

River reaches export fine and coarse sediment at rates approximately equal to sediment inputs. The amount and mode of sediment storage within a given river reach fluctuates, but sustains channel morphology in dynamic quasi-equilibrium when averaged over many years. A balanced coarse sediment budget implies bedload continuity: most particle sizes of the channel bed must be transported through the river reach.

ATTRIBUTE No. 6. Periodic channel migration

The channel migrates at variable rates and establishes meander wavelengths consistent with regional rivers with similar flow regimes, valley slopes, confinement, sediment supply, and sediment caliber (Figure 3-19). In gravel-bedded reaches, channel relocation can also occur by avulsion, where the channel moves from one location to another, leaving much of the abandoned channel morphology intact. In sand-bedded reaches, meanders decrease their radius of curvature over time, and are eventually bisected, leaving oxbows.

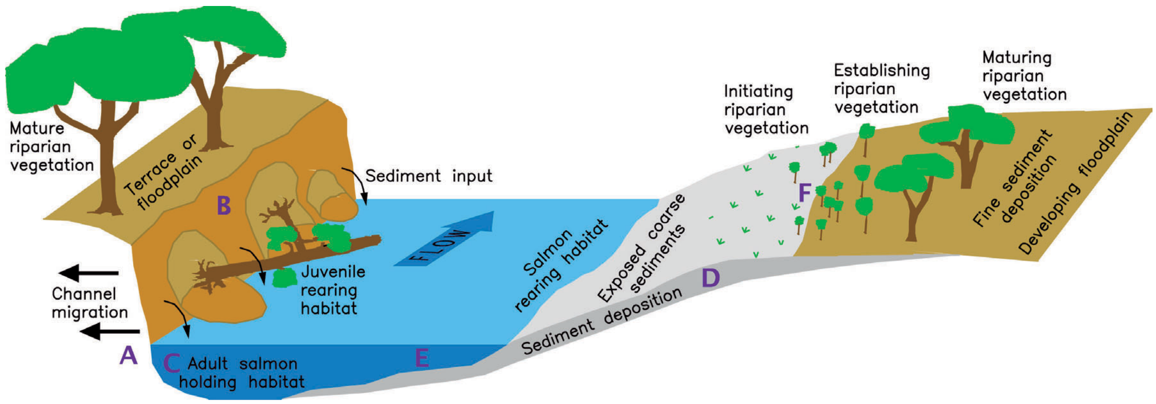
ATTRIBUTE No. 7. A functional floodplain

On average, floodplains are inundated once annually by high flows equaling or exceeding bankfull stage. Lower terraces are inundated by less frequent floods, with their expected inundation frequencies dependent on norms exhibited by similar, but unregulated river channels. These floods also deposit finer sediment onto the floodplain and low terraces (Figure 3-19).

ATTRIBUTE No. 8. Infrequent channel resetting floods

Single large floods (e.g., exceeding 10-yr to 20-yr recurrences) cause channel avulsions, rejuvenate mature riparian stands to early-successional stages, form and maintain side channels, and create off-channel wetlands (e.g., oxbows). Resetting floods are as essential for creating and maintaining channel complexity as lesser magnitude floods, but occur less frequently.

These attributes cumulatively provide the physical foundation for salmonid habitat: diverse, high quality, and abundant aquatic habitat for all life stages (spawning, egg incubation, fry rearing, and juvenile rearing) of salmonids. These attributes are unique to each river system, and should not be directly applied to the San Joaquin River without further analysis; however, these attributes provide a good starting point for evaluating primary components of the fluvial system. Some notable differences between the Tuolumne River and the San Joaquin River are discussed below.



Conceptual linkages between channel migration and fish habitat. (A) A channel with adequate space to migrate erodes the channel bank on the outside of the meander bend during high flows, (B) encouraging mature riparian trees to topple into the channel. (C) The pool along with large wood on the outside of the bend provide structural complexity for good fish habitat. As bank erosion continues, the pool "migrates" laterally and downstream, but high quality habitat is maintained. (D) On the inside of the bend high flows scour and redeposit sediments (gravel in Reach 1, sand in downstream reaches), forming a shallow bar on the inside of the bend. (E) In Reach 1, this area provides slow-water rearing conditions for fry and juvenile chinook salmon, as well as habitat for aquatic insects (fish food), amphibians and reptiles. (F) Progressively higher up the gravel bar surface, receding water levels during the spring snowmelt allow riparian seedlings to establish. Newly established woody riparian seedlings are sporadically scoured out, but those established high enough on the bank become mature to eventually topple into the channel as the river migrates back across the valley (A). Large floods create scour channels on upper bar surfaces and inundate floodplains, providing juvenile salmon rearing habitat during higher flows.

Figure 3-19. Conceptual role of channel migration in creating spatially and temporally complex riparian corridor habitat (from McBain and Trush, 1998).

The gravel-bedded portion of these streams (spatially analogous to Reach 1 of the San Joaquin River) is steeper than Reach 1 of the San Joaquin River; thus some of these attributes are not directly applicable. The slope of the Tuolumne and Merced rivers in the gravel bedded reaches are approximately 0.0015 (0.15%), whereas the steepest local slope for Reach 1 is 0.0010 (0.1%), the average slope for Reach 1A is 0.00065 (Figure 3-20), and the average slope for Reach 1B is 0.00045 (Figure 3-21). These slopes are based on modeled water surface slopes for an 8,000 cfs release using present-day topography, thus these slopes differ from the 1914 values shown in Table 3-4. The lower slope (less than ½ the slope of the Merced and Tuolumne rivers) potentially results in less energy expended on the channel during periods of high flows (in reaches with similar valley or terrace confinement), such that higher flows would be required to initiate the fluvial processes described in the attributes of alluvial river integrity above than on the Tuolumne and Merced rivers. Correspondingly, the frequency of these fluvial processes being accomplished under unimpaired conditions was likely less than on the Tuolumne and Merced rivers. Examining the 1937 aerial photographs provides evidence that fluvial processes characterized by the attributes above did occur during historic flow regime.

Figure 3-6 shows a portion of Reach 1 that illustrates some of these fluvial processes. First, exposed and submerged gravel bars are clearly visible on the photograph, demonstrating that the channel bed is mobilized (Attribute 3). The aerial photographs cannot prove that bed scour occurs (Attribute 4), but the absence of riparian vegetation on the exposed bars suggests that some degree of bed scour occurs that removes riparian seedlings. Likewise, the aerial photographs cannot prove that there is a

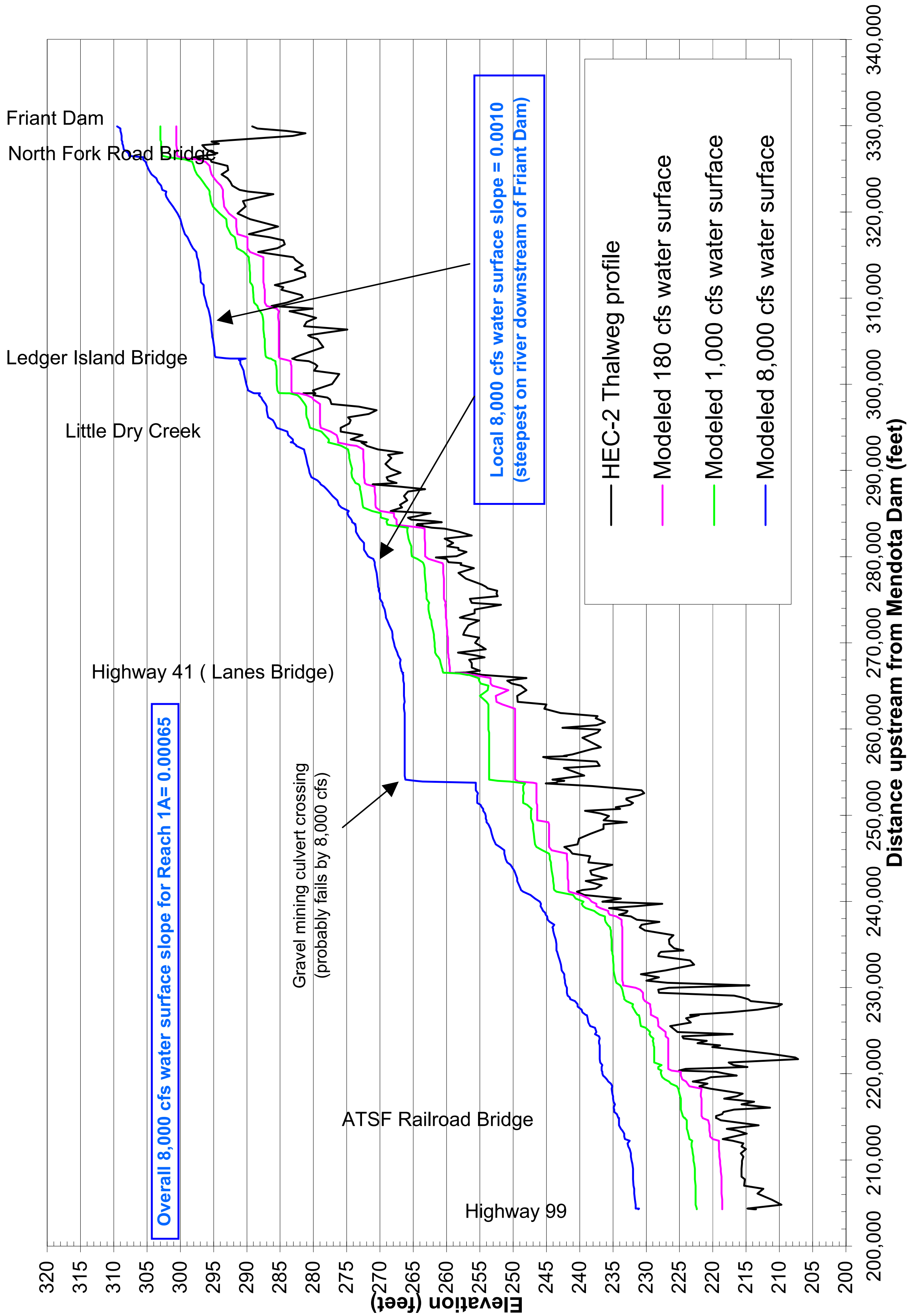


Figure 3-20. Thalweg and modeled water surface profiles for Reach 1A, showing overall reach slope and short reach representing the steepest slope in the entire study area (from MEI 2000a).

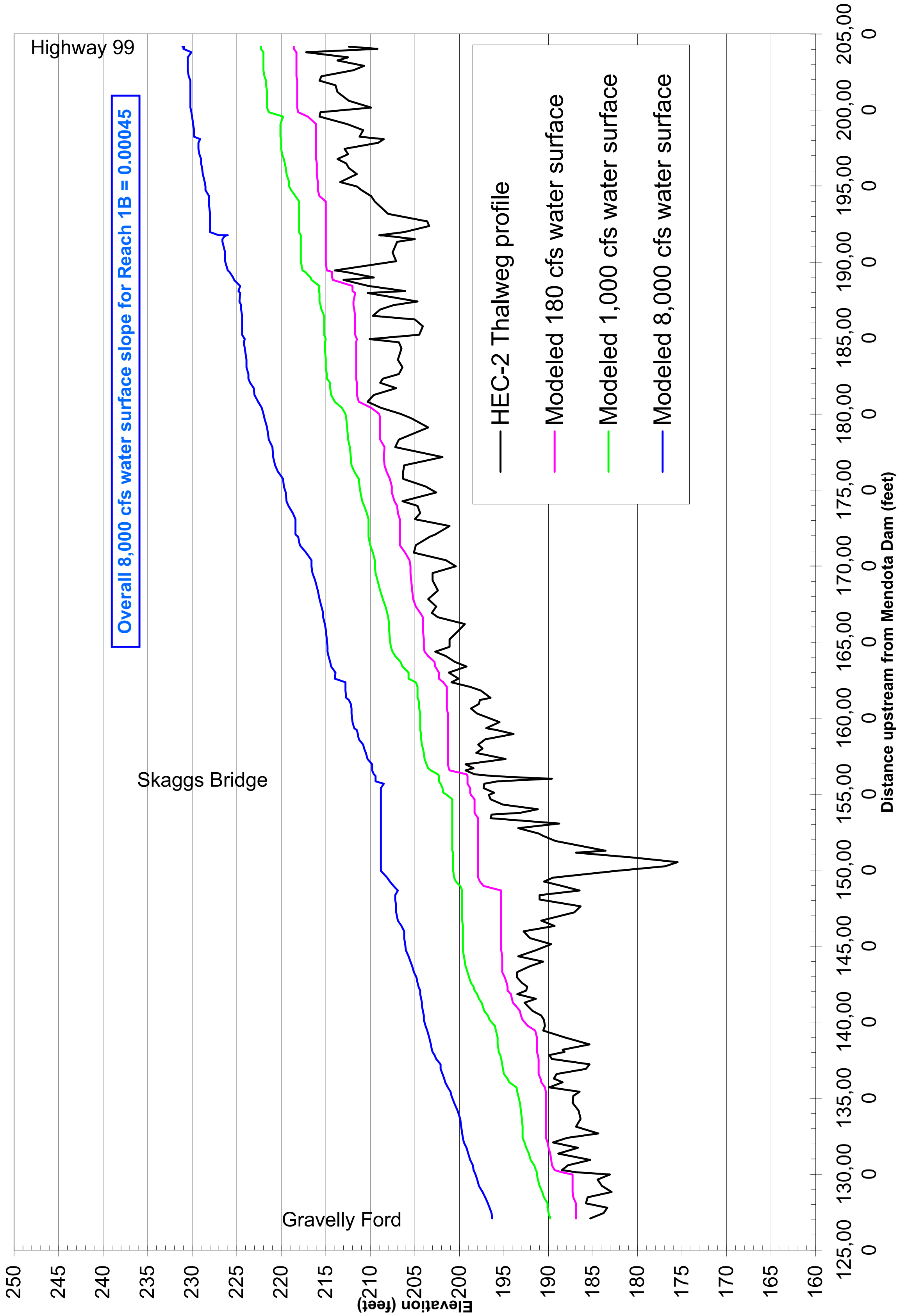


Figure 3-21. Thalweg and modeled water surface profiles for Reach 1B, showing overall reach slope (from MEI 2000a).

balanced sediment budget; there is no evidence that there is any substantial channel aggradation in the reach, although there could be degradation of the channel bed. A small amount of channel migration (Attribute 7) is observable on the downstream end of the photograph, where the channel migration is creating a medial bar as the channel widens. There are no scroll bars or new floodplains visible, so the rate of migration is likely very low. In the not so recent past, a high flow created the side channels in the center and upstream end of the photograph (Attribute 8). The frequency of these avulsion events is not known, but is likely much greater than the 10 to 20-year recurrence interval estimated for Attribute 8. Lastly, channel migration and avulsion, albeit slow and infrequent, allow functional floodplains to form (e.g., downstream end of photo where channel has migrated). The observations on this photo need to be considered in context of the high flow events preceding the date of the photo. On February 6, 1937, a short duration high flow event of 36,400 cfs (daily average = 17,900 cfs) occurred, which was approximately a 9.5-year flood event under the pre-Friant Dam flood frequency. Additionally, there were seven days during the subsequent snowmelt runoff hydrograph that were larger than 10,000 cfs. Therefore, it is safe to assume that these high flows mobilized the bed surface due to the clearly active bar features evident shown on Figure 3-6, and floodplain inundation likely occurred, but it is difficult to determine if other fluvial geomorphic thresholds (e.g., channel migration, bed scour) were surpassed by high flows in water year 1937.

The rates of these fluvial processes under historic conditions are not estimated due to the lack of data under these historic conditions. The possible exception is that channel migration and avulsion rates and frequency could be estimated by conducting an historic channel analysis using maps and aerial photographs dating back to 1854. This analysis was not performed for this report, but an example can be observed on Figure 3-22 where one map (1854) and two aerial photographs (1937 and 1998) show the limited change in channel location over time at RM 259. The only large-scale channel location change between 1937 and 1998 occurred in the southern channel, where the meander bends migrated downstream a short distance. This minimal movement over the 49 intervening years is likely due to the low slope and sediment supply in the reach, and perhaps to some unknown extent, stabilization efforts by adjacent landowners.

3.7.1.4. Incipient Motion Analyses

A potential objective of future restoration efforts may include increasing the frequency and duration of bedload transport. Mobilizing the bed surface is one of many important geomorphic processes, and can benefit salmonids by creating and maintaining high quality spawning and rearing habitat, and contributes to channel migration and bar formation that provides complex aquatic habitats for salmonids and other species. In unimpaired alluvial rivers, the gravel bed often mobilizes by a flow of approximately 1.2 to 1.5 year recurrence (Parker et al,, 1982). Several analyses have been conducted to estimate the bed mobility threshold (incipient motion) under current channel morphology and particle size conditions.

Contemporary bed mobility thresholds have been estimated empirically by Cain (1997), and more recently estimated by modeling approaches by Mussetter Engineering (in JSA 2002). Cain (1997) placed tracer rocks representing the D_{84} particle size at three separate cross sections at a study site at approximate RM 266.3. After placement, a peak flow of 8,000 cfs occurred, which did not mobilize any of the rocks (Cain, personal communication). Later, a 12,500 cfs flow occurred, mobilizing a portion of the tracer rocks. Marked rocks were recovered at two of the cross sections, but not at the third cross section (presumably because the rocks were buried, per Cain 1997). The D_{84} at one of the two remaining cross sections was 215 mm, and the D_{84} at the other cross section was 220 mm. A total of 13 rocks were placed at the two cross sections, and of these 13 sets, nine of the rocks (76%) were mobilized from the cross section, suggesting that the 12,500 cfs flood event was moderately

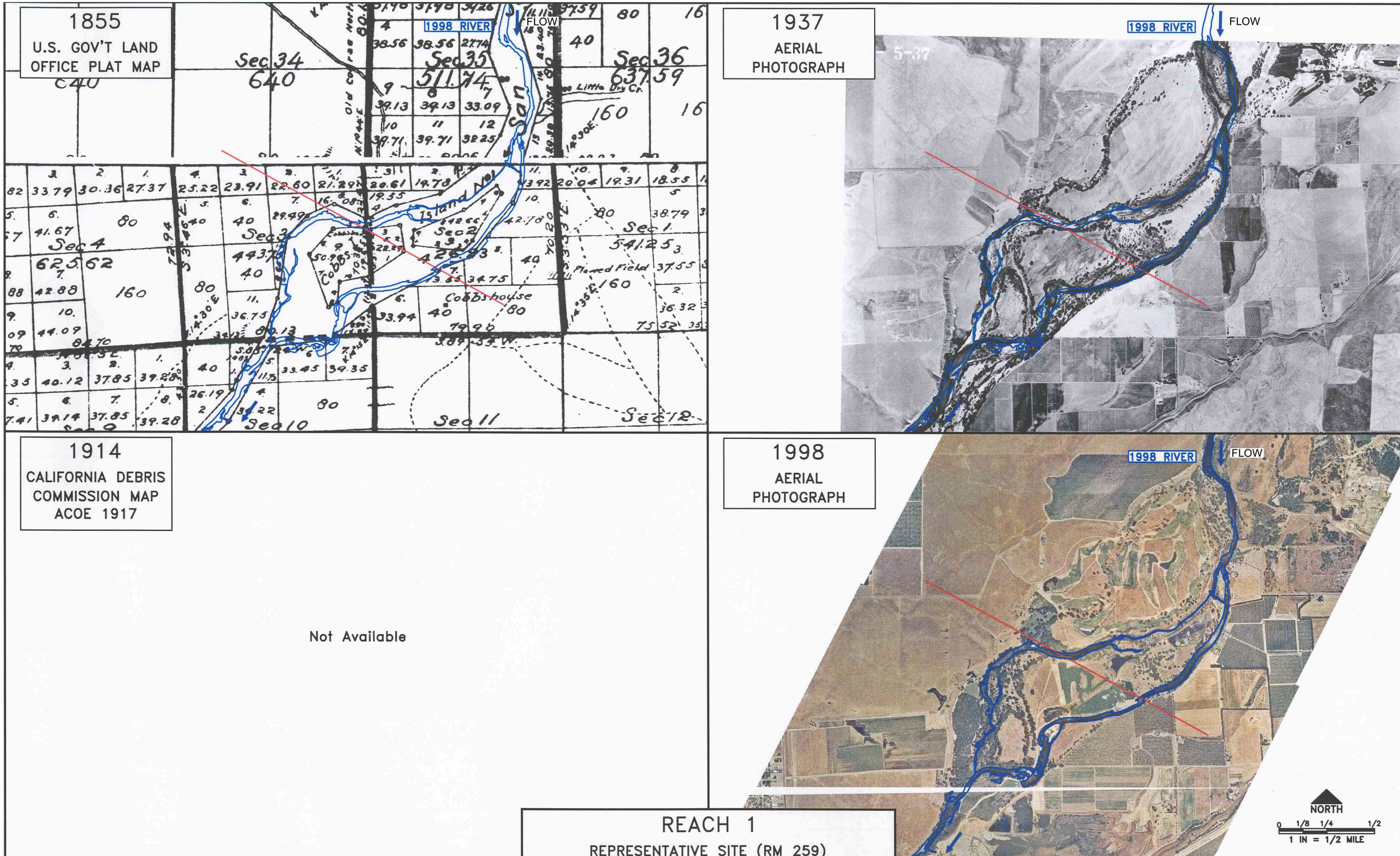


Figure 3-22. Example planform evolution in Reach 1A (RM 259), showing 1855 plat map, 1937 air photo, and 1998 air photo.

sufficient to mobilize rocks exceeding 200 mm diameter. This conclusion is somewhat tempered in that the rocks were not placed fully within the armored bed surface due to the degree of armoring (Cain, 1997). Therefore, the tracer rocks may have been artificially protruding from the bed surface to a larger degree than the surrounding parent rocks. Additionally, they were likely not as tightly packed as the surrounding parent rocks.

The incipient motion analysis conducted by Mussetter Engineering (in JSA 2002) used a standard tractive force approach to estimate bed mobility thresholds (Shields 1936). The incipient motion analysis was performed by evaluating the effective shear stress on the channel bed in relation to the amount of shear stress that is required to move the sediment sizes that are present. This was accomplished by computing the grain shear stress ratio, which is the ratio of the grain shear stress to the critical shear stress for particle mobilization. Theoretically, when this ratio exceeds a value of 1.0, the particle size mobilizes. This ratio is dependent on channel velocity, the energy slope, and gravel size. The grain shear stress was used in the calculations rather than the total shear stress because the grain shear stress is a better representation of the near-bed hydraulic forces acting on the individual sediment particles on the bed. The total shear stress over-estimates the forces that are effective in mobilizing sediment because it includes the effects of form roughness associated with irregularities in the channel bed and banks, and other obstructions such as vegetation, that reduce energy in the flow.

In gravel and cobble bed streams, when the critical shear stress for the median (D_{50}) particle size is exceeded, the bed is mobilized, and all sizes up to about 5 times the median size are capable of being transported by the flow (Parker et al., 1982; Andrews, 1984). At lower shear stresses, the bed is effectively immobile. Considering Neill's (1968) observations, when the grain shear stress ratio is approximately 1.0, the bed begins to mobilize, and substantial transport of the bed material occurs when the shear stress ratio exceeds about 1.3. Flow thresholds to achieve a ratio of 1.0 and 1.3 were computed, providing a range of flow predictions for gravel mobilization.

Shear stress is estimated from the output of the HEC-2 hydraulic model prepared by MEI (2000a). Because the HEC-2 model is a one-dimensional hydraulic model, the accuracy of the shear stress predictions is best at locations with simple channel morphology that best approaches uniform flow conditions. Riffles tend to provide the best channel conditions for applying this model. Therefore, only cross sections in riffles were used to perform the estimates. Results of the modeling suggest that most riffles do not mobilize up to the maximum flow modeled (16,400 cfs), with only a small number of riffles in all reaches predicted to mobilize by flows less than 8,000 cfs (Figure 3-23 and Figure 3-24). The wide variability of incipient motion thresholds shown in Figure 3-23 is likely due to a combination of factors, including (1) inaccuracies in applying a one-dimensional hydraulic model to predict hydraulic conditions in a complex channel morphology, (2) insufficient detail in local particle size estimates, and (3) inappropriate precision in ground topography used in the hydraulic model. More detailed ground surveys of hydraulically simple riffles would likely improve these predictions, as would more empirical studies of bed mobility; regardless, the results of both analyses strongly suggest that flows greater than 12,000 cfs are required to cause mobility of cobbles and gravels in most of Reach 1.

To estimate differing assumptions in Shields equation, as well as narrowing channel dimensions and reducing particle size via simulated gravel introduction projects, the incipient motion analysis was run for a single hypothetical cross section with varying (1) slopes, (2) Shields parameter for incipient motion, (3) particle size, (4) width-to-depth ratio, and (5) shear ratio (shear stress on the D_{50} versus shear stress needed to mobilize the D_{50}). A matrix was developed of results (Table 3-9), showing that due to the inherently low slope for the reach, developing combinations of (1) through (5) to achieve bed mobility thresholds is still very difficult with a reasonable width-to-depth ratio (width-to-depth ratio>25) appropriate for Reach 1. This analysis suggests that under best-case scenario (steepest reach shown in Figure 3-20, smallest particle size, and most mobile estimate of Shields parameter), flows greater than 7,600 cfs would be required to mobilize the D_{50} particle size.

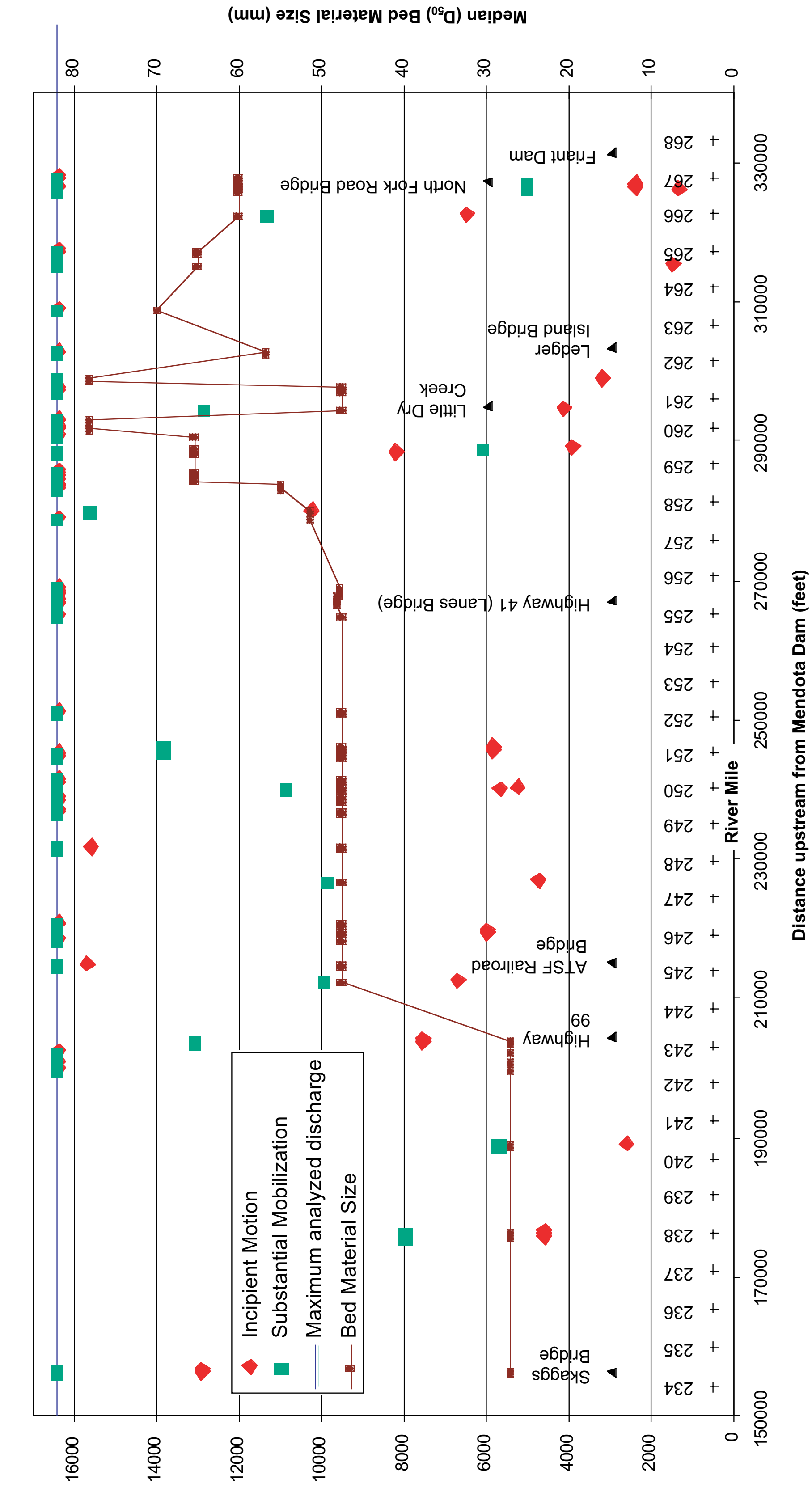


Figure 3-23. Predicted discharge to initiate motion of D_{50} particle size (shear ratio=1.0) and cause substantial transport of D_{50} particle size (shear ratio=1.3). D_{50} particle size used to model incipient motion at each riffle is shown on secondary axis.

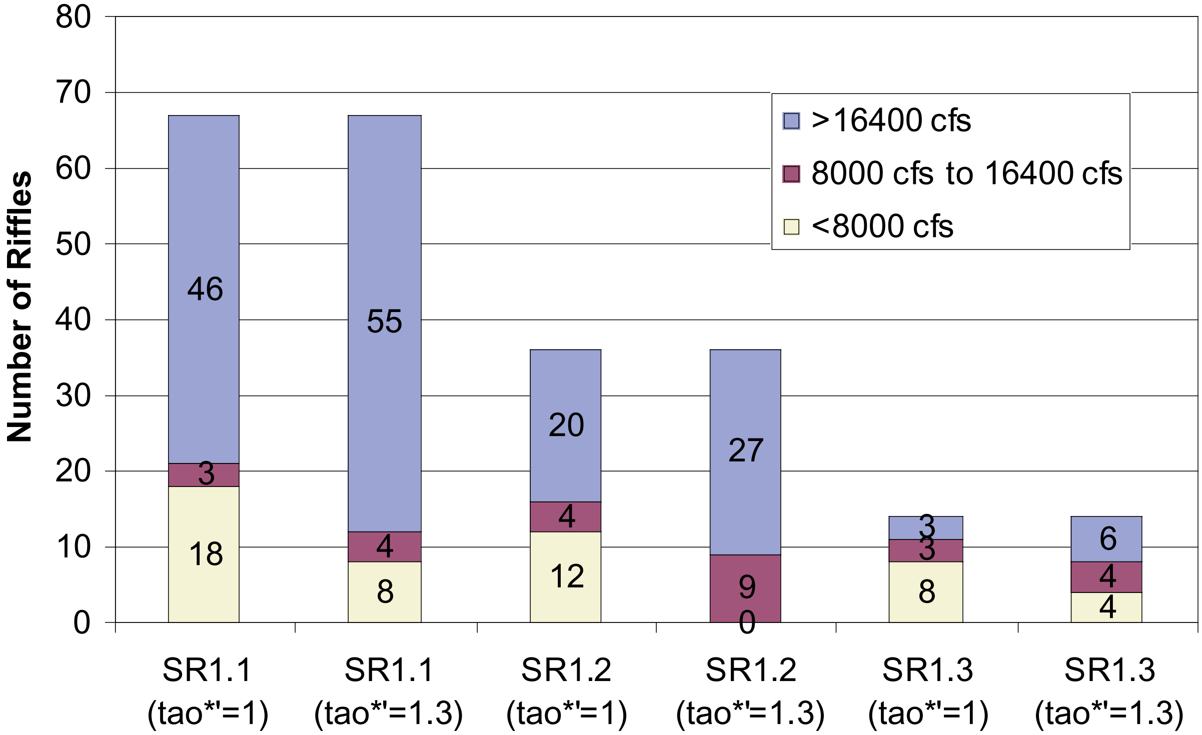


Figure 3-24. Number of riffles in which the critical discharge for incipient motion (shear ratio=1.0) and substantial transport (shear ratio=1.3) under existing D_{50} bed particle size conditions.

Table 3-9. Summary matrix of predicted incipient motion thresholds for a single cross section using a variety of slopes, particle sizes, width-to-dept ratios, Shields parameter, and shear ratio.

Assume Shields parameter = 0.030						
Slope	D_{50} (mm)	Depth (feet)	Width-to-Depth ratio	Width (feet)	Discharge (cfs) if shear ratio=1.0	Discharge (cfs) if shear ratio=1.3
0.0007	40	11.2	15	168	10,500	16,700
0.0010	40	7.6	15	115	4,600	7,300
0.0007	50	13.2	15	198	16,400	26,000
0.0010	50	9.0	15	135	7,100	11,400
0.0007	40	11.2	25	279	17,600	27,800
0.0010	40	7.6	25	191	7,600	12,100
0.0007	50	13.2	25	330	27,400	43,300
0.0010	50	9.0	25	225	11,900	18,900
Assume Shields parameter = 0.035						
Slope	D_{50} (mm)	Depth (feet)	Width-to-Depth ratio	Width (feet)	Discharge (cfs) if shear ratio=1.0	Discharge (cfs) if shear ratio=1.3
0.0007	40	13.1	15	197	10,500	16,700
0.0010	40	9.0	15	135	4,600	7,300
0.0007	50	15.5	15	233	16,400	26,000
0.0010	50	10.6	15	160	7,100	11,400
0.0007	40	13.1	25	329	17,600	27,800
0.0010	40	9.0	25	225	7,600	12,100
0.0007	50	15.5	25	388	27,400	43,300
0.0010	50	10.6	25	266	11,900	18,900

3.7.1.3. Planform Morphology

Channel morphology in Reach 1 is similar to gravel-bed rivers draining from the Sierra Nevada to the north (Tuolumne River, Merced River), with a few notable exceptions. The primary difference is that the San Joaquin River channel morphology is likely much more stable, and less dynamic than its northern cousins under unimpaired conditions. This is largely due to the smaller slope downstream of Friant Dam and lower sediment supply. The following sections further develop conceptual models of channel morphology, as well as changes resulting from human land use in the watershed.

Historical channel morphology for Reach 1 is best provided by 1937 aerial photographs (Figures 3-6 and Figure 3-22). Reach 1B is supplemented by the ACOE (1917) maps from Herndon downstream to Gravelly Ford (Figure 3-25). While these historic maps and aerial photographs do not provide true representation of unimpaired channel morphology on the San Joaquin River, they do provide useful insights to what the unimpaired channel morphology would have been. The aerial photographs and ACOE maps show that the river has multiple channels around islands and river bends. The channel morphology from the Friant Dam site downstream approximately 4 miles is straight, confined between the bluffs to the north and a terrace on the south. Downstream of RM 263, the San Joaquin River is a meandering alternate bar morphology, but the meanders are variable in size and morphology, typical of gravel-bedded reaches of rivers exiting the Sierra Nevada. Channel sinuosity is defined as the ratio of channel length to valley length, and based on the 1914 maps, sinuosity in Reach 1B is 1.2. Reach 1A sinuosity was estimated from 1937 aerial photographs, and had a sinuosity of 1.14.

Alternate bars are evident on the photographs and 1914 maps. Alternate bars and other complex channel features are important in providing diverse, high quality habitat for salmonids. Figure 3-26 illustrates some of the conceptual relationships between features within an alternate bar sequence and (1) particle sorting, (2) salmonid habitat, and (3) riparian vegetation. The complex particle sorting, hydraulics, and bar features provides complex and diverse habitat for all life stages of salmonids (spawning, egg incubation, fry rearing, juvenile rearing). Observations of the 1937 aerial photographs show riparian vegetation absent from some point bars and in-channel islands, suggesting that high flows scour these features frequently, but many other bars are heavily vegetated, even after a 9.5 year flood (Figure 3-6 and Figure 3-22). Compared to similar reaches of the Tuolumne River and Merced River, the planform morphology appears much more influenced by riparian vegetation, or from another perspective, fluvial geomorphic processes are not as effective at removing riparian vegetation as steeper rivers to the north (Figure 3-6). Backwater channels are associated with most channel bends, and at many locations, the channel has migrated to the terrace or bluff control on the outside of the bend. These meander bends have corresponding point bars that were not colonized by vegetation, but intervening reaches between point bars tend to be well vegetated.

Side channels were also very common in the unimpaired channel morphology. Cain (1997) estimated that the main channel length in 1939 for Reach 1A was 16.3 miles; secondary channel and high flow channel lengths added another 7.8 miles of channel. These secondary channels likely provided high quality fry and juvenile salmonid rearing habitat during winter baseflows, as well as some high velocity refugia areas during higher flows. By 1989, the total channel length (main channel + secondary channel + high flow channels) was reduced from 24.1 miles to 16.3 miles, a 32% reduction. Many of these historic secondary channels have been converted to diversion intakes. The net result of reduced side channel length is a corresponding reduction in existing fry and juvenile salmonid rearing habitat.

The current channel morphology is greatly altered from its historic state. The channel form has been simplified to a single channel that only splits at a few islands or when the channel has been captured by adjacent or in-stream gravel pits. The channel is much narrower than the historic channel and

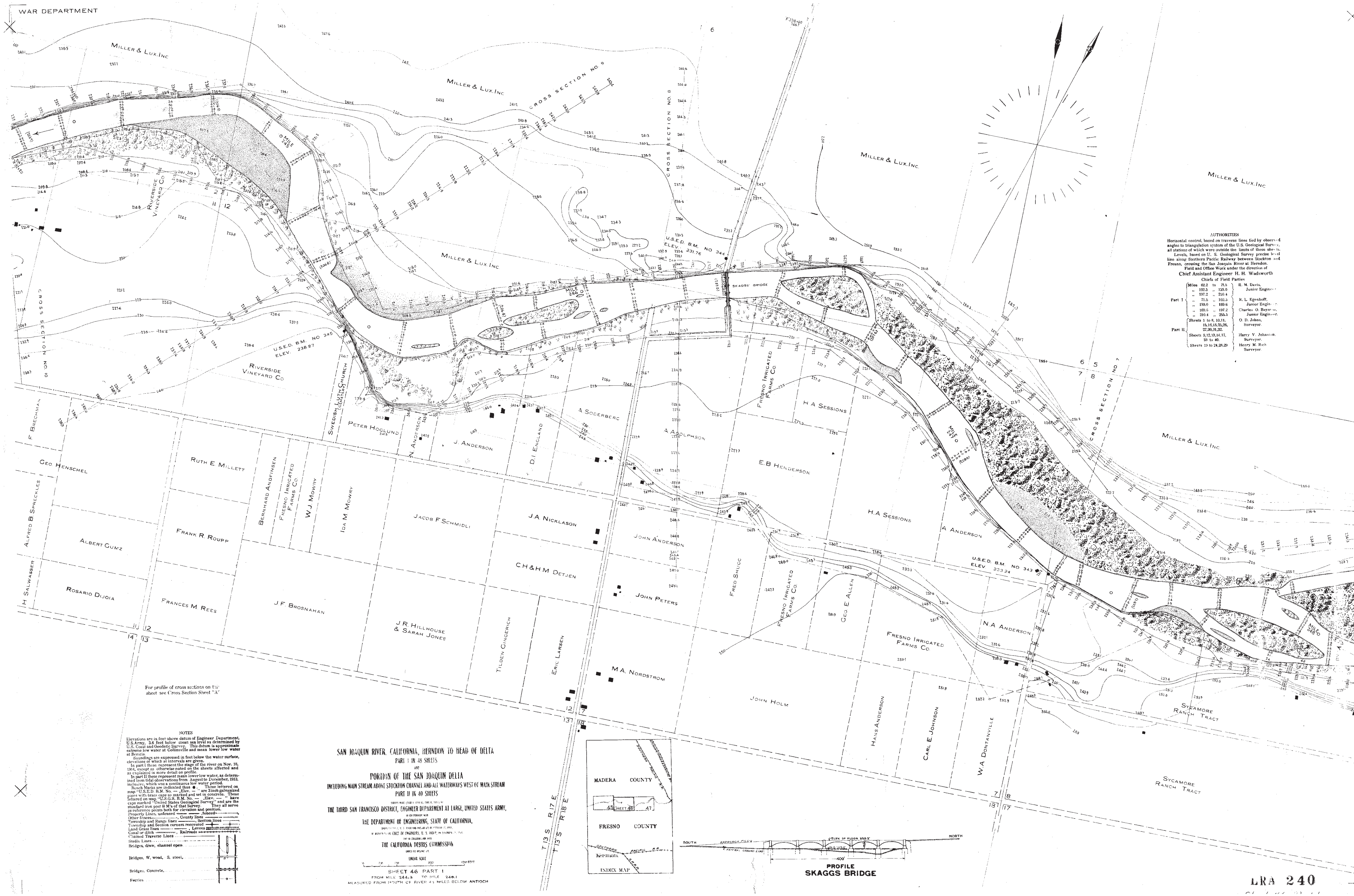


Figure 3-25. 1914 CDC map (ACOE 1917) showing Reach 1B planform morphology and cross section 9 location.

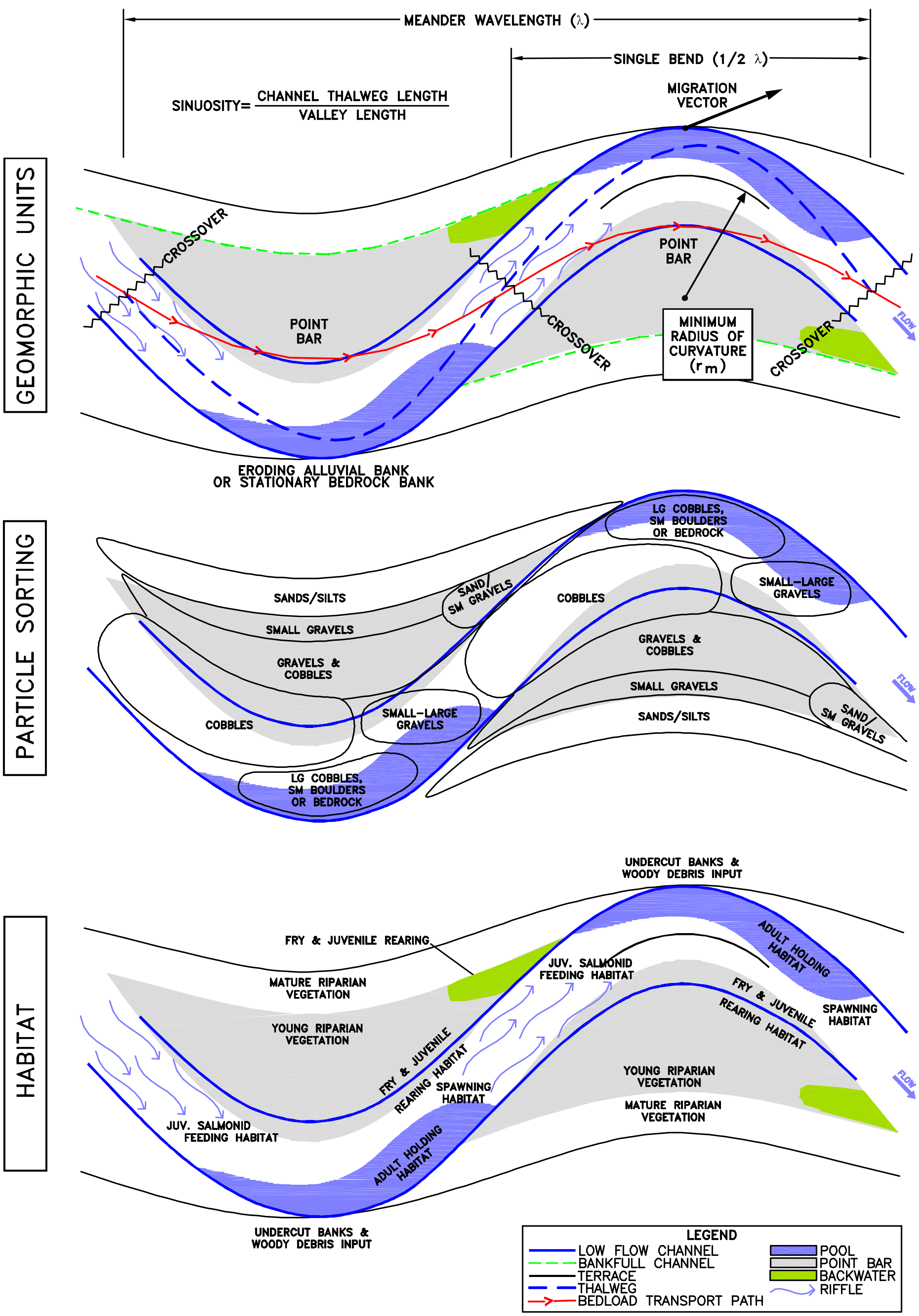


Figure 3-26. Idealized alternate bar unit, modified from Dietrich (1987) and McBain and Trush (1997). Morphological components of alternate bar correspond to tendencies in particle sorting, fish habitat, and riparian vegetation.

is armored with riparian vegetation (Figure 3-27). Exposed gravel point bars are virtually non-existent because infrequent bed mobility and scour has permitted riparian encroachment of these formerly exposed gravel bars. Another striking difference is the reduction in the number of small in-stream islands between the historical maps and the current aerial photographs (Figure 3-22). The few remaining small in-channel islands are now heavily vegetated, while the historical islands were primarily scoured of riparian vegetation (Figure 3-22). These remaining small in-channel islands are not naturally formed features, but rather mostly related to eddys and hydraulics associated with breached gravel pit levees (Figure 3-18). Large sections of riparian forest have been replaced by active and abandoned gravel mines and large sections of the channel have been radically altered by dredging for gravel, in-channel gravel mining, and the capture of gravel pits by the active channel (Figure 3-18). In the reach between Lane's Bridge (RM 255.2) and two miles downstream, the channel appears more similar to a lake than a river because of the captured gravel pits. Very few of the backwater complexes still exist; however, in one or two cases, permanent channels have been established around major islands or gravel mining complexes. Gravel mining continues downstream to Skagg's Bridge, but in lesser extent than the two mile reach downstream of Skagg's Bridge. Downstream of Skagg's Bridge, gravel mining activity tapers off, and the river is still moderately confined by terraces (Figure 3-28).

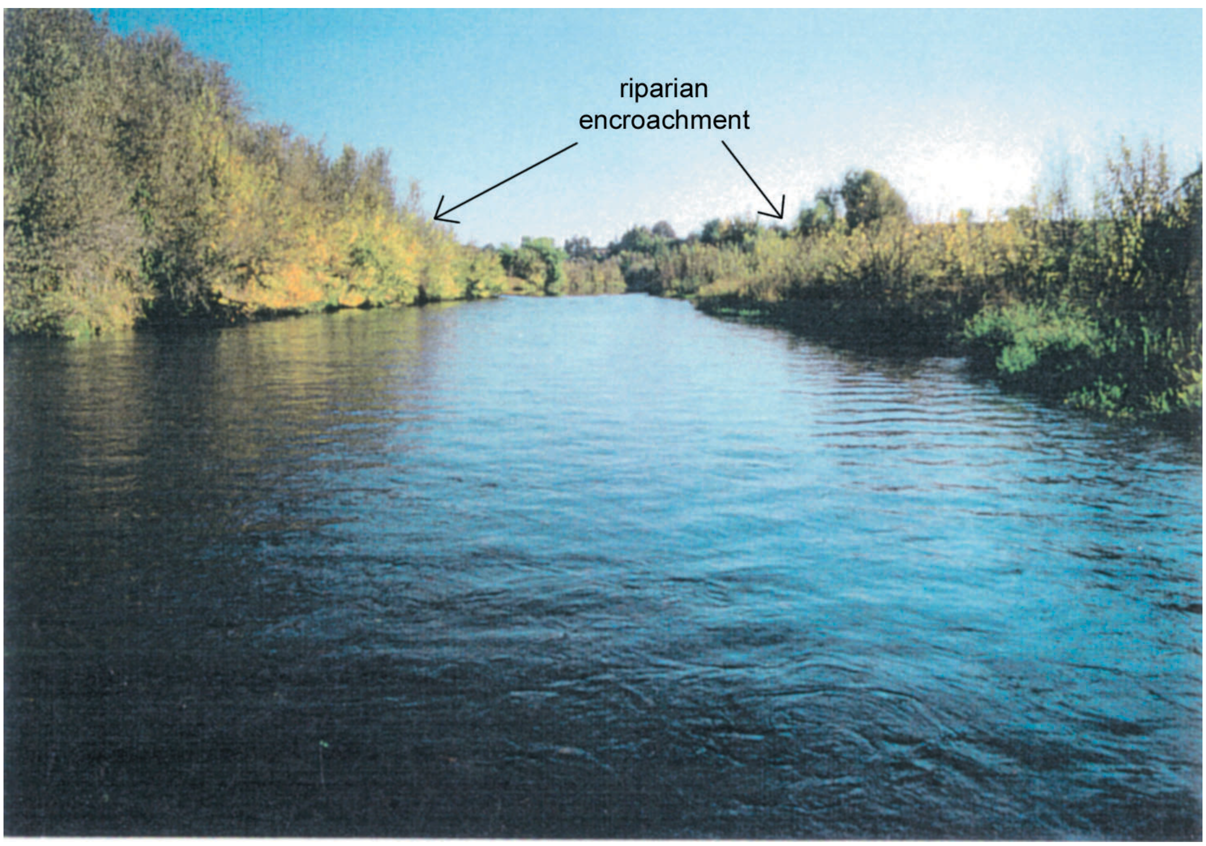


Figure 3-27. View upstream of the San Joaquin River at RM 240. The narrow strip of riparian vegetation that borders the channel is maintained by the in-stream flows required for maintenance of water rights. The D_{50} of the bed material in this reach is 40mm (from JSA and MEI 1998).

Figure 3-28. View upstream of the San Joaquin River at about RM 237. The channel is bounded by alluvial terraces, and has not been mined for sand and gravel in this specific location. From JSA and MEI (1998).

3.7.1.5. Channel Geometry

Referring to Table 3-4 and Table 3-5, cross section data indicate a net degradational trend in the two upstream cross sections immediately downstream of Friant Dam, then cross sections C3 and C4 show slight aggradation (Figure 3-29). Gravel was extracted from the reach represented by these two cross sections in the 1930s, and the aggradation shown there may be a function of the pits filling in slightly through 1996. These cross sections are also located between two bedrock ridges, such that if these ridges were controlling grade in 1939, one would expect these grade controls to discourage channel incision from 1939-1996. Cross sections C1 and C2 are upstream of these grade controls, such that channel downcutting from 1939-1996 would be expected. Cross sections C5 and C6 are located in a reach that is less disturbed than the rest of Reach 1; the slight aggradation at C5 is not considered significant, although the thalweg has shifted from the right bank to the left bank. The downcutting at cross section C6 appears more substantial, possibly influenced by downstream gravel mining (Figure 3-30). The large negative values at cross sections C7, C8, C9, and 9 result directly from sand and gravel mining. Lesser negative values through the reach are the result of general degradation induced by the sand and gravel mining (Cain 1997). Degradation in the reach may well have been greater if outcrops of bedrock at RM 255.5 and RM 265 had not provided local base level control (Cain 1997).

3.7.1.6. Changes in Width and Depth

Cain (1997) used the USBR 1939 survey records of the river below Friant Dam as a baseline condition for his comparative analysis of changes in channel geometry in Reach 1A, and JSA and

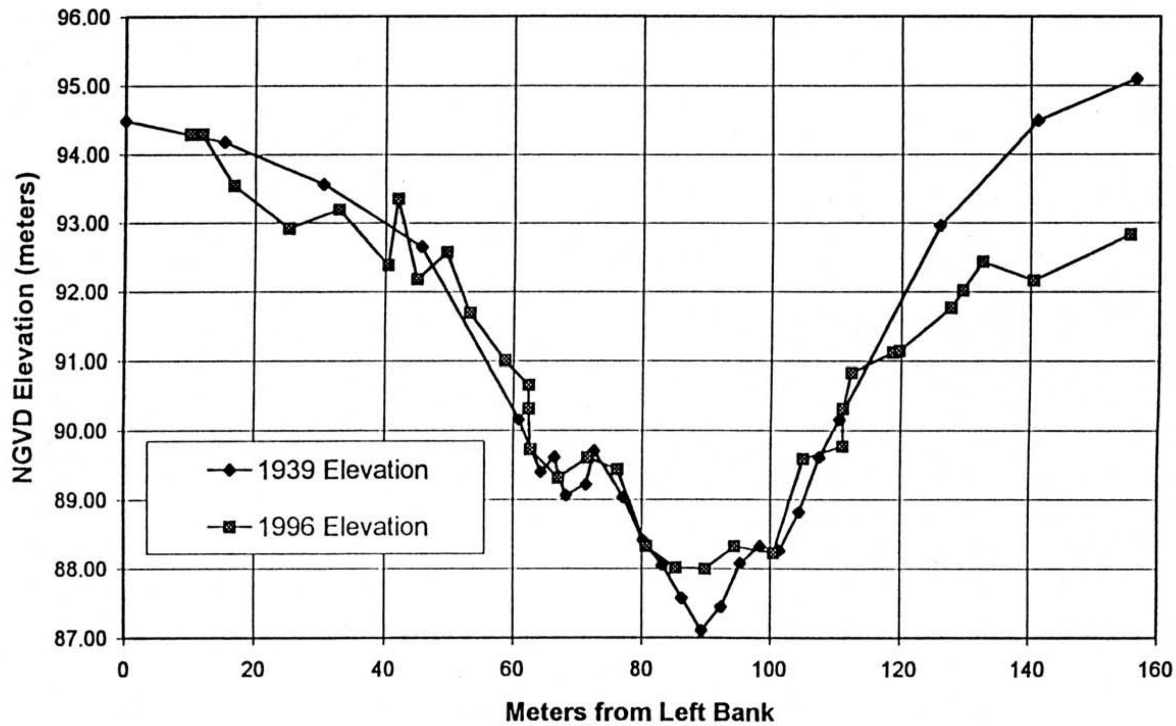


Figure 3-29. Comparison of 1939 and 1996 cross section C3 in Reach 1 (RM 265.4), showing example of cross section that has incised since 1939 (1 meter = 3.2808 feet).

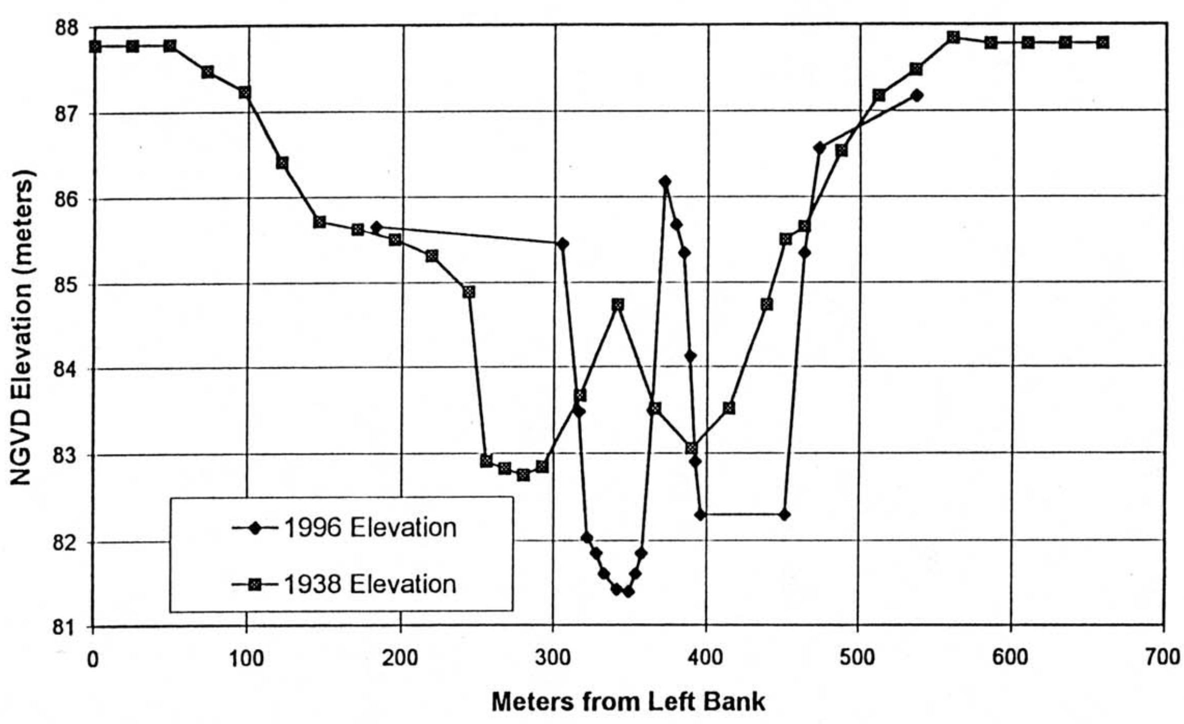


Figure 3-30. Comparison of 1939 and 1996 cross section C6 in Reach 1 (RM 259.3), showing example of cross section that has aggraded slightly since 1939 (1 meter = 3.2808 feet).

MEI (1998) used the 1914 ACOE cross sections for comparisons in Reach 1B (Table 3-6). Assuming that the active channel was equivalent to the bankfull or dominant discharge channel (Leopold et al. 1964), Cain (1997) showed that the average active channel width in the reach was about 1,200 feet in 1939. The average low flow channel width in the reach in 1939 was about 300 feet (Cain 1997). Cain (1997) compared the ratios of the low-flow channel widths in 1939 and 1989 to the 1939 active channel widths and the ratio of the 1980 high-flow channel width to the 1939 active channel width and concluded that the channel in Reach 1A had narrowed over time.

The width of the wetted channel from four representative ACOE (1917) cross sections in Reach 1B averaged 400 feet (flow approximately 500 cfs). Two of these Reach 1B cross sections are used to compare changes in width between 1914 and 1998 (Table 3-6), which do not indicate a clear trend between 1914 and 1998. This unclear trend is not unexpected, considering the extent of sand and gravel mining that has occurred in the reach (Cain 1997). Cross section 9 is located in an area that was mined and the channel appears to have widened. At cross section 2, the channel appears to have become narrower and shallower. Bankfull depth has decreased at cross section 2, but change in bankfull depth at cross section 9 was virtually zero.

Table 3-6 also illustrates longitudinal changes in bankfull width; bankfull width in 1914 decreases from Reach 1B (875 feet) to Reach 4A (277 feet), where the multichanneled anabranching system commences. Channel widths increase slightly in Reaches 4B (311 feet) and 5 (386 feet) (Figure 3-11). Average channel depths at bankfull stage are remarkably constant from Reach 2 to Reach 4A (14 feet) (Figure 3-12). Depth is highest in Reach 1B (18 feet) and lowest in Reach 4B (9 feet). Channel depth increases to 13 feet in Reach 5. Width-depth ratios show a general decrease in the downstream direction from about 50 in Reach 1B to 20 in Reach 4A (Table 3-6, Figure 3-13). Width-depth ratios increase again in Reaches 4B and 5 to 35 and 30, respectively. The width-depth ratio trends can be correlated with the resistance to erosion of the channel banks (Schumm 1963). The reaches with a higher width-depth ratio have more erodible banks, whereas those with lower values have more erosion resistant banks. The lower values of width-depth ratio in Reaches 4A, 4B, and 5 are also consistent with the required channel adjustments to maintain the continuity of sediment and water through the lower reaches, where there is a rising base level (Nanson and Huang 1997).

3.7.1.7. Historic Inundation Thresholds

Frequent and prolonged inundation of floodplains provides important juvenile and smolting salmonid rearing habitat during winter and spring months. Research conducted on the Yolo Bypass has shown that juvenile salmonid rearing on inundated floodplains can greatly increase growth rates (and thus survival) due to the expanded food base. Historically, the San Joaquin River frequently inundated floodplains (in Reach 1 and 2) and floodbasins (in Reach 3, 4, and 5). JSA and MEI (1998) estimated historical inundation patterns for Reaches 1-5 by applying a normal depth analysis with the HEC-RAS hydraulic model to a subset of 1914 cross sections assumed to be representative of the reach. Additionally, Cain (1997) estimates that the historical bankfull discharge was probably in the range of 11,600 cfs to 22,000 cfs, but does not identify the source of these estimates. The JSA and MEI (1998) analysis of 1914 cross section at RM 233.3 (Reach 1B) suggests that a small floodplain on the right bank is inundated by a flow of 10,000 cfs (approximately a 1.5-year pre-Friant Dam flood), but terrace inundation does not occur until flows exceed 43,000 cfs (approximately a 18-year pre-Friant Dam flood) (Figure 3-31). Even though these two estimates of floodplain inundation are similar, there is uncertainty in the estimates because of the limited amount of data used in the analysis, and the topographic variability inherent in Reach 1. Regardless, the frequency and long duration of the historic snowmelt runoff hydrograph, and periodic rainfall-generated storm events, inundated floodplains in Reach 1 from days to weeks. The virtual elimination of the snowmelt runoff period

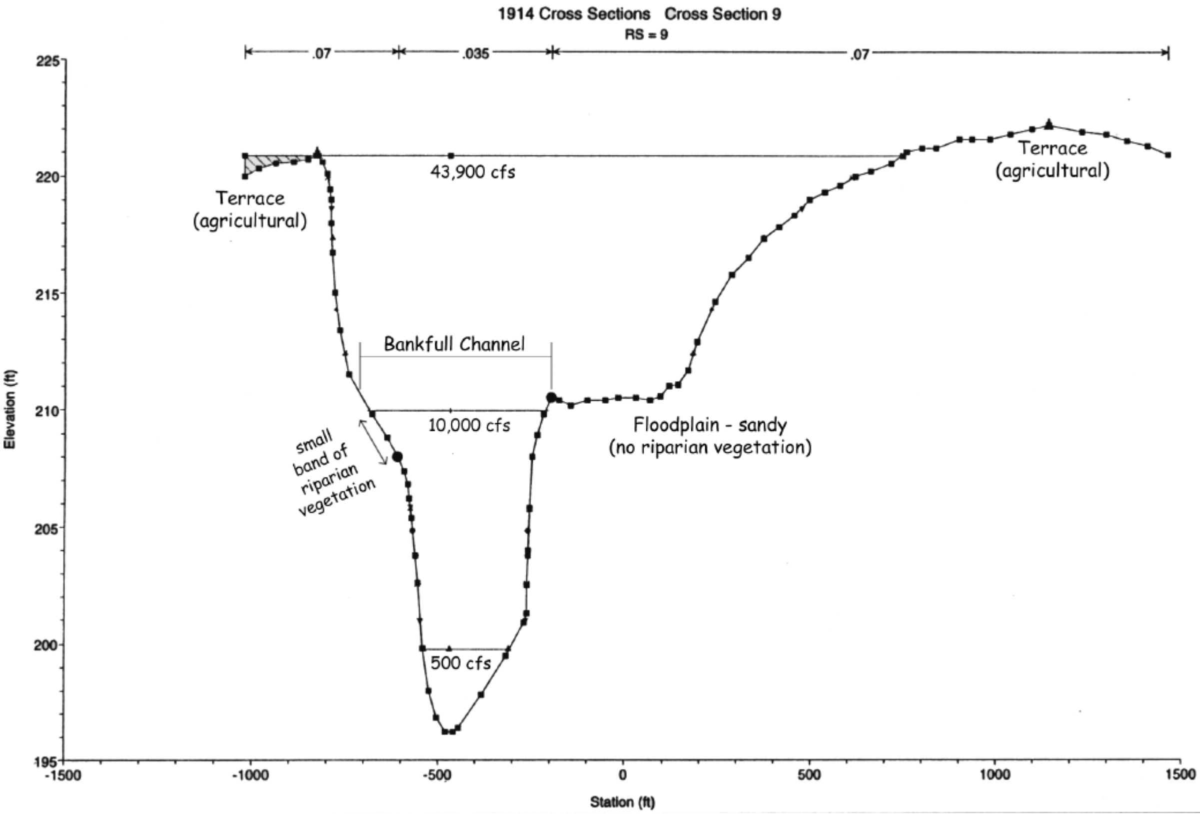


Figure 3-31. ACOE (1917) cross section 9 in Reach 1B (RM 233.3), showing predicted discharge thresholds to inundate key geomorphic surfaces in historic channel morphology.

downstream of Friant Dam (except during very wet years when flood control releases are required) has greatly reduced the duration and frequency of floodplain inundation, thus reduced juvenile salmonid rearing potential.

3.7.2. Reach 2

Reach 2 is subdivided into two reaches: Reach 2A extends from Gravelly Ford (RM 229.0) to the Chowchilla Bifurcation Structure (RM 216.1), and Reach 2B extends from the Chowchilla Bifurcation Structure to Mendota Dam (RM 204.8) (Figure 3-2). Reach 2 is the beginning of the sand-bedded reach, and the bluffs that confined the channel in Reach 1 no longer confine the channel. The downstream boundary of Reach 2 is located at Mendota Pool, which also marks the location where the San Joaquin River turns north as it leaves the San Joaquin River alluvial fan and hits the prograding alluvial fans of the Coast Range. The northern branch of the Kings River overflow also joins the San Joaquin River at this location via Fresno Slough (Figure 3-32). Channel morphology is sand-bedded, with moderate meandering in Reach 2A (Figure 3-33), and highly sinuous meanders in Reach 2B (Figure 3-34) as the San Joaquin River begins to be influenced by the collision with the alluvial fans of the Coast Range (lower slope due to backwater effect from fans and Fresno Slough).

3.7.2.1. Sediment Regime

Quantification of the historical sediment regime has not been estimated for Reach 2; however, sediment supply likely decreased from Reach 1B through Reach 2 as it deposited on floodplains

Figure 3-32. View of Mendota Pool at the Reach 2B/3 boundary (RM 205), looking north (downstream) into Reach 3 of the San Joaquin River. From JSA and MEI (1998).

comprising the larger-scale alluvial fan of the San Joaquin River. Sediment was clearly routing through Reach 2 to Reach 3 based on the 1914 ACOE maps, as evidenced by exposed sand bars in both reaches.

Construction and operation of Chowchilla Bifurcation Structure has greatly reduced sediment supply to Reach 2B, as most high flows and sediment are routed through the Chowchilla Bypass. Mendota Dam may also cause temporary interruption of sediment routing from Reach 2 to Reach 3. Review of longitudinal profiles through Mendota Pool does not indicate long-term aggradation in the pool (compared to the magnitude of sediment deposited and mechanically removed from the Chowchilla Bypass), suggesting that periodic pulling of boards on Mendota Dam during high flows, as well as scheduled draining of Mendota Pool for dam inspection, allows sediment to eventually be routed through the pool to Reach 3.

3.7.2.2. Fluvial Processes and Channel Morphology

The transition from Reach 1 to Reach 2 results in key changes in fluvial processes and channel morphology. The high flow gradient is reduced to 0.000415 in Reach 2A and even lower (0.00023) in Reach 2B (Figure 3-35). Additionally, valley slope decreases from 0.0077 in Reach 1B to 0.0057 in Reach 2 (these slopes are based on modeled water surface slopes using present-day topography, thus these slopes differ from the 1914 values shown in Table 3-4). This reduction in slope from the steeper, moderately confined, and predominately gravel-bedded Reach 1 causes the channel to shift

Figure 3-33. View looking upstream of sediment deposition in bed of the San Joaquin River in Reach 2A (RM 223) near the upstream end of the project levees and upstream of the Chowchilla Bifurcation Structure. This reach is usually dry most of the year. Erosion of the floodplain is the source of the majority of the sediment. From JSA and MEI (1998).

to a sand-bedded, meandering channel morphology. The ACOE (1917) maps show that the active channel narrows and the meander frequency increases compared to Reach 1 (Figure 3-7, Figure 3-36). The channel form changes from a wide channel with multiple islands to a narrower channel with large, alternating, and exposed sand point bars. Review of all 1914 maps and 1937 aerial photographs shows that channel morphology is straight at the upstream end of Reach 2 (Gravelly Ford) to RM 228, and meander amplitude increases in the downstream direction. The size of the exposed point bars decreases as the channel meanders grow in size and in frequency in the downstream direction, and the meanders increase in amplitude and are more sinuous (compare Figures 3-33 to Figure 3-34). As the channel narrows, the number of instream islands decreases. The large unvegetated point bars in the 1914 maps and 1937 aerial photographs suggest that the channel is either actively migrating across its floodplain or flow is sufficiently high and frequent to scour riparian vegetation from the bars (Figure 3-36). Review of the representative reach in Figure 3-36, as well as the recent photo in Figure 3-33, shows that the baseflow channel migrates within the overall meanders of the bankfull channel, but that migration of the bankfull channel is minimal. Oxbow lakes are not observed on either the ACOE (1917) maps or the 1937 aerial photographs, further supporting the assertion that the channel was migrating at a very slow rate under historic conditions (and perhaps under unimpaired conditions).

This reach was moderately confined, and the flow required to exceed channel capacity decreased in the downstream direction through Reach 2. Flows exceeded channel banks when discharges exceeded

Figure 3-34. View looking downstream of a high amplitude bend in the San Joaquin River in Reach 2B (RM 215). Channel capacity is reduced by sediment deposition in the bed of the channel. Within-levee design capacity within this reach of the river is about 2,000 cfs. This reach is usually dry most of the year. From JSA and MEI (1998).

8,000 to 14,000 cfs in the upper portion of Reach 2A, but were somewhat confined by the declining terraces (see Section 3.6.4). Downstream of RM 225 (still in Reach 2A), the terraces on both banks merge into floodplains to the point where evidence of high flows flowing north (Lone Willow Slough) and south (eventually into Fresno Slough) is clear (Figure 3-36). The boundary of Reach 2A and 2B at the present-day location of Chowchilla Bifurcation Structure also marks the beginning evidence of large-scale sloughs (e.g., Lone Willow Slough) characteristic of the lower portions of the San Joaquin River study area. However, the entrance elevations to sloughs in Reach 2 appear to be a greater distance above the low flow channel than those in Reach 4, thus flow into the sloughs would occur at discharges greater than typical baseflows. The larger amplitude and more sinuous meander pattern evident in Reach 2B are likely due to the reduced slope as the San Joaquin River approaches the prograding Coast Range alluvial fans.

The sloughs in Reach 2 have been converted to irrigation canals in the 1914 maps and 1937 aerial photographs. These sloughs were later abandoned as irrigation canals as upstream surface supplies were developed (Friant Unit of the Central Valley Project) and increased groundwater resources continued to develop. With the construction of the San Joaquin River Flood Control Project, some of the northern sloughs were incorporated into the Chowchilla Bypass system. This conversion of sloughs, reduction of the high flow regime, and agricultural conversion of formerly active flood plains in Reach 2B and the lower portions of Reach 2A eliminated the high flow scour channels and flood

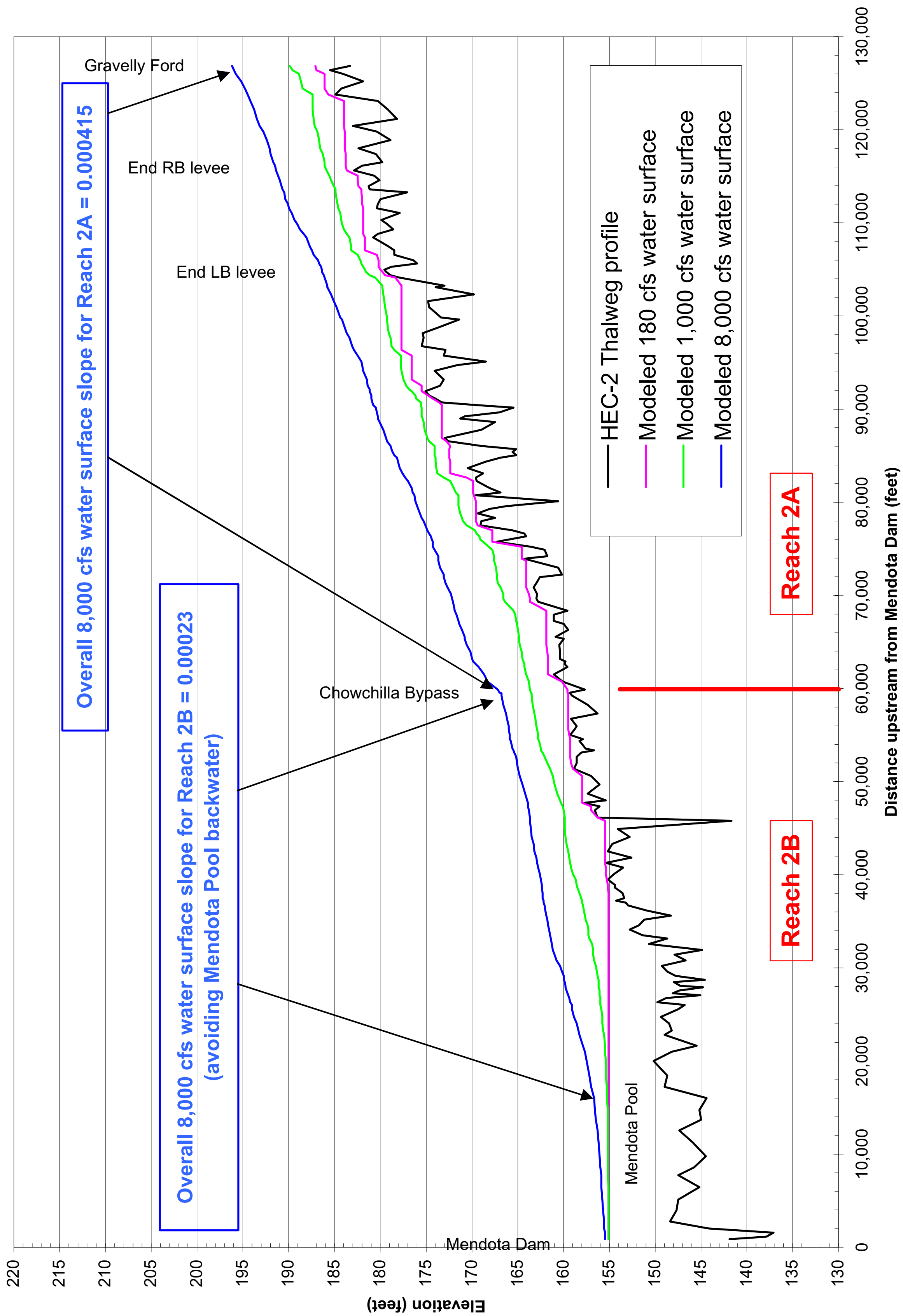


Figure 3-35. Thalweg and modeled water surface profiles for Reach 2A and Reach 2B, showing overall reach slope and slope change caused by the backwater effect of Mendota Pool (from MEI 2000a).

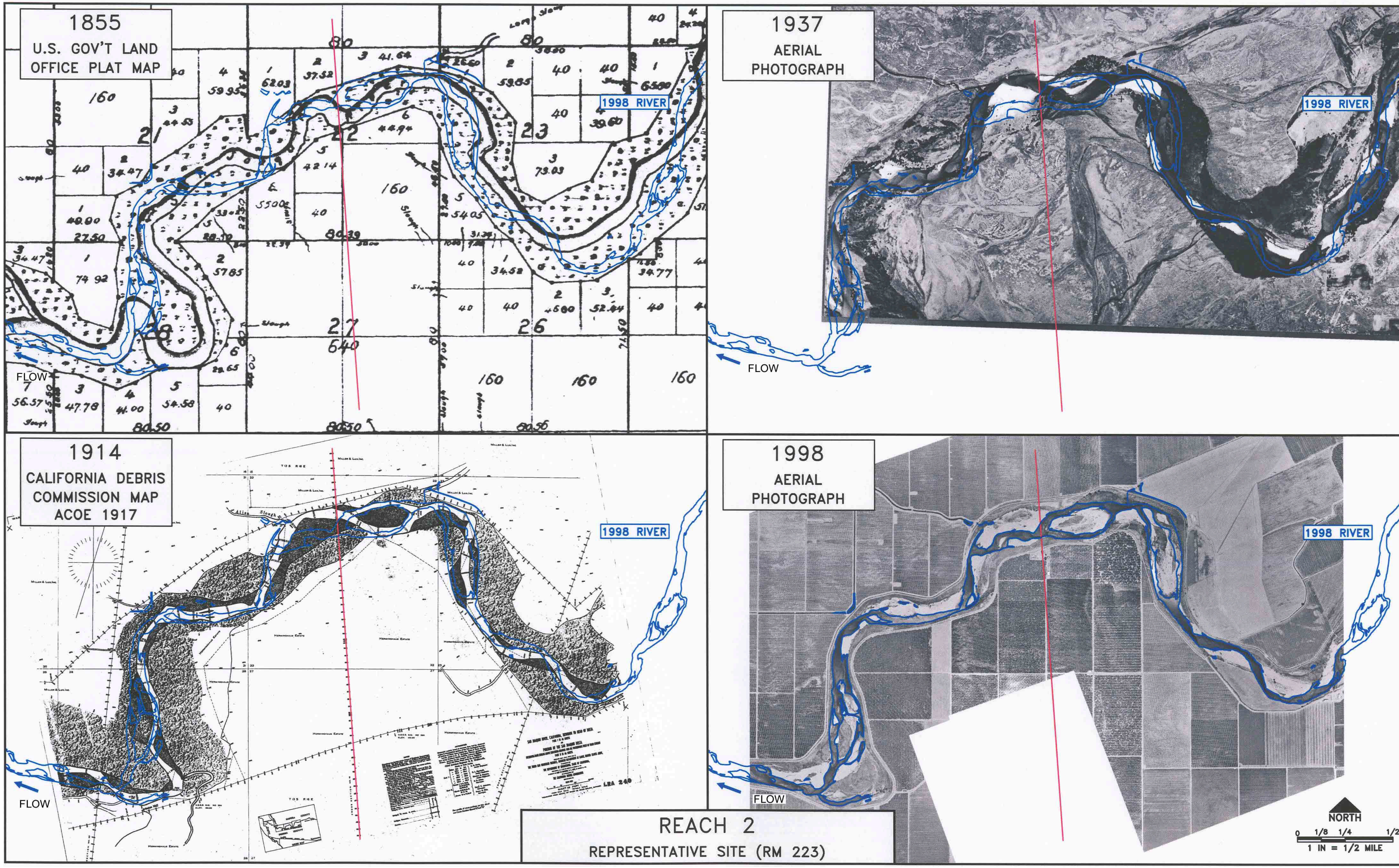


Figure 3-36. Example planform evolution in Reach 2 (RM 223), showing 1855 plat map, 1914 CDC map, 1937 air photo, and 1998 air photo.

access to the Fresno Slough (except during very large floods as occurred in 1997). Construction of project levees and additional agricultural reclamation along lower surfaces in Reach 2 further reduced the channel footprint, reducing the length of primary and secondary channels (channel simplification and fossilization). Reach 2 is now normally dewatered most of the time and groundwater overdraft has greatly reduced the elevation of the shallow groundwater aquifer in this reach (see Chapter 4). The combination of vegetation removal within the floodway and loss of surface and subsurface hydrology has cumulatively discouraged riparian recruitment and survival in this reach. Review of historical maps and photographs shows that riparian vegetation in this reach has been reduced (Figure 3-36).

The perseverance of exposed sand bars between 1914 and 1998 has occurred for different reasons. The pre-Friant Dam high flow regime scoured bars on a frequent basis, preventing riparian encroachment of the bars; the post-Friant Dam flow regime and depressed shallow groundwater aquifer has prevented riparian vegetation from initiating and surviving in this reach, such that the sand bars are still maintained relatively free of riparian vegetation. Periodic riparian clearing for flood control and local sediment accumulation upstream of the Chowchilla Bypass, may also contribute to reduced riparian vegetation on the bars. While there is no data available to quantify historic or contemporary thresholds of key fluvial processes, such as bed mobility, bed scour, channel migration, and avulsion, the thresholds of bed mobility and scour are likely low. Bed mobility likely occurs at most baseflows, and bed scour likely occurs at moderate flows in the few thousands of cubic feet per second. Channel migration and avulsion can still occur within the confining project levees, and still occurs in part because the lack of riparian vegetation allows the banks to erode easily.

Change in bankfull channel width and depth has been mixed in Reach 2 (JSA and MEI 1998). Cross sections 19 and 14 show opposing trends (Table 3-6). Cross section 19, located upstream of the Chowchilla Bifurcation Structure at RM 222.6, shows channel widening (880 feet to 1,110 feet) but little change in channel depth (11.1 feet to 11.4 feet). In contrast, the channel narrowed and deepened at cross section 14 (RM 228.4). Channel width at cross section 14 narrowed from 810 feet to 530 feet, and depth increased from 15.9 feet to 21.4 feet. The changes at cross section 14 could be a result of local extraction of sand and gravel from the channel between 1986 and 1995 (Hill pers. comm.).

Thalweg elevations for the two cross sections in Reach 2 have decreased slightly (2.1 feet decrease for both). Both are located upstream of the Chowchilla Bifurcation Structure. These two cross sections are located upstream of the short section immediately upstream of the Chowchilla Bifurcation Structure where field observations suggest local channel aggradation caused by the backwater effect of the bifurcation structure. JSA and MEI (1998) did not compare any cross sections downstream of the Chowchilla Bifurcation Structure but slight degradation may have occurred in the upper portions of Reach 2B due to reduced sediment supply (due to the Chowchilla Bifurcation Structure diverting high flows and sediment into the bypass system).

3.7.2.3. Historic Inundation Thresholds

JSA and MEI (1998) estimated historical inundation patterns for Reach 2 by applying a normal depth analysis with the HEC-RAS hydraulic model to a subset of 1914 cross sections assumed to be representative of the reach. Two cross sections were analyzed in Reach 2A, and no cross sections were analyzed in Reach 2B. The analysis of cross section 14 at RM 228.4 suggests that a small floodplain on the left bank is inundated by a flow of 8,000 cfs (approximately a 1.3-year pre-Friant Dam flood), but terrace inundation does not occur until flows exceed 26,000 cfs (approximately a 5-year pre-Friant Dam flood assuming no flood peak attenuation). Analysis of cross section 19 at RM 222.6 suggests that the floodplain on the left bank is inundated by a flow of 13,800 cfs (approximately a 2.0-year pre-Friant Dam flood) (Figure 3-37). There are no higher elevation flat surfaces shown on cross section 19, so an evaluation of terrace inundation could not be conducted.

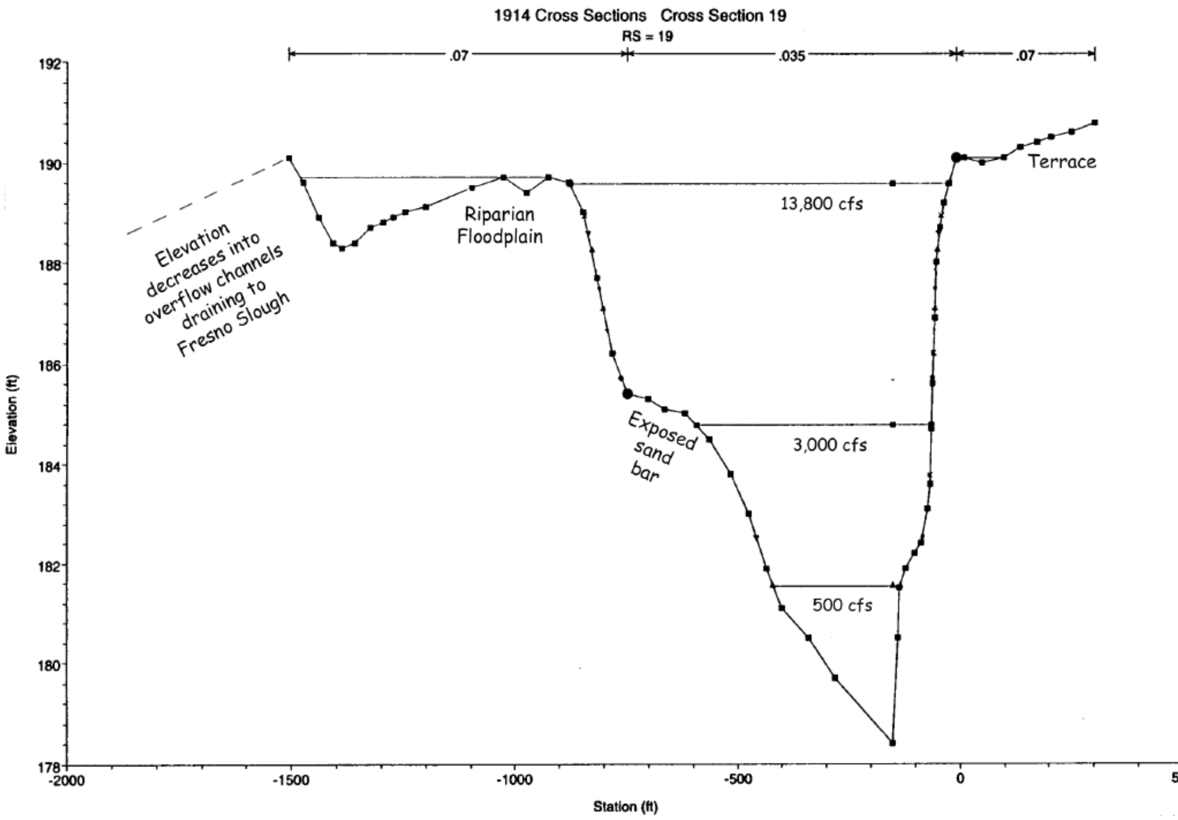


Figure 3-37. ACOE (1917) cross section 19 in Reach 2A (RM 222.6), showing predicted discharge thresholds to inundate key geomorphic surfaces in historic channel morphology.

3.7.3. Reach 3

Reach 3 extends from Mendota Dam (RM 204.8) to Sack Dam (RM 182.0) (Figure 3-2), and flows north along the axis of the San Joaquin Valley. Reach 3 was a meandering sand-bedded channel, with a fairly consistent meander pattern. The reach is entirely alluvial, with no geologic control other than the left (west) bank where prograding alluvial fans from streams draining the Coast Range historically confined the river.

3.7.3.1. Sediment Regime

As with Reach 2, there has been no quantification of the historical sediment regime for Reach 3. Sediment supply likely decreased from Reach 2 through Reach 3 as it deposited on floodplains predominately on the right (east) bank of the San Joaquin River as the river flowed down the axis of the San Joaquin Valley. Floodplains appear to be extensive and confining as in Reach 2, indicating that sediment supply was large enough to build floodplains. Sediment was clearly routing through Reach 3 to Reach 4 based on the 1914 ACOE maps, as evidenced by exposed sand bars in both reaches.

Construction and operation of Chowchilla Bifurcation Structure has greatly reduced sediment supply to Reach 3, as flows and sediment are routed through the Chowchilla Bypass. As described for Reach 2, Mendota Dam may also cause temporary interruption of sediment routing from Reach 2 to Reach 3, but eventually routes into Reach 3.

3.7.3.2. Fluvial Processes and Channel Morphology

The transition from Reach 2 to Reach 3 resulted in another slight decrease in slope, from 0.00023 in Reach 2B to 0.00022 based on modeled water surface profiles (Figure 3-38). Additionally, valley slope again decreases, from 0.0057 in Reach 2 to 0.0033 in Reach 3 (these slopes are based on the 1914 values shown in Table 3-4). Review of the 1914 maps and 1937 aerial photographs do not indicate a significant change in channel morphology between the two reaches. Channel morphology continues to be meandering, sand-bedded channel morphology. The meanders are still highly sinuous, but the meander wavelength and patterns are not as consistent as with Reach 2B (Figure 3-39 and Figure 3-8). Channel migration and avulsion processes are evident in the 1914 map and 1937 aerial photographs, but comparison with the 1998 aerial photographs suggests that the migration rates are low (albeit the comparison period occurs during extensive flow regulation and land management activities). Reviewing the historical maps and aerial photographs can be deceiving; the abandoned channel evident at the downstream end of the 1914 map (Figure 3-39) appears to have recently avulsed when observing the 1937 photo. However, this avulsion had occurred at least 23 years earlier. Although no oxbow lakes are mapped between Mendota Dam and Firebaugh, high flow cut-off channels are mapped, and one meander above Firebaugh has been cut off (Figure 3-8), but much of the original 1914 channel was still wetted in 1998.

By 1914, levees and canal embankments had already begun confining much of Reach 3 and additional confinement has occurred since then. Between Mendota and Firebaugh, canals confine the channel, but the canals are set back further from the historic bankfull channel. Below Firebaugh, the channel is tightly confined by levees and the channel is much straighter. The levees and canals tend to follow the meandering pattern of the historic bankfull channel, dissecting the floodplain from the bankfull channel. Figure 3-40 shows a current photograph of Reach 3 upstream of Firebaugh (RM 200), showing the canals dissecting the historic floodplain on both banks, and agricultural reclamation of the floodplain on both sides of the canals. To protect the agricultural lands between the canals (within the river corridor), small dikes have been constructed to prevent flows up to 4,500 cfs from inundating these lands (JSA and MEI 1998). These nonproject levees further confine the channel and reduce the frequency of overbank flows, channel migration, and channel avulsion. The photo shown in Figure 3-41 is in a reach with a remnant point bar and portion of the historic floodplain still remaining; most of Reach 3 is more confined between canals and nonproject levees. Figure 3-41 shows the reach at Sack Dam (boundary between Reach 3 and 4A), with more extensive confinement by canals and levees.

Changes in bankfull width and depth are estimated by comparing the 1914 cross sections with 1998 resurveys (Table 3-5). Two cross sections were compared; cross section 29 at RM 201.6 and cross section 36 at RM 193.7. The channel width consistently narrowed at cross sections 29 and 36. Channel width at cross section 29 decreased from 790 feet in 1914 to 384 feet in 1998, and channel width at cross section 36 decreased from 460 feet in 1914 to 307 feet in 1998. Changes in depth were inconsistent. Channel depth at cross section 29 increased slightly from 13.2 feet in 1914 to 14 feet in 1998, and channel depth at cross section 36 decreased from 19 feet in 1914 to 12.9 feet in 1998. The substantial change in channel width at cross section 29 could be as result of a slight change in the alignment of the repeat cross-section survey. However, channel narrowing is the expected response of the reduction in flows resulting from the flood bypasses and reduction of flood flows delivered to the San Joaquin River from the Kings River North.

Thalweg elevations for the two cross sections in Reach 3 have decreased to varying degrees (Table 3-6). Cross section 29, located approximately 3 miles downstream of Mendota Dam, had 10.8 feet of channel degradation, whereas cross section 36 only had a slight channel degradation of 1.5 feet. The large amount of channel degradation at cross section 29 may be caused by a combination of factors. First, base level changes due to subsidence are large in this reach, where 5-6 feet of subsidence has

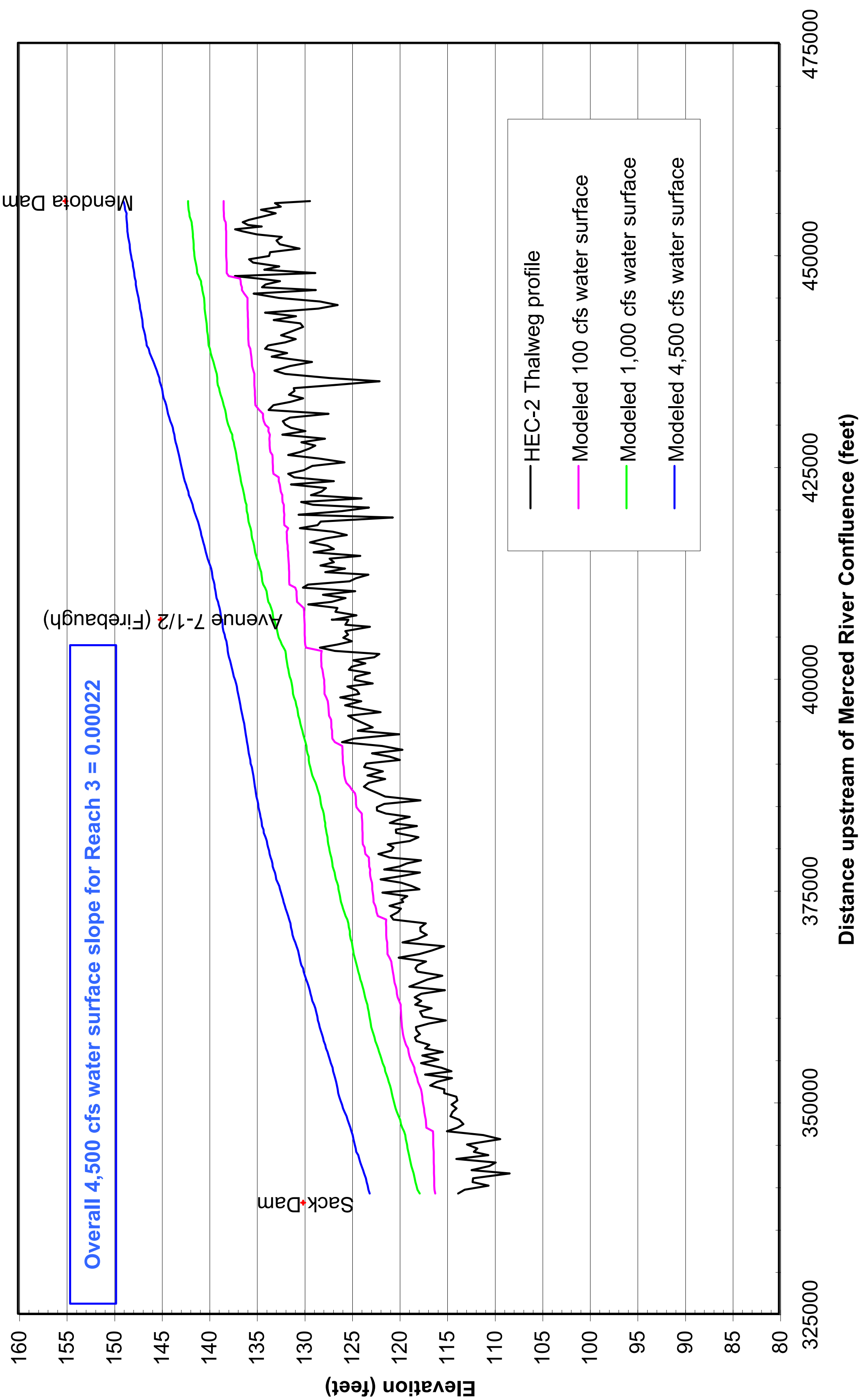


Figure 3-38. Thalweg and modeled water surface profiles for Reach 3, showing overall reach slope downstream of Mendota Pool (from MEI 2000a).

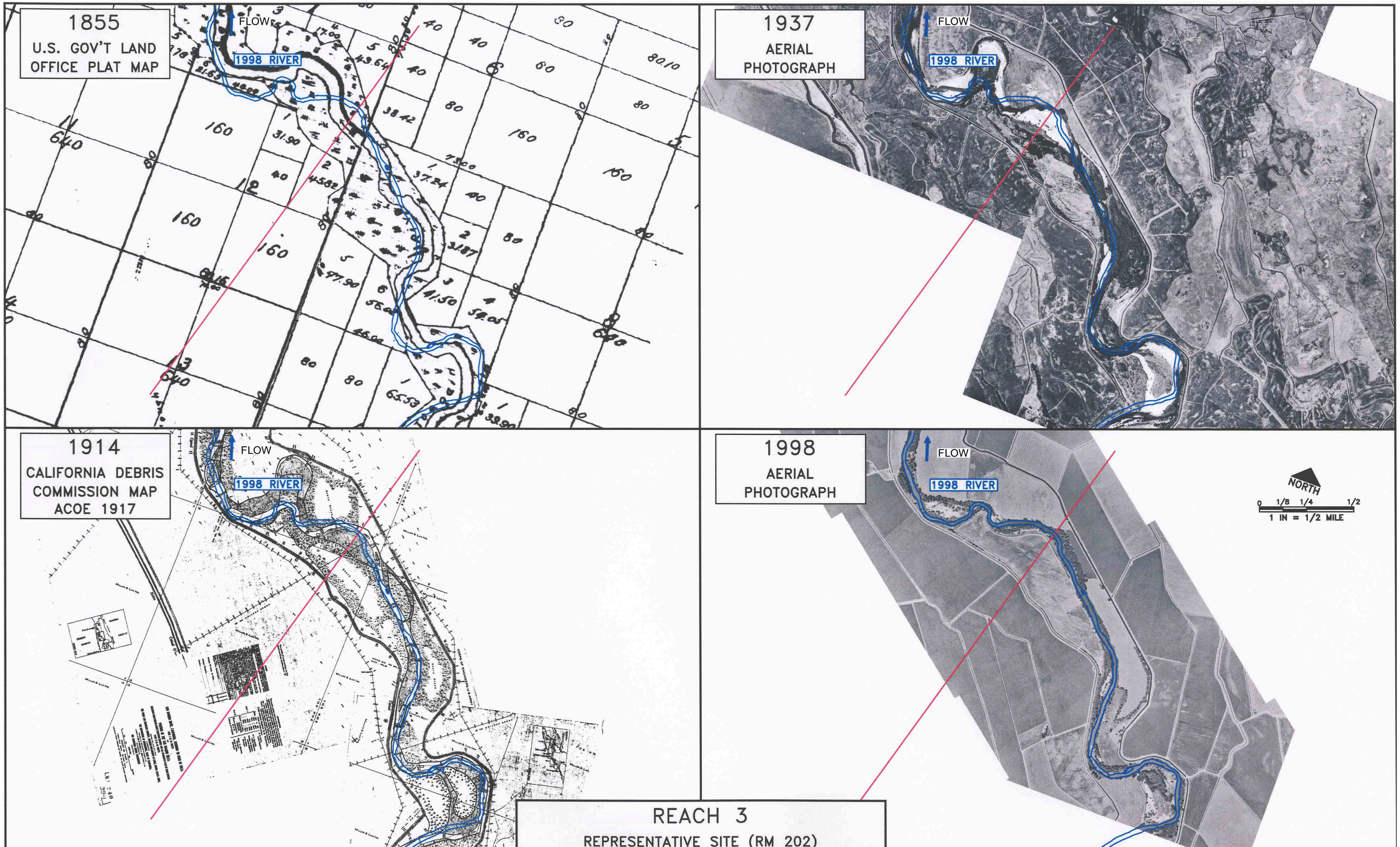


Figure 3-39. Example planform evolution in Reach 3 (RM 202), showing 1855 plat map, 1914 CDC map, 1937 air photo, and 1998 air photo.

Figure 3-40. View looking downstream of the San Joaquin River at RM 200. The Columbia Canal is located on the right bank and the Helm Ditch is located on the left bank (looking downstream). The area between the river and the Helm Ditch is part of the historical floodplain of the river that has been isolated by a local levee. The Helm Ditch is situated on the margin of a terrace with about 8 feet of relief. From JSA and MEI (1998).

been reported (Ouchi 1983). Second, reduction of sediment supply from the Chowchilla Bifurcation Structure, combined with augmented sediment-free flows from the Delta Mendota Canal, has likely cause sediment transport capacity to exceed supply (causing channel degradation). The reported subsidence diminishes in the downstream direction to about one foot at about the Sand Slough Control Structure, which correlates fairly well with the data in Table 3-5.

3.7.3.3. Historic Inundation Thresholds

JSA and MEI (1998) estimated historical inundation patterns for Reach 3 by applying a normal depth analysis with the HEC-RAS hydraulic model to a subset of 1914 cross sections assumed to be representative of the reach. Two cross sections were analyzed in Reach 3. The analysis of cross section 29 at RM 201.6 suggests that a small bench on the left bank is inundated by a flow of 5,000 cfs; this small bench appears to be within the bankfull channel rather than being a true floodplain. The floodplain surface on the left bank is inundated by a flow of 13,000 cfs (approximately a 1.9-year pre-Friant Dam flood assuming no flood peak attenuation or flow contribution from Fresno Slough), with the higher surface (terrace?) on the right bank inundated at a slightly higher flow in the 18,000 cfs to 20,000 cfs range (Figure 3-42). Analysis of cross section 36 at RM 193.7 shows that the floodplain on the left bank is inundated by a flow of 10,000 cfs (approximately a 1.5-year pre-Friant Dam flood).

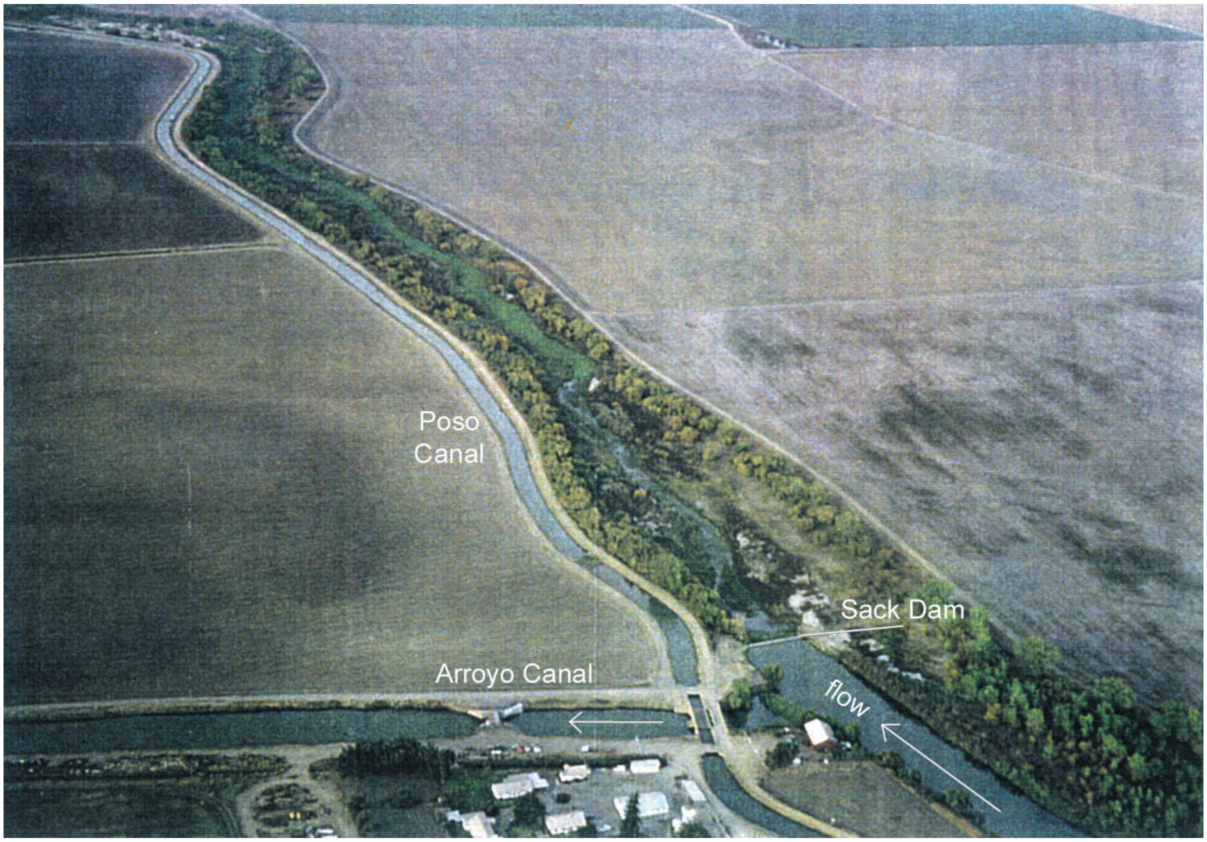


Figure 3-41. View looking downstream of Sack Dam and the headgates for the Arroyo Canal at RM 182. The dam is the terminus for Delta-Mendota water conveyed down the San Joaquin River. The Poso Canal parallels the river on the left bank. From JSA and MEI (1998).

There are no higher elevation flat surfaces shown on either cross section, so an evaluation of terrace inundation (if they even exist) could not be conducted. The inundation thresholds for Reach 2 and 3 show some consistency, in that it requires a moderate flood (>10,000 cfs) to exceed the banks of the channel and spill onto the floodplain.

3.7.4. Reach 4

Reach 4 is subdivided into two reaches: Reach 4A extends from Sack Dam (RM 182.0) to the Sand Slough Control Structure (RM 168.5), and Reach 4B extends from the Sand Slough Control Structure to the Bear Creek/Eastside Bypass confluence (RM 135.8) (Figure 3-2). Reach 4 continues to flow north along the axis of the San Joaquin Valley. Reach 4 was a meandering sand-bedded channel, but also marked the beginning of the extensive flood basin of the lower San Joaquin River. Numerous anabranching sloughs conveyed summer and winter baseflows along with the primary San Joaquin River channel. The reach is entirely alluvial, and possibly beginning to be influenced by the Merced River alluvial fan entering at the downstream end of Reach 5. Riparian levees provided moderate confinement of the river on both banks, with extensive tule marsh flood basins beyond the riparian levees.

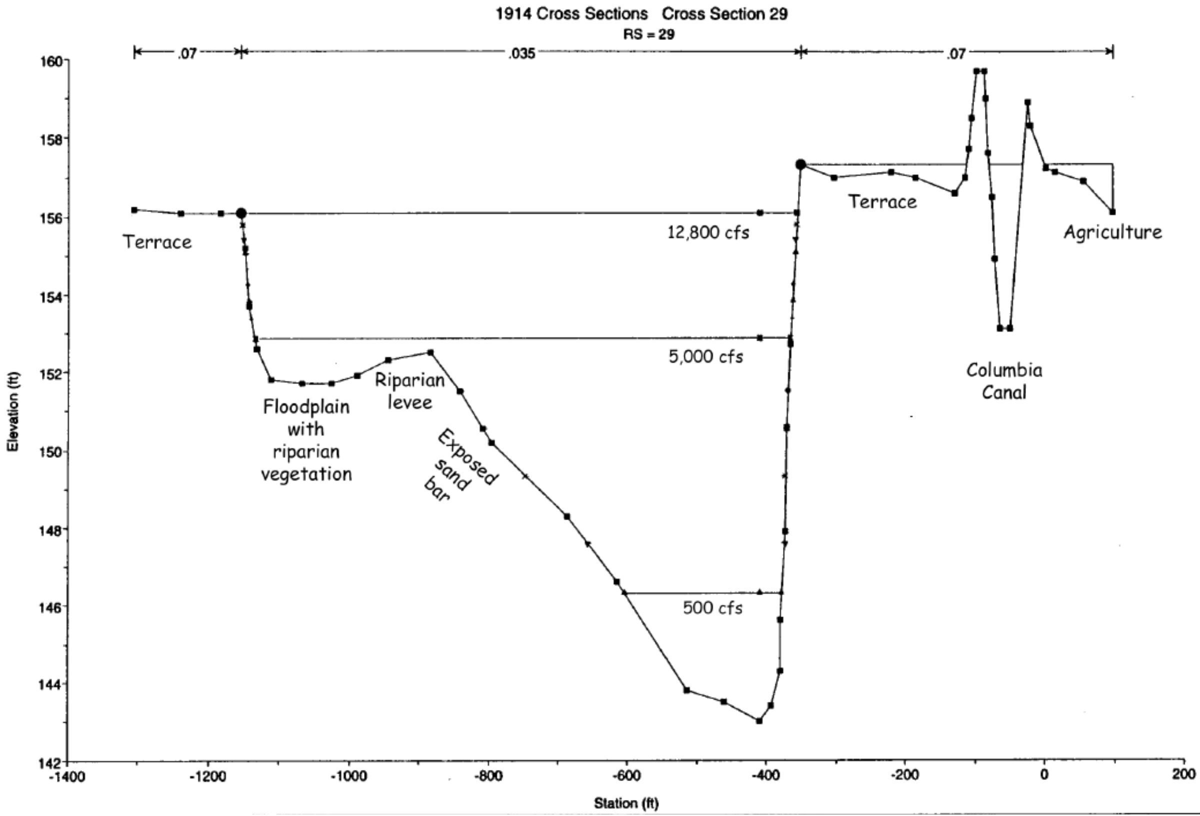


Figure 3-42. ACOE (1917) cross section 29 in Reach 3 (RM 201.6), showing predicted discharge thresholds to inundate key geomorphic surfaces in historic channel morphology.

3.7.4.1. Sediment Regime

Again, there has been no quantification of the historical sediment regime for Reach 4. Sediment supply was likely decreasing from Reach 3 through Reach 4 as it deposited on floodplains as the river flowed down the axis of the San Joaquin Valley. Review of 1914 cross sections suggests that unimpaired confinement and floodplain development decrease in the upper portions of Reach 4 (Figure 3-43), marking a transition from floodplains to the flood basins typical of Reach 4 and 5. The confining floodplains in the upper portions of Reach 4 transition into riparian levees along the primary channels in most of Reach 4. This transition is indicative of a cumulatively reduced sediment supply in the longitudinal direction; sediment supply is too small to create large-scale depositional floodplains, and sediment only accumulates along the rough vegetated boundaries of the primary channels. Areas behind the riparian levees remain low elevation tule marshes that had a small sediment supply. Within the primary channels, sediment routed through Reach 4 based on the 1914 ACOE maps, as evidenced by exposed sand bars in all reaches. Sediment appears to be transported and routed through the anabranching channels/sloughs in Reach 4, as the 1914 maps show exposed sand bars in the larger sloughs (e.g., Mariposa Slough, Pick Anderson Slough, Salt Slough).

Construction and operation of Chowchilla Bifurcation Structure has greatly reduced sediment supply to Reach 4, as flows and sediment are routed through the Chowchilla Bypass, and Mendota Dam may also cause temporary interruption of sediment routing from Reach 2 to Reach 4. Sack Dam, at the boundary between Reaches 3 and 4, may also divert some sediment from the San Joaquin River into Arroyo Canal, but because the capacity of Arroyo Canal is low (approximately 600 cfs), high flows

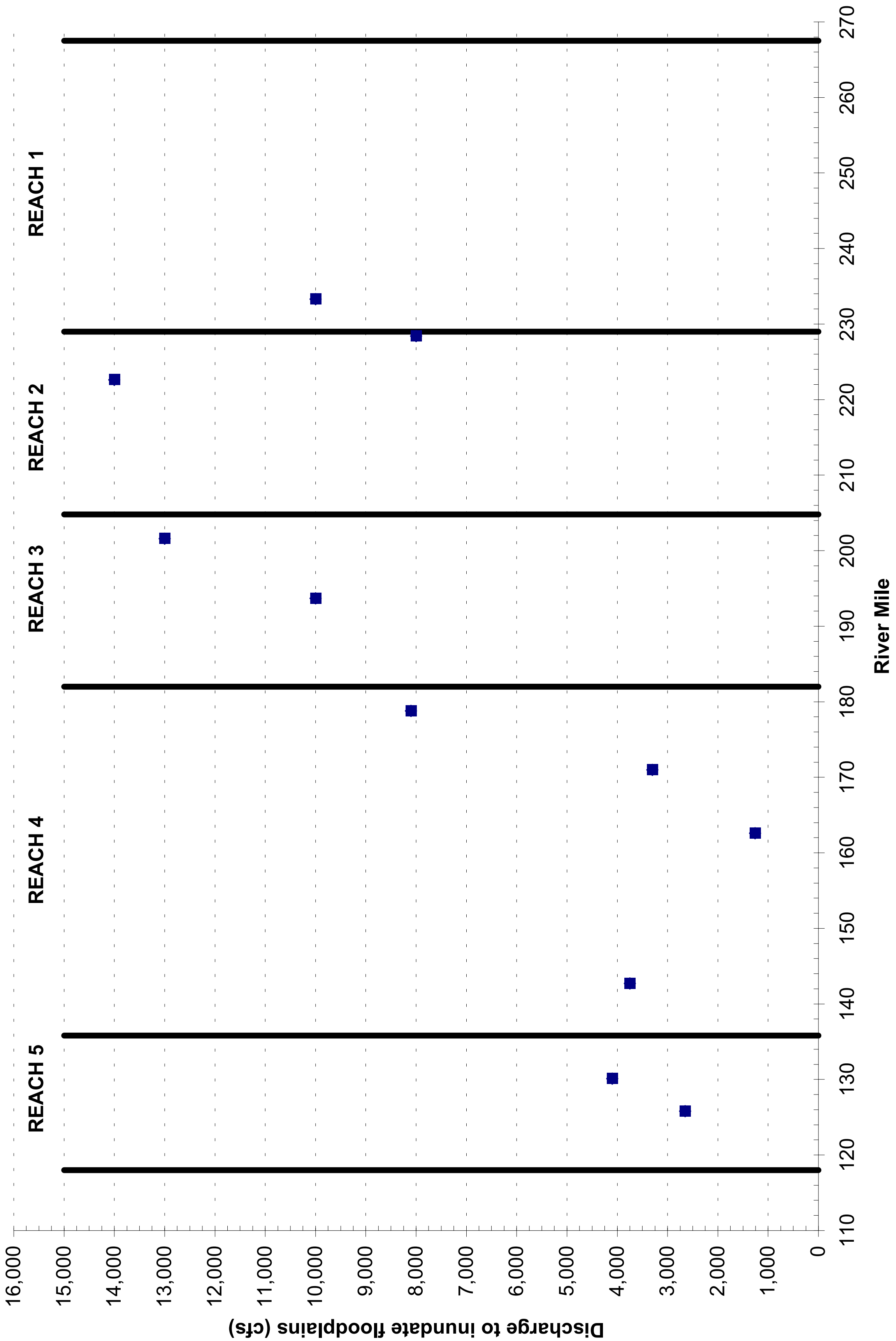


Figure 3-43. Longitudinal plot over Reach 1 to Reach 5 of flow threshold needed to initiate overbank flow on 1914 cross sections.

(and likely a majority of the sediment supply) route past Sack Dam into Reach 4A. The Sand Slough Control Structure, located at the boundary between Reach 4A and 4B, routes all flows and sediment into the Eastside Bypass, such that sediment supply into Reach 4B is zero. Mariposa Bypass delivers flow and sediment from Reach 4A and the bypass system back into Reach 4B. An undetermined amount of additional sediment is supplied to Reach 4B downstream of the Mariposa Bypass by (1) sediment derived from erosion of the Chowchilla and Eastside bypasses (JSA and MEI 1998), and (2) agricultural return flows in Reach 4B.

3.7.4.2. Fluvial Processes and Channel Morphology

The transition from Reach 3 to Reach 4 resulted in a small changes in channel slope, where Reach 3 channel slope is 0.00022, Reach 4A channel slope is 0.00028, and Reach 4B channel slope is 0.00022 based on 1914 surveys (Table 3-4). Additionally, valley slope remains similar, with a valley slope of 0.00033 in Reach 3, and valley slope in both Reach 4A and 4B of 0.00037. Longitudinal profiles of modeled water surfaces under current conditions estimate high flow gradient is 0.00023 in Reach 4A (Figure 3-44), and is approximately the same in the upper portion of Reach 4B (Figure 3-45) and lower portion of Reach 4B (Figure 3-46).

While the valley slope and channel slope does not significantly change between Reach 3 and Reach 4, channel morphology undergoes a transition in the upstream portion of Reach 4A. The moderately confined channel geometry typical of Reaches 2 and 3 transitions into the extensive flood basin morphology of much of Reach 4 and all of Reach 5. The channel confinement reduces the flow (such that overbank flows are much more frequent), riparian levees provide the channel confinement rather than the bankfull channel and floodplains, and numerous large-scale anabranching sloughs originate in the reach (Figure 3-47 and Figure 3-9). The 1914 maps also illustrate the narrow riparian levees along the primary channel margins, and the extensive marsh vegetation (tules) beyond the riparian levees (although outer boundaries are not noted). In the upstream portion of Reach 4, large point bars similar to those in Reach 3 still exist; however, after the confluence with Santa Rita Slough (RM 176.3), the size of the point bars decreases. Below Santa Rita Bridge, extensive areas of marsh designation are delineated on the 1914 maps. The marsh area continues for approximately 30 river miles, and the marsh area is typically mapped as being confined to the area between the mainstem and adjacent sloughs or canals. The channel form is simplified for this same 30-mile reach. The channel is narrow and relatively straight, with only a few point bars that are much smaller than the point bars mapped in upstream reaches. By the confluence with the Mariposa Slough at RM 148, oxbow lakes become a common feature and the channel has regained its large meander bends and unvegetated point bars. Again, these maps do not reflect unimpaired conditions, because extensive reclamation had already occurred by 1914.

The primary San Joaquin River channel and associated anabranching sloughs are sand-bedded. Exposed sand bars are still evident based on review of the 1914 maps, but they are much less extensive than Reach 2 and Reach 3. This reduction in exposed sand bar extent, and transition from extensive floodplains to smaller-scale riparian levees are indicative of the cumulative attrition of sediment supply by upstream deposition and lack of re-supply from tributaries or terrace erosion. Many of the large-scale sloughs are illustrated with exposed sand bars on the 1914 maps. The threshold for mobilizing the sand deposits in the channel was probably low (less than 1,000 cfs), but may have required a slightly larger discharge to mobilize than Reaches 2 and 3 due to smaller sediment supply and more cohesive finer-grained sediments. Larger flows (in the few thousands of cfs) also likely caused enough bar scour to prevent riparian encroachment onto the bars.

Channel morphology measurements of the sloughs were also made from the ACOE (1917) cross sections in Reaches 4A and 4B (Table 3-4). In Reaches 4B and 4A, the slough slopes were about 50%

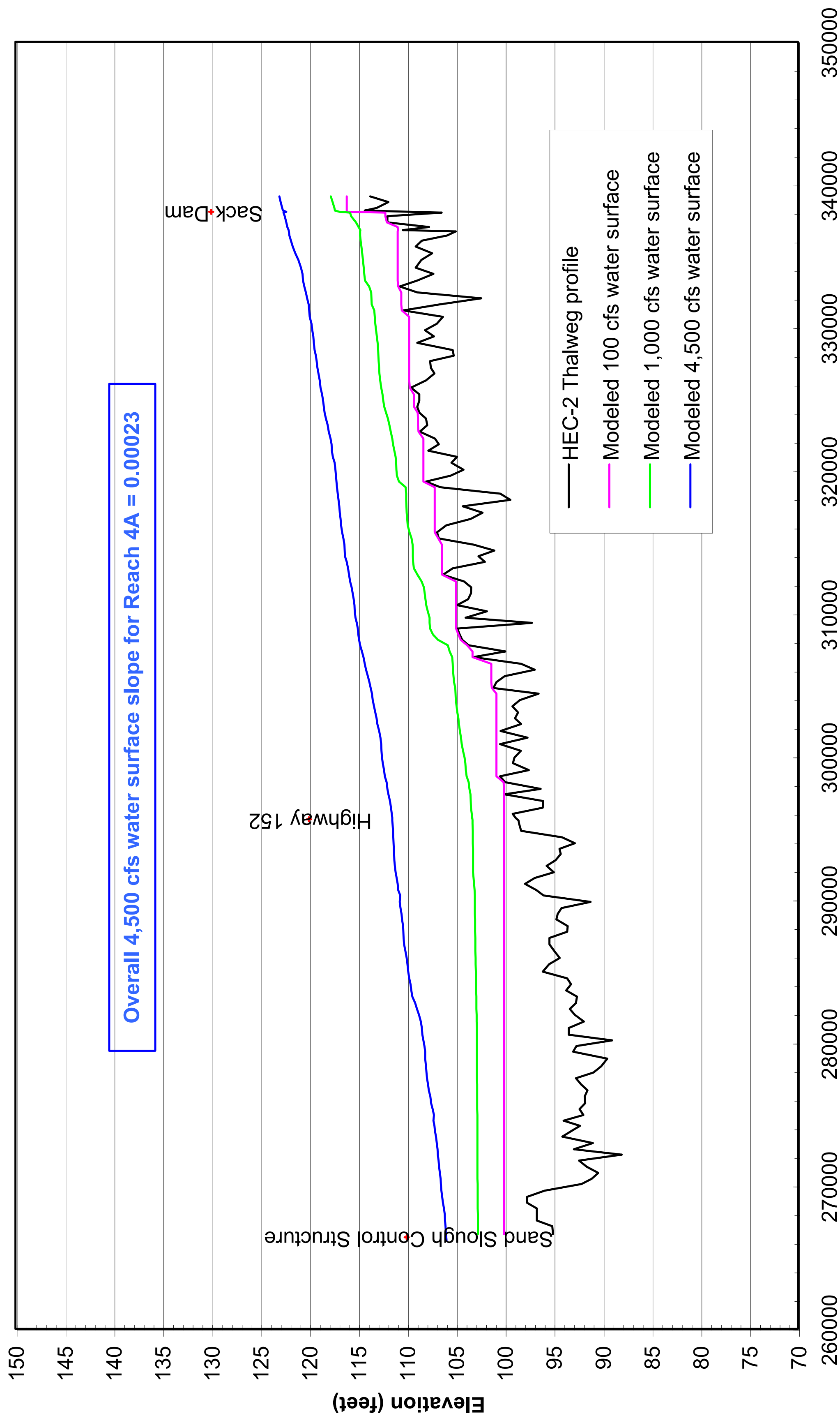


Figure 3-44. Reach 4A plot of thalweg and water surface profiles computed from HEC-2 hydraulic model with adjacent dike and levee elevations to compare computed reach capacities with advertised reach capacities. Upper graph (A) is from Sack Dam to the SR 152 Bridge, lower graph (B) is from the SR 152 Bridge to the Sand Slough Control Structure.

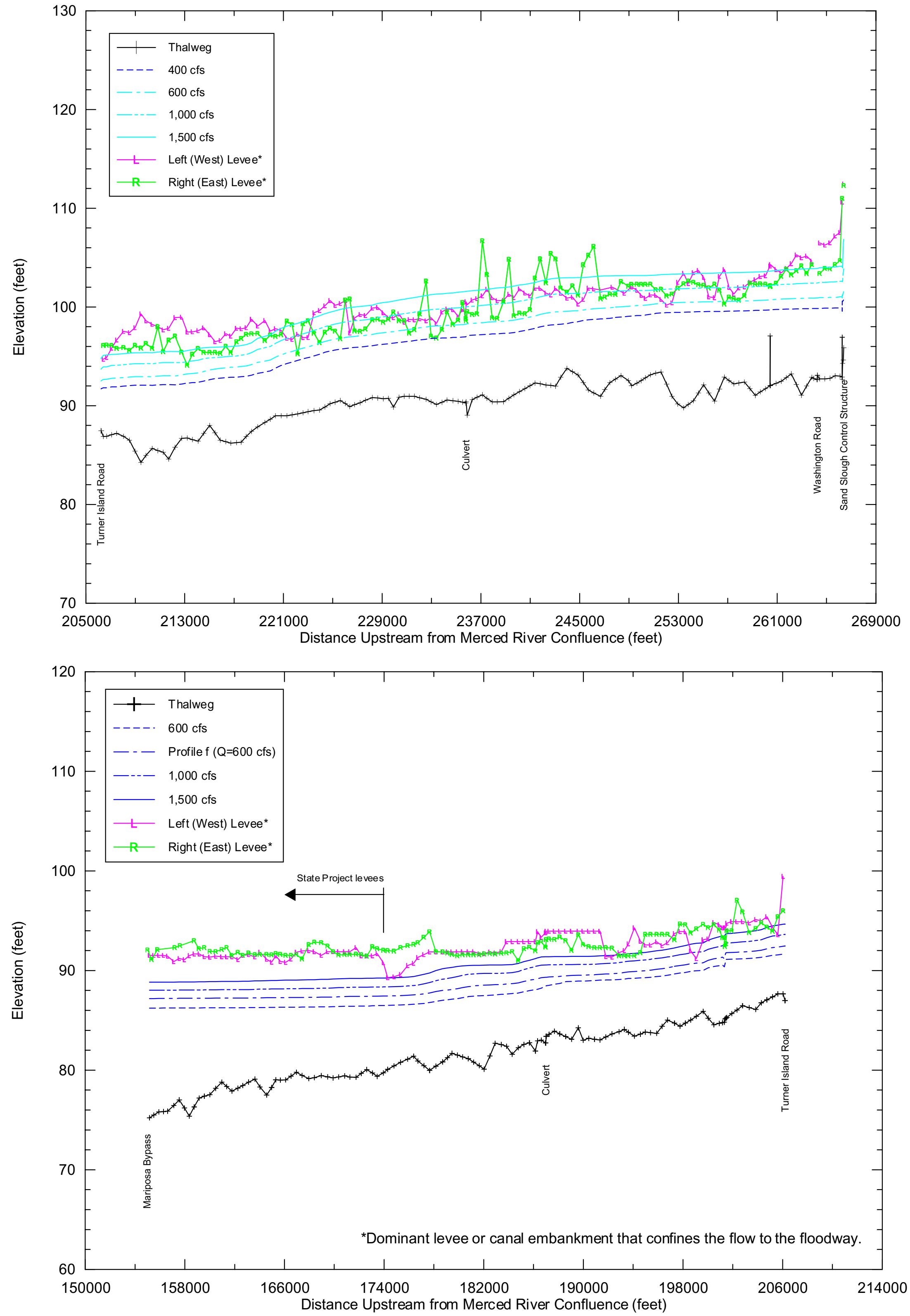


Figure 3-45. Upper portion of the Reach 4B plot of thalweg and water surface profiles computed from HEC-2 hydraulic model with adjacent dike and levee elevations to compare computed reach capacities with advertised reach capacities. Upper graph (A) is from Sand Slough Control Structure to the Turner Island Bridge, lower graph (B) is from the Turner Island Bridge to the Mariposa Bypass confluence.

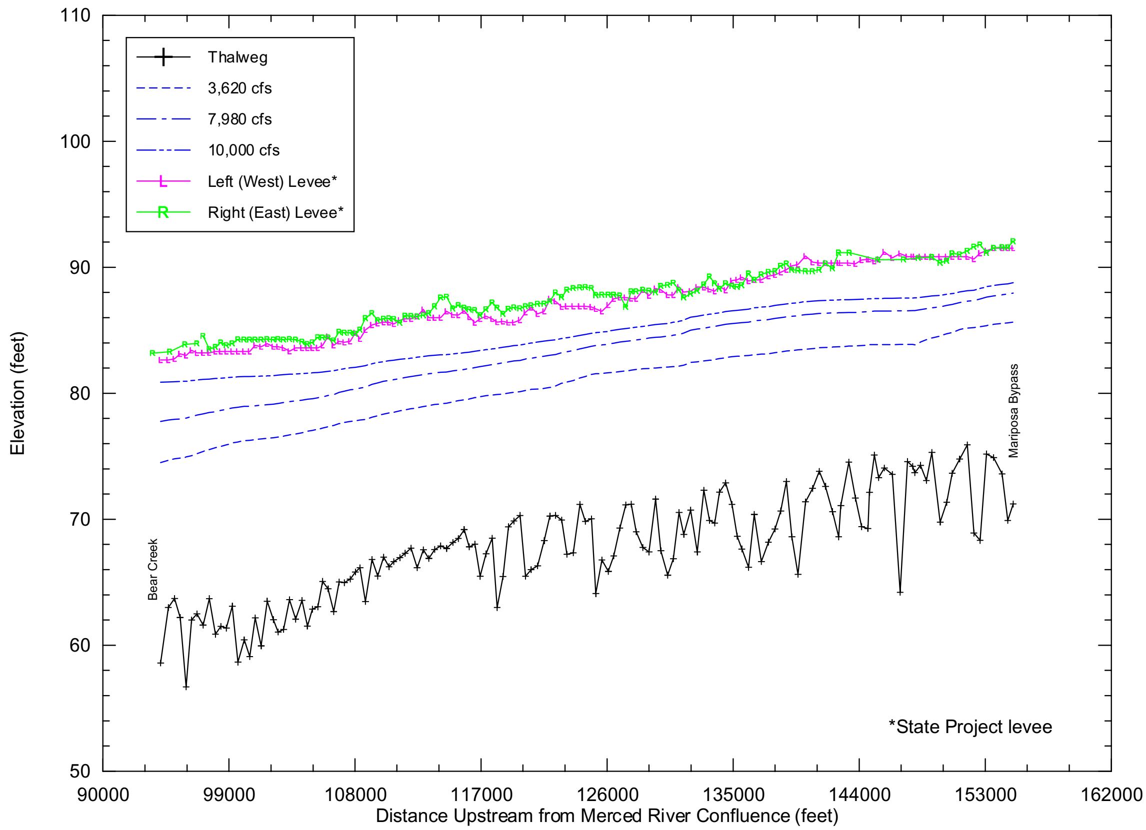


Figure 3-46. Lower portion of the Reach 4B plot of thalweg and water surface profiles computed from HEC-2 hydraulic model with adjacent dike and levee elevations to compare computed reach capacities with advertised reach capacities. Graph is from the Mariposa Bypass confluence to the Bear Creek and Eastside Bypass confluence.

steeper than the mainstem channel slope, which again is consistent with channel adjustment in an anabranched reach (Nanson and Huang 1997). Table 3-4 shows that the average widths and depths of the sloughs in Reaches 4A and 4B are less than those of the mainstem river. Width-depth ratios are similar for the sloughs and the mainstem, but because the sloughs are steeper, the sediment transport capacities of the sloughs were likely higher in these reaches (Colby 1964).

There is some uncertainty whether these sloughs flowed at low baseflows. Anabranching channels typically convey baseflows, and it is likely that the sloughs in Reach 4 conveyed winter baseflows and high summer baseflows. Review of the 1914 maps shows some of the sloughs as dry (noted as dry on the maps), the Santa Rita slough as dry via exposed sand bars at its entrance, but many other sloughs as flowing. Because of the extensive manipulation of the sloughs for agricultural irrigation efforts by 1914, the 1914 maps are of limited use in definitively concluding how these sloughs functioned during historic baseflows. One useful piece of evidence to suggest that these sloughs did flow during typical baseflows is an 1841 sketch map of the Santa Rita Ranch (Figure 3-48). This map clearly shows the Santa Rita Slough as a dominant channel feature of the lower river, as well as another slough between the Santa Rita Slough and the San Joaquin River. There is no precise date or general season noted on the map; however, it is assumed that the mapping would have been conducted when land-based travel through the extensive bottomlands and tule marshes would have been easiest, which would have been during late summer or fall baseflows rather than during winter or spring snowmelt floods.

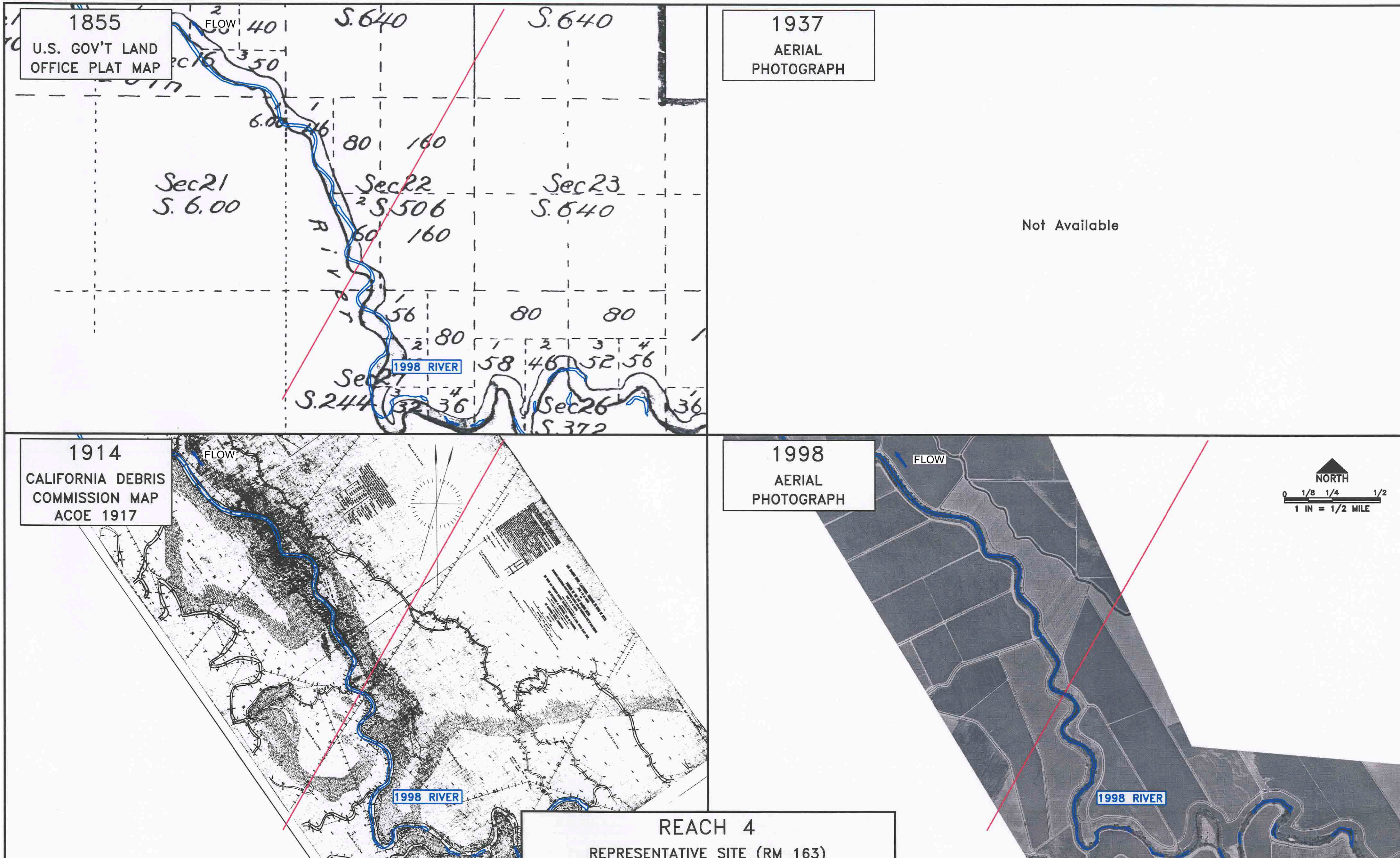


Figure 3-47. Example planform evolution in Reach 4 (RM 163), showing 1855 plat map, 1914 CDC map, and 1998 air photo.

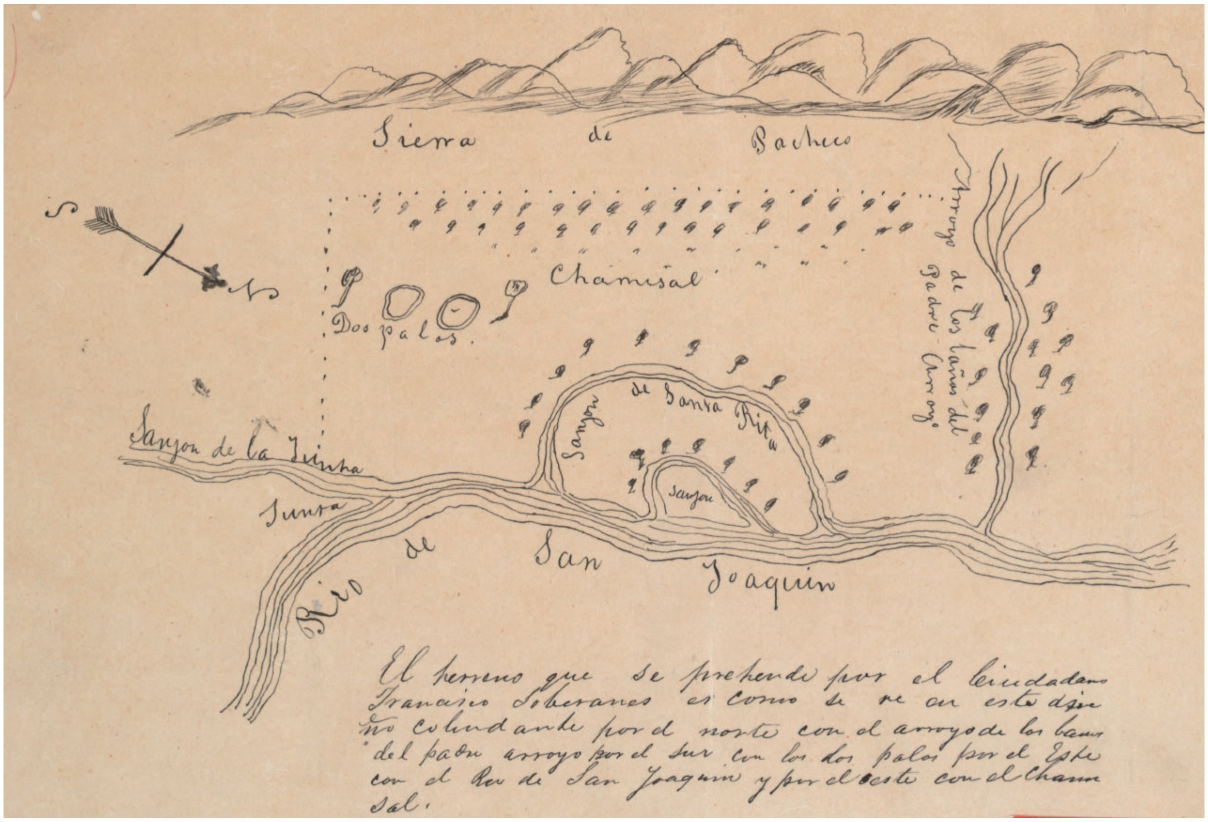


Figure 3-48. 1841 sketch of Rancho Santa Rita, suggesting that Santa Rita Slough and others were flowing at typical baseflows. There is no precise day or season of the sketch; it is assumed that the sketch would be made during a time when travel across the valley would have been easiest (summer baseflows) rather than during the winter flood season.

Historical channel migration and avulsion were likely very slow and infrequent, and probably less frequent than in Reaches 2 and 3 due to the low sediment supply and low stream energy as high flows spilled out into the flood basins. Comparison of the 1855 maps with 1914 maps and 1998 aerial photographs show virtually no change in channel location over that time (Figure 3-47). The 1855 map for this reach had poor control points, so the exact location of the channel needs to be adjusted by eye. The most dramatic change that has occurred since 1855 has been the complete reclamation of the flood basin to agriculture. The San Joaquin River and its flood basin extended for miles in both directions in Reaches 4 and 5; the contemporary floodway in this reach under current conditions (excluding the Eastside Bypass) is now less than 300 feet in most locations. Photos of these more confined conditions are illustrated in Figure 3-49 through Figure 3-51. Figure 3-49 shows the present-day channel in Reach 4A. Sack Dam typically diverts all flows up to 600 cfs from the San Joaquin River, such that flows in Reach 4A are typically limited to seepage and agricultural return flows (which are subsequently pumped from the river and re-used). Sack Dam allows high flows to route to Reach 4A, but the lack of baseflows discourages riparian vegetation on floodplains (Figure 3-49). The Sand Slough Control Structure, located at the boundary between Reach 4A and Reach 4B, diverts all flow into the Eastside Bypass, such that Reach 4B no longer receives any flows (Figure 3-50). The remaining portions of the San Joaquin River channel in Reach 4B is often choked with riparian vegetation because flows are no longer routed through the upper portion of the reach. Further downstream in Reach 4B, agricultural return flows and the confluence of the Mariposa Bypass return flows to the channel (Figure 3-51).

Figure 3-49. View looking upstream at sediment deposition in the bed of the San Joaquin River at about RM 175. Much of the sand appears to be derived from bank erosion. The within-levee capacity in this reach of the river is about 4,500 cfs. From JSA and MEI (1998).

Changes in bankfull width and depth are estimated by comparing the 1914 cross sections with 1998 resurveys (Table 3-5). Two cross sections were compared for Reach 4A; cross section 48 at RM 178.8, and cross section 53 at RM 171.0. Channel width changes at cross sections 53 and 48 show opposing trends. Channel width at cross section 48 decreased from 360 feet in 1914 to 279 feet in 1998, and channel width at cross section 53 increased from 160 feet in 1914 to 234 feet in 1998. Changes in depth were inconsistent. Channel depth at cross section 48 decreased slightly from 11.0 feet in 1914 to 9.8 feet in 1998, and channel depth at cross section 53 increased slightly from 16.0 feet in 1914 to 18.0 feet in 1998. Two additional cross sections were compared for Reach 4B; cross section 58 at RM 162.6, and cross section 70 at RM 142.7. Channel width changes at cross sections 53 and 48 again show opposing trends. Channel width at cross section 58 decreased from 230 feet in 1914 to 143 feet in 1998, and channel width at cross section 70 increased from 210 feet in 1914 to 259 feet in 1998. Changes in depth were also inconsistent. Channel depth at cross section 58 increased slightly from 7.70 feet in 1914 to 8.5 feet in 1998, and channel depth at cross section 53 decreased from 13.0 feet in 1914 to 7.6 feet in 1998. The cause of channel width and depths are unclear; it may be caused by locally variable manipulation of channel geometry as part of agricultural or levee maintenance activities.

Thalweg elevations for three of the four cross sections in Reach 4 have decreased slightly, with one cross section showing a substantial increase in elevation (Table 3-6). Cross sections 48, 53, and 58

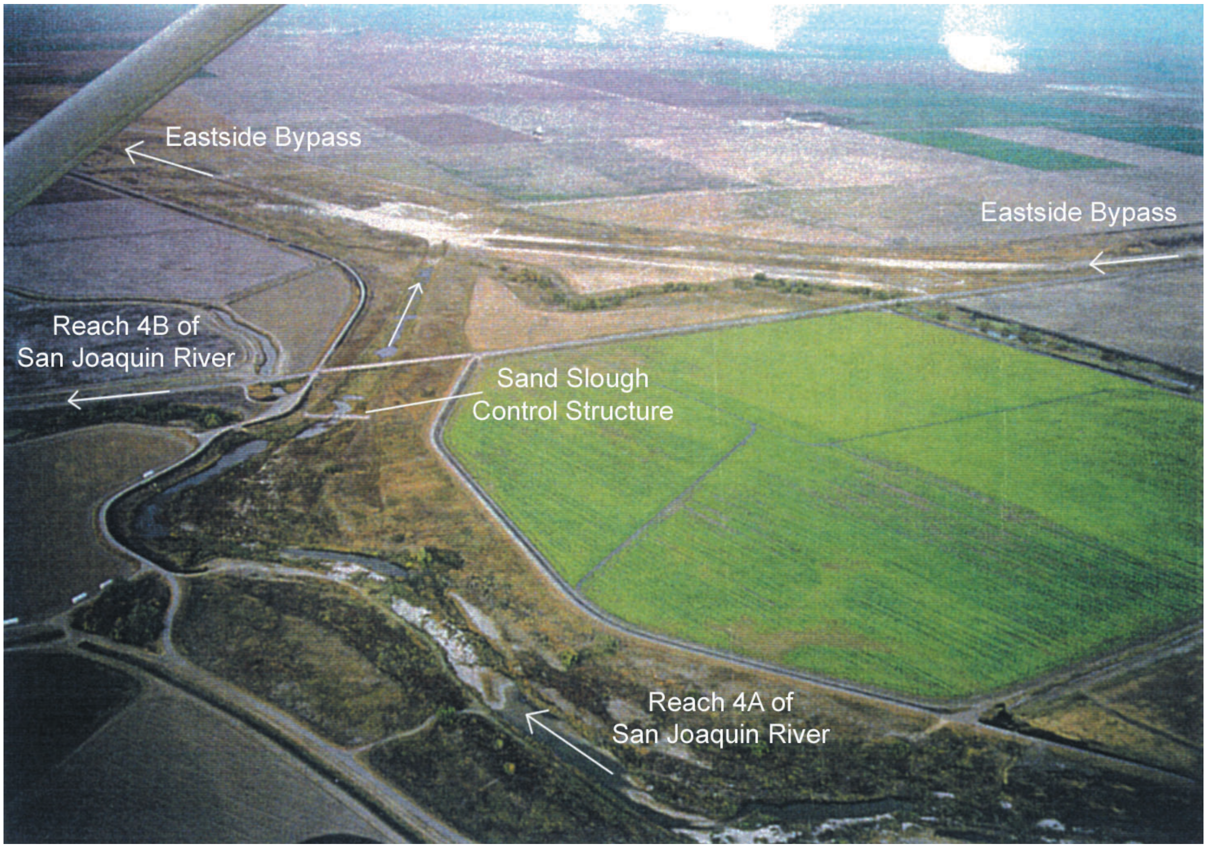


Figure 3-50. View looking downstream at the Sand Slough control structure reach of the San Joaquin River at RM 168. The San Joaquin River upstream of the structures bifurcates into San Joaquin River (left channel, well vegetated banks), Sand Slough (center channel, unvegetated banks), and the Eastside Bypass. Note sediment deposit deposition in the bypass channel. Design capacity of the bypass channel is about 16,500 cfs. From JSA and MEI (1998).

degraded by 3.9 feet, 2.2 feet, and 1.0 feet, respectively, while cross section 70 aggraded 6.7 feet. The small amount of channel degradation at cross sections 48, 53, and 58 may be caused by the small amount of subsidence in this reach. Degradation at cross sections 48 and 53 in Reach 4A may also be influenced by a combination of reduced sediment supply from upstream sources, and increased transport capacity due to levee confinement. Cross section 58 is located in a portion of Reach 4B that no longer receives flood flows, so fluvial causes of degradation are unlikely. Cross section 70 is downstream of the Mariposa Bypass confluence, so sediment derived from erosion of the Eastside Bypass may be depositing in this portion of Reach 4B, causing the aggradation.

3.7.4.3. Historic Inundation Thresholds

JSA and MEI (1998) estimated historical inundation patterns for Reach 4 by applying a normal depth analysis with the HEC-RAS hydraulic model to a subset of 1914 cross sections assumed to be representative of the reach. Two cross sections were analyzed in Reach 4A, and two cross sections were analyzed in Reach 4B. The analysis of cross section 48 at RM 201.6 (Reach 4A) suggests that the floodplains on both banks are inundated by a flow of 8,100 cfs. In contrast, cross section 53 at RM 171.0 (Reach 4A, just 8 miles downstream) shows that the floodplains on both banks are inundated

Figure 3-51. View looking upstream at the San Joaquin River at Turner Island Road crossing, RM 157. Design capacity of the channel and levees is about 1,500 cfs; however, actual capacity in many portions of this reach is much less. From JSA and MEI (1998).

by a flow of 3,300 cfs. Analysis of cross section 58 at RM 162.6 (Reach 4B) shows that the floodplain on both banks are inundated by a flow of 1,260 cfs (Figure 3-52), and floodplains at cross section 70 at RM 142.7 are inundated by a flow of 3,750 cfs. Terraces do not exist in this reach. The inundation thresholds for the latter three cross sections are consistently lower than all the upstream cross sections. This is most likely documenting the transition into the Reach 4 and Reach 5 flood basin. Moderate confinement by the bankfull channel and floodplain decreases at the upstream end of Reach 4, and downstream reaches are inundated by moderate flows at a very frequent recurrence interval (<1.2-year flood).

3.7.5. Reach 5

Reach 5 extends from the Bear Creek/Eastside Bypass confluence (RM 135.8) to the Merced River confluence (RM 118.0) (Figure 3-2). Reach 5 continues to flow north along the axis of the San Joaquin Valley. Reach 5 was within the extensive flood basin of the lower San Joaquin River and had numerous anabranching sloughs that conveyed summer and winter baseflows along with the primary San Joaquin River channel. The reach is entirely alluvial, with the Merced River alluvial fan entering at the downstream end of Reach 5 and influencing base level control of the river (JSA and MEI 1998). Riparian levees provided moderate confinement of the river on both banks, with extensive tule marsh flood basins beyond the riparian levees.

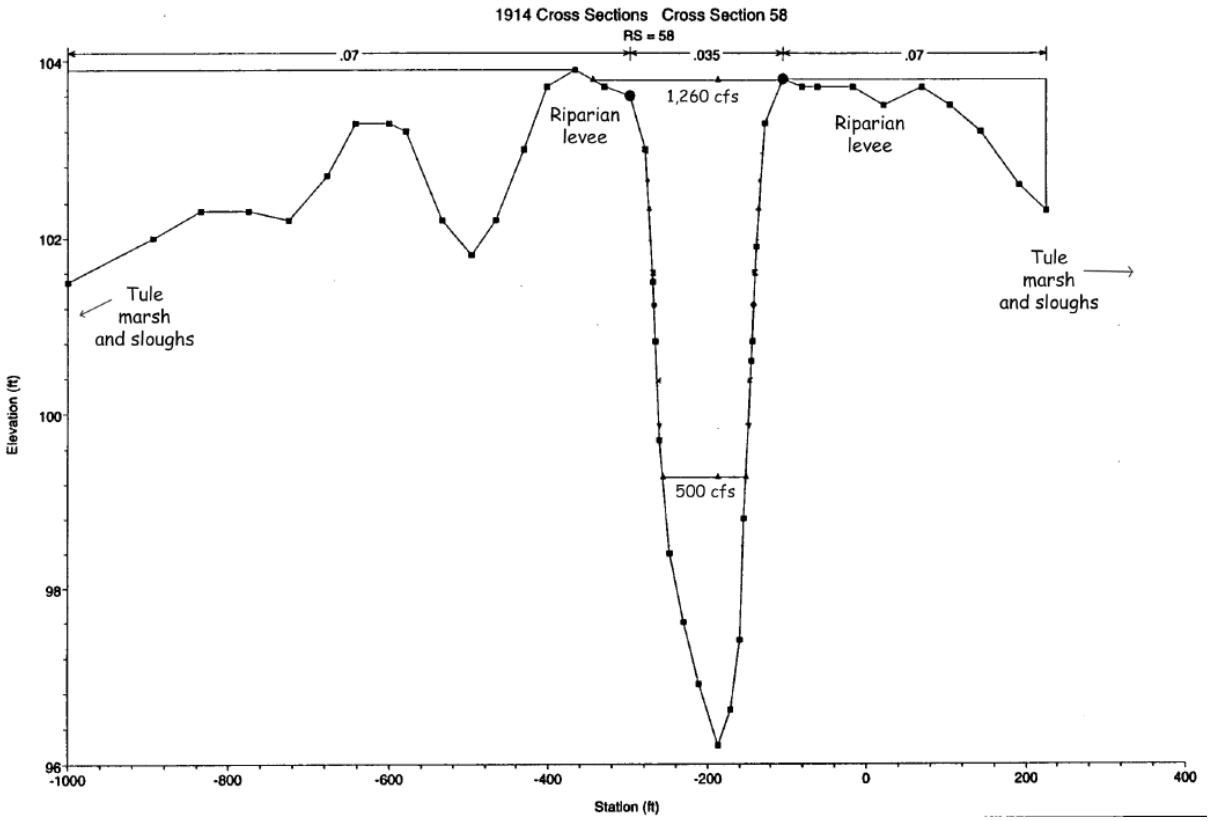


Figure 3-52. ACOE (1917) cross section 58 in Reach 4B (RM 162.6), showing predicted discharge thresholds to inundate key geomorphic surfaces in historic channel morphology.

3.7.5.1. Sediment Regime

Again, there has been no quantification of the historical sediment regime for Reach 5. Historical sediment supply delivered to Reach 5 from Reach 4 likely continued to be low as it deposited on riparian levees adjacent to primary channels of the San Joaquin River. Review of 1914 cross sections show that unimpaired confinement and floodplain development is low in all portions of Reach 5 (Figure 3-43), typical of the riparian levees and flood basin morphology of Reach 4 and Reach 5. Areas behind the riparian levees remain low elevation tule marshes with low sediment supply. Within the primary channels, sediment routed through Reach 4 based on the 1914 ACOE maps, as evidenced by exposed sand bars in all reaches. Sediment transport and routing through the anabranching channels/sloughs appeared to occur in Reach 5 as well as Reach 4, as several of the sloughs on the 1914 maps show exposed sand bars, particularly on the lower portions of Salt and Mud sloughs.

The cumulative impacts of upstream structures (Chowchilla Bifurcation Structure, Mariposa Bifurcation Structure, Sack Dam, etc.), as well as the reduction in sediment supply by Friant Dam, has reduced sediment supply to Reach 5. However, sediment contribution from agricultural return flows along the river and from Mud and Salt sloughs, as well as erosion of the bypass system, has likely increased sediment supply to Reach 5. The net effect on the sediment regime in Reach 5 is therefore unknown.

3.7.5.2. Fluvial Processes and Channel Morphology

The transition from Reach 4 to Reach 5 again results in minor changes in channel slope, where Reach 4B channel slope is 0.00022, Reach 5 channel slope is 0.00021 based on 1914 surveys (Table 3-4). Additionally, valley slope remains similar, with a valley slope of 0.00037 in Reach 4B and valley slope in Reach 5 of 0.00036. Longitudinal profiles of modeled water surfaces under current conditions predict a consistent high flow gradient from the upstream end of Reach 5 downstream to Fremont Ford, downstream of which the slope flattens as the San Joaquin River approaches the Merced River confluence (Figure 3-53).

The valley and channel slopes do not significantly change between Reaches 3 and 4, and historic channel morphology appears to be very similar between Reaches 4 and 5. The extensive flood basin morphology of Reach 4 continues through Reach 5 to the Merced River confluence. The additional sediment supply provided by the Merced River, as well as removal of a downstream base level control downstream to the tidal zone, eliminated the flood basin morphology downstream of Reach 5, and extensive floodplains are again evident between the Merced River and the Stanislaus River. The low channel confinement continues in Reach 5, such that overbank flows are frequent, and riparian levees provide some limited channel confinement rather than the bankfull channel and floodplains. Many of the numerous large-scale anabranching sloughs that originated in Reach 4 converge back to the San Joaquin River in Reach 5 (e.g., Mud Slough, Salt Slough). The 1914 maps continue to illustrate the narrow riparian levees along the primary channel margins, and the extensive marsh vegetation (tules) beyond the riparian levees (although outer boundaries are again not noted) (Figure 3-54 and Figure 3-10). Small scale exposed point bars are still evident in the primary San Joaquin River channel in Reach 5, and small bars are also evident on some of the sloughs (Figure 3-10). There are many side channel and sloughs that connect meanders to one another. Salt Slough has more than one confluence with the mainstem, and in other areas it appears that the two channels could be connected during high flow events. Oxbow lakes are a common feature throughout much of Reach 5, and the channel has large, highly sinuous, irregular meander bends. Compared to the agricultural development in Reach 4, the Reach 5 maps show less agricultural development; however, these maps should not be interpreted to precisely represent “unimpaired conditions”.

As with Reach 4, the threshold for mobilizing the sand deposits in the channel is probably low (less than 1,000 cfs), and again may require a slightly larger discharge to mobilize than Reaches 2 and 3 due to lower slope, smaller sediment supply, and more cohesive finer-grained sediments. Larger flows (in the few thousands of cfs) also have likely caused enough bar scour to prevent riparian encroachment onto the bars.

Of all reaches in the San Joaquin River study area, Reach 5 is the least disturbed. Large tracts of public lands (Fremont Ford State Park and San Luis Wildlife Refuge) encompass much of Reach 5, and agricultural reclamation of these lands has been limited compared to upstream reaches. While these lands are largely managed differently than under unimpaired conditions (waterfowl habitat), much of the natural channel morphology remains (Figure 3-55). Remnant abandoned channels, scroll bars, and riparian vegetation are common in much of Reach 5.

Changes in bankfull width and depth are again estimated by comparing the 1914 cross sections with 1998 resurveys (Table 3-5). Two cross sections were compared for Reach 5; cross section 78 at RM 130.1, and cross section 85 at RM 125.8. Channel width has increased at both cross sections; width at cross section 78 increased from 200 feet in 1914 to 295 feet in 1998, and channel width at cross section 85 increased slightly from 370 feet in 1914 to 374 feet in 1998. Channel depth at cross section 78 increased substantially from 9.6 feet in 1914 to 15.5 feet in 1998, and channel depth at cross section 85 remained virtually unchanged at 25 feet. The width-depth ratio remained essentially the same at cross section 78 (21 versus 19). The changes in width and depth at cross section 78

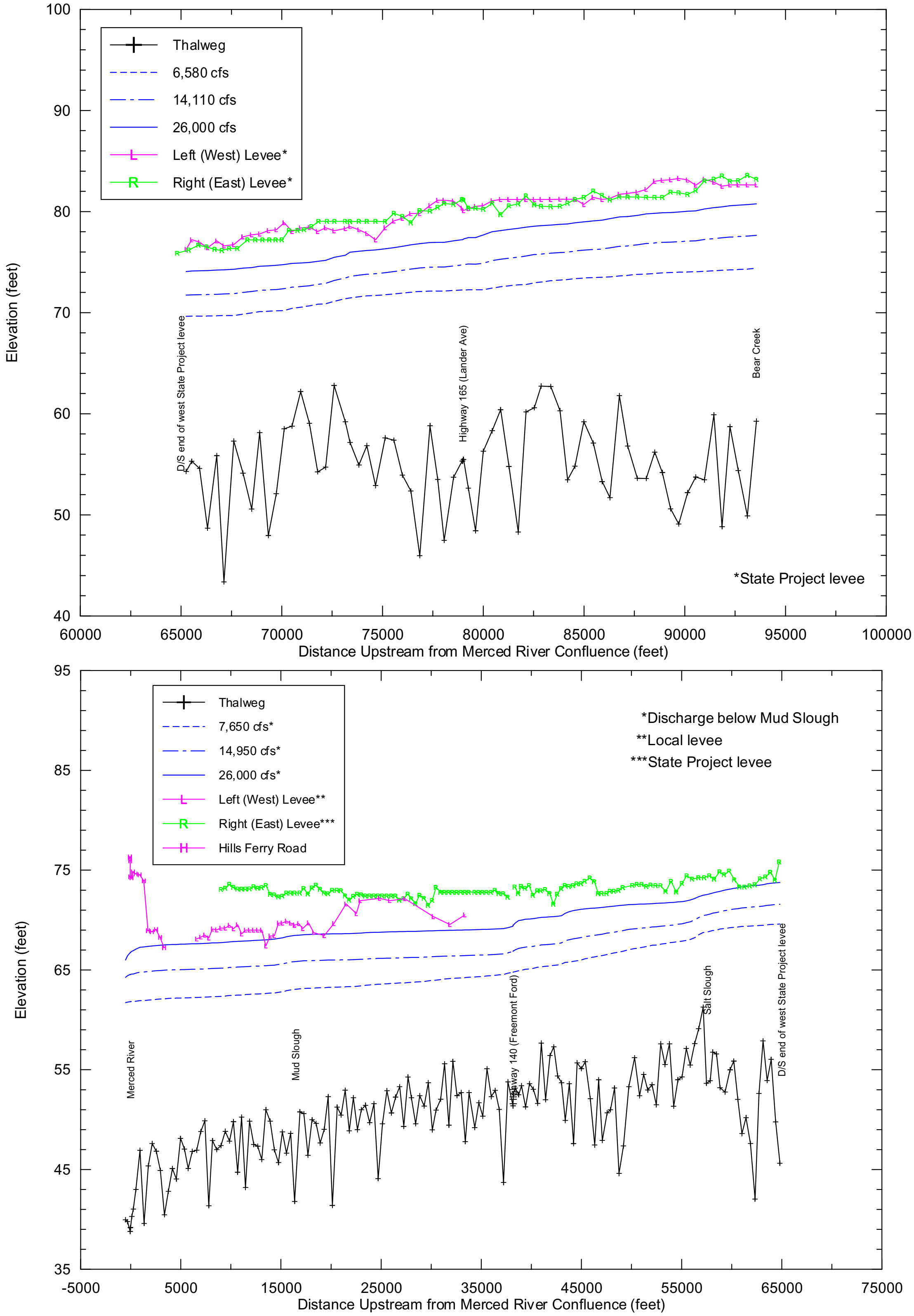


Figure 3-53. Reach 5 plot of water surface profiles computed from HEC-2 hydraulic model with adjacent dike and levee elevations to compare computed reach capacities with advertised reach capacities. Upper graph (A) is from Bear Creek and Eastside Bypass confluence to the end of the project levee on the left (west) bank of the river, lower graph (B) is from the end of the project levee on the left (west) bank of the river to the Merced River confluence.

could be the result of the hydrological changes imposed by the bypass system. Historically, the flows were distributed at this latitude among the sloughs and the San Joaquin River. The Eastside Bypass now conveys a large portion of flood flows to a point at the head of the reach where flood flows are discharged back to the San Joaquin River. The concentration of flows in this area, as well as the reduction in flood peak attenuation by loss of the historic flood basin, may be partially responsible for the increased channel size. There is no apparent physical manipulation of channel geometry for either cross section that would cause this change in width and depth between the two periods.

Thalweg elevations for three cross sections were compared between 1914 and 1998 (Table 3-5). Cross sections 78 degraded by 8.5 feet, cross section 81 aggraded 2.0 feet, and there was no change at cross section 85. Cross section 85 is at the mouth of the Merced River and thus reflects combined conditions between the two rivers. The substantial amount of channel degradation at cross section 78 may be caused by the concentration of high flows from the bypass system, which would be consistent with the increase in channel size at this location. Changes in thalweg elevation at cross sections 81 and 85 are minor.

3.7.5.3. Historic Inundation Thresholds

JSA and MEI (1998) estimated historical inundation patterns for Reach 5 by applying a normal depth analysis with the HEC-RAS hydraulic model to a subset of 1914 cross sections assumed to be representative of the reach. Two cross sections were analyzed in Reach 5. Analysis of cross section 78 at RM 130.1 suggests that the floodplain on the right bank is inundated by a flow of 4,100 cfs and the riparian levee on the left bank is overtopped by a flow of approximately 5,100 cfs. Analysis of cross section 81 at RM 125.8 shows that the floodplain on the right bank is inundated by a flow of approximately 2,400 cfs, and the floodplain on the left bank inundated at a discharge slightly larger than 2,650 cfs (Figure 3-56). Terraces do not exist in this reach, with the exception of near the Merced River delta. The inundation thresholds for these two cross sections are consistent with the lower three in Reach 4, again reflecting the low flow threshold required for inundation of the flood basin in Reaches 4 and 5. The flood magnitude required to inundate flood basins in Reaches 4 and 5 is moderate, and occurred at a very frequent recurrence interval (<1.2-year flood). The Fremont Ford gaging station had an insufficient pre-Friant Dam period of record to be more precise on the flood recurrence estimate needed to cause overbank flows.

3.8. HISTORICAL CHANNEL MORPHOLOGY CONCEPTUAL MODELS

Based on the limited anecdotal and quantitative historical information, and more recent quantitative information, descriptions and conceptual models of channel form and processes are developed for each reach in the following sections. These sections attempt to summarize available information collected to date on a reach-by-reach basis. These conceptual models focus on the relationship between historical channel geometry, fluvial processes, and hydrograph components. In other words, “What surfaces were inundated by different parts of the unimpaired flow regime, and what geomorphic processes occurred during those flows?” Each conceptual model is based on a representative historic cross section obtained from the ACOE surveying effort in 1914-1915 (ACOE 1917). These conceptual models are also developed based on the hydraulic modeling results on the 1914 cross sections, review of 1937 aerial photographs, field observations, pre-Friant Dam hydrology (see Chapter 2), and the general understanding of gravel-bedded and sand-bedded rivers (Figures 3-57 through 3-61). The conceptual cross sections are located within the example planform series for each reach (Figures 3-22, 3-36, 3-39, 3-47, and 3-54). These cross sections are also used in Chapter 8 to develop similar conceptual model of historic relationships between hydrology, channel morphology, and riparian vegetation for each reach.

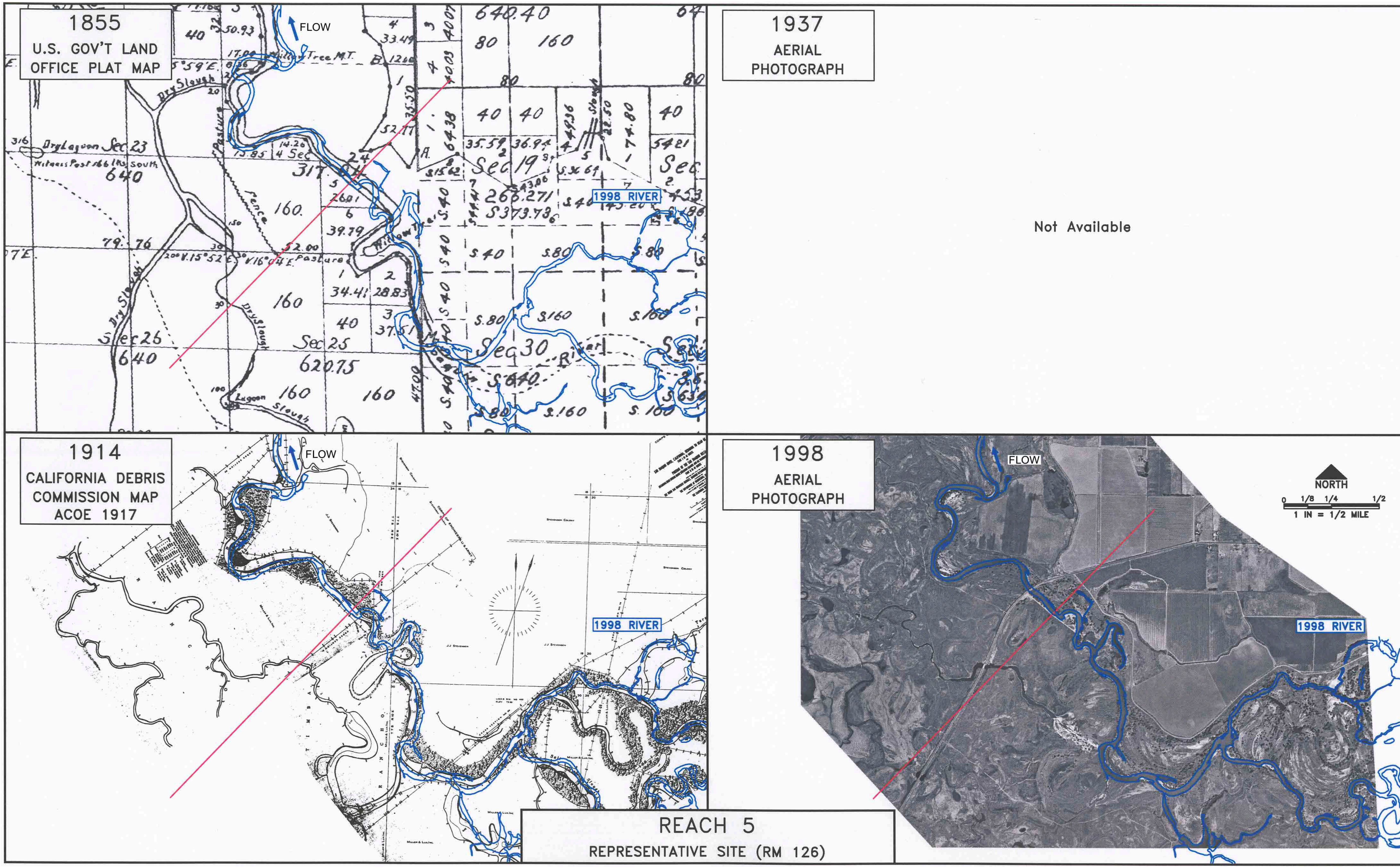


Figure 3-54. Example planform evolution in Reach 5 (RM 126), showing 1855 plat map, 1914 CDC map, and 1998 air photo.

Figure 3-55. View looking downstream at confluence of Salt Slough (left channel) and San Joaquin River at RM 127.7. Note the multiple anabranch channels(sloughs)and the meander scroll topography on the floodplain. From JSA and MEI (1998).

In addition to the conceptual cross section, a pre-Friant Dam hydrograph was chosen to help related hydrograph components to fundamental fluvial processes and inundation of geomorphic surfaces. The water year 1938 hydrograph was chosen because (1) it is an Extremely Wet year that has high winter floods as well as a large snowmelt hydrograph that likely exceeded many fluvial process thresholds, and (2) gaging stations at Friant and Fremont Ford documented flows at the upstream and downstream ends of the study reach for this water year. Because we wished to illustrate how conceptual flow-geomorphology relationships change among the five reaches, we needed to estimate how the 1938 hydrographs changed through the reaches, as there were no other gaging stations available other than the Friant and the Fremont Ford stations. In order to approximate flows in each reach, hydrographs for Reaches 2, 3, and 4 were "interpolated" between the Reach 1 hydrograph at Friant and the Reach 5 hydrograph at Fremont Ford (Figure 3-62). This was done by assigning a portion of the total peak flow lag time between the two stations (9 days) to each reach (i.e., 2-day lag for Reach 2, 4-day lag for Reach 3, and 7-day lag for Reach 4). The longer lag was given to Reach 4 due to its long length and it marks the beginning of the flood basin that would have greatly attenuated flood peaks. We know that between these two gaging stations, flood peaks attenuated, tributaries augmented flows (Fresno Slough, Orestimba Creek, Fresno River, Chowchilla River, and Bear Creek), and diversions occurred for irrigation. Additionally, some flows periodically bypassed the Fremont Ford gage through Salt Slough during periods of high flow, based on the USGS gaging station summary. Regardless of these uncertainties, the hydrographs give a general illustration of how a wetter year annual hydrograph would have adjusted longitudinally along the San Joaquin River.

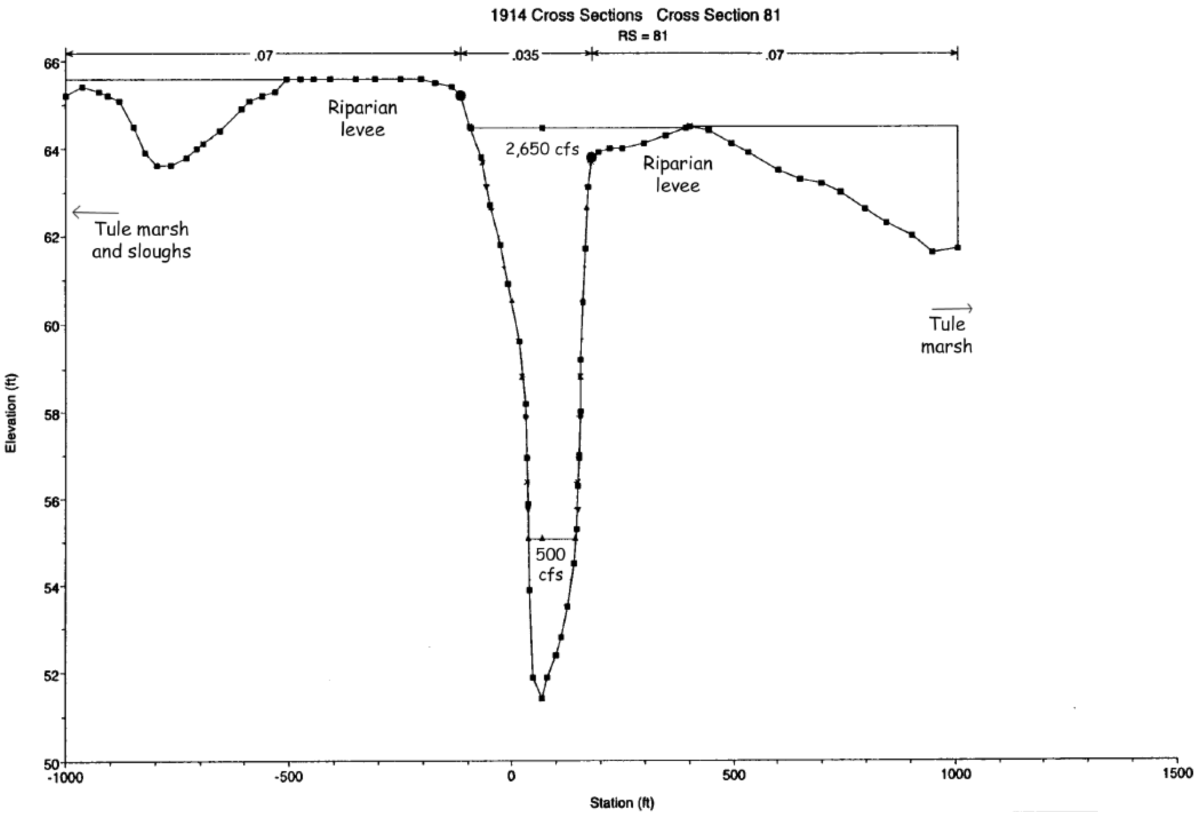


Figure 3-56. ACOE (1917) cross section 81 in Reach 5 (RM 125.8), showing predicted discharge thresholds to inundate key geomorphic surfaces in historic channel morphology.

These conceptual models are largely qualitative due to the limited historical information on the reach, and not intended to serve as the definitive argument on how Reach 1 functioned under unimpaired conditions, but can serve as a beginning point in understanding how the historic channel functioned. Furthermore, this conceptual model is not intended to serve for specific restoration goals per se, but to provide insights on how the river historically functioned that may improve and help guide future restoration efforts.

3.8.1. Reach 1

Figure 3-57 illustrates a conceptual cross section at river mile 259, which is shown on Figure 3-22). The cross section illustrates the primary channel, plus a side channel that flows during high summer baseflows and typical winter baseflows. The channel bed is comprised of cobbles and gravels, and because the slope in Reach 1 of the San Joaquin River is lower than other regional rivers exiting the foothills of the Sierra Nevada, the threshold for bed mobility is likely equal to or larger than the bankfull discharge (10,000 cfs to 16,000 cfs). Bed scour would have required an even larger flood event, perhaps near the discharge that would be required to initiate channel migration or channel avulsion. The threshold for initiating channel migration or avulsion in Reach 1 is unknown, but is likely equal to or larger than the 45,000 cfs indicated on Figure 3-57. The bankfull discharge begins inundating floodplains and high flow scour channels, and the 1914 cross sections suggest that the bankfull discharge is approximately 10,000 cfs. This corresponds to the pre-Friant Dam 1.5-year flood of 10,200 cfs (see Figure 2-5). This conceptual figure illustrates that floodplains were likely inundated for short periods of time during winter floods (days), and a bit longer for the snowmelt peak runoff

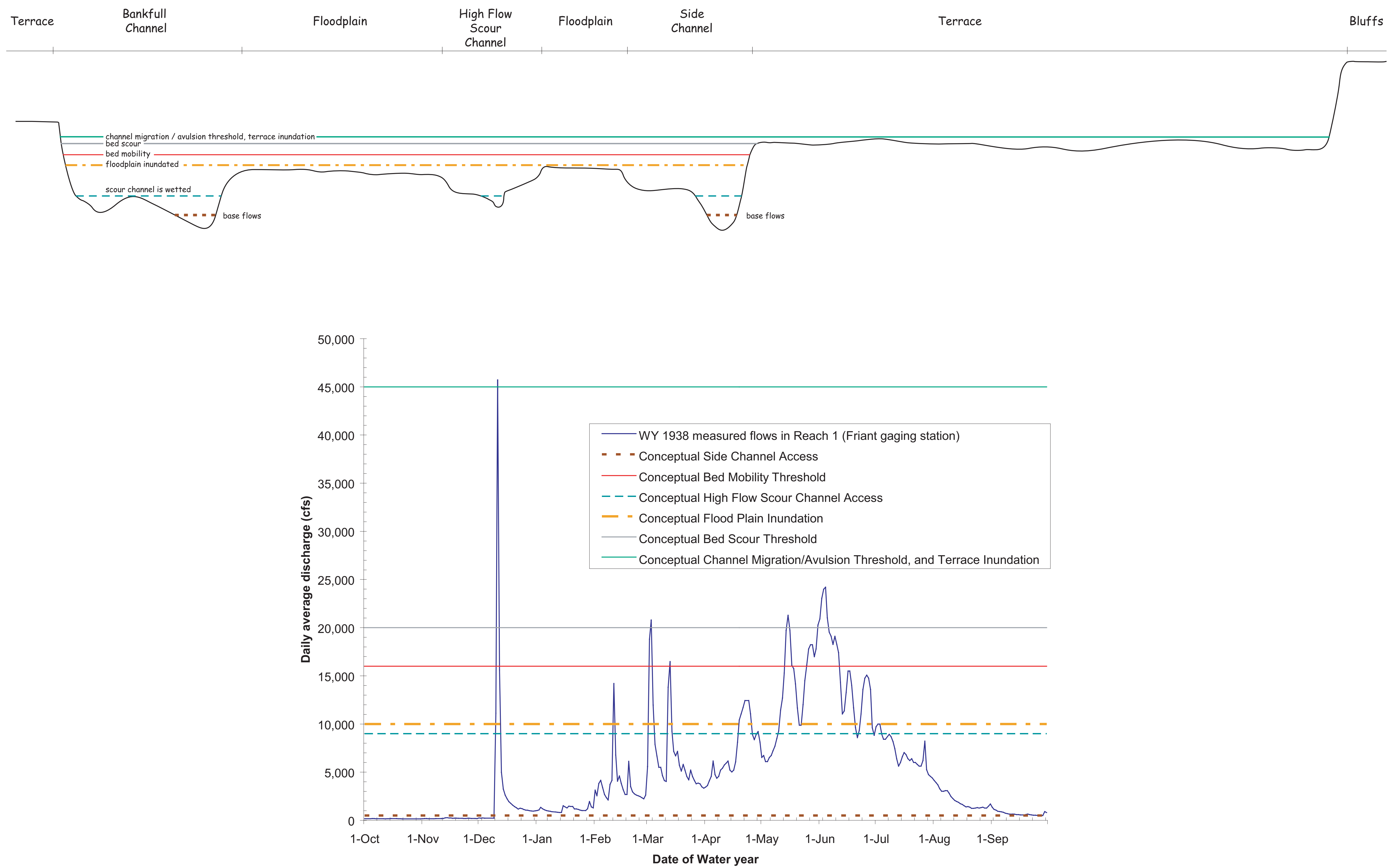


Figure 3-57. Conceptual cross section morphology of Reach 1, showing relationship between hydrograph components, fluvial geomorphic thresholds, and channel morphology. Relationship is purely conceptual, not based on measured data, and is subject to refinement.

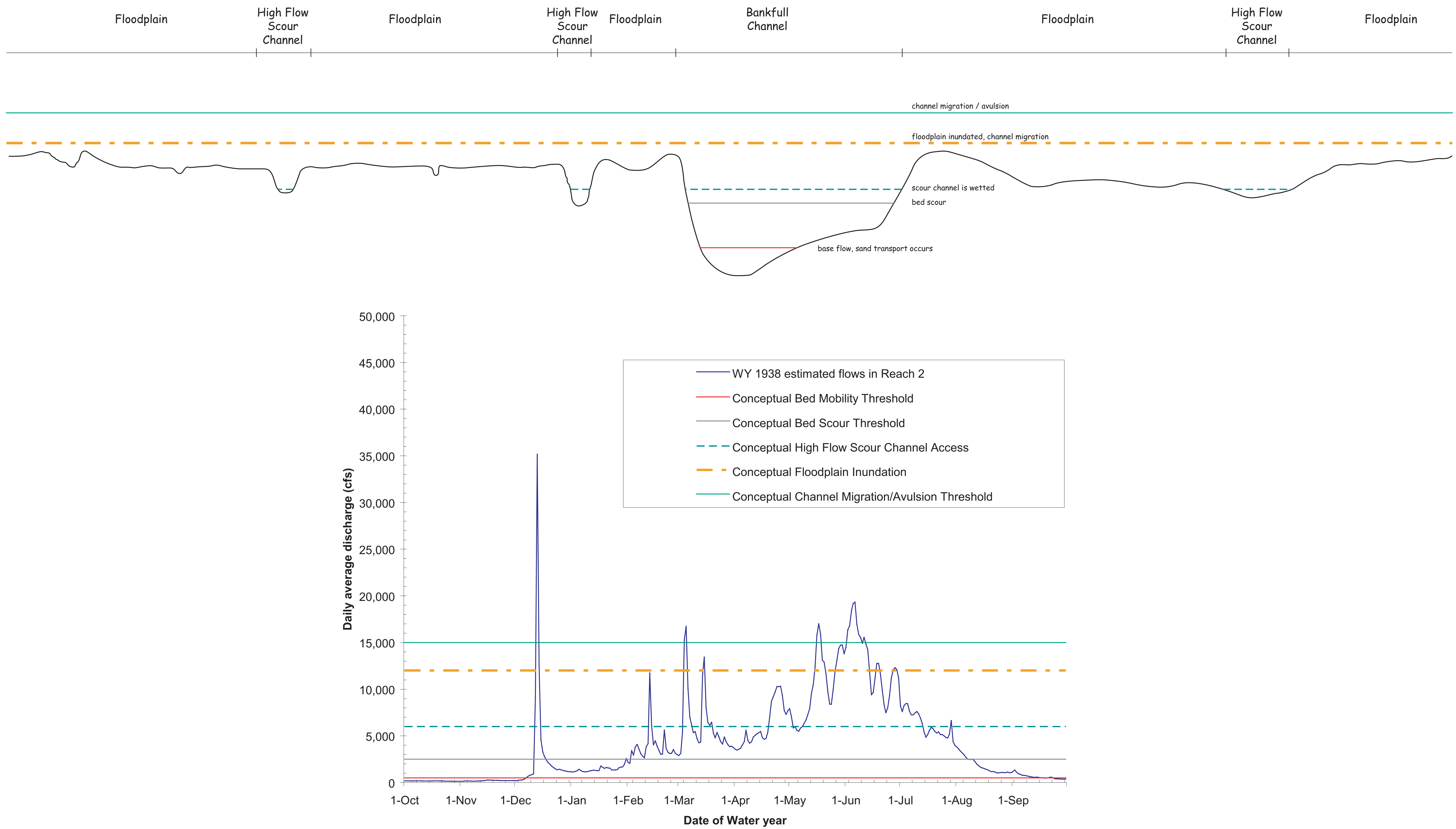


Figure 3-58. Conceptual cross section morphology of Reach 2, showing relationship between hydrograph components, fluvial geomorphic thresholds, and channel morphology. Relationship is purely conceptual, not based on measured data, and is subject to refinement.

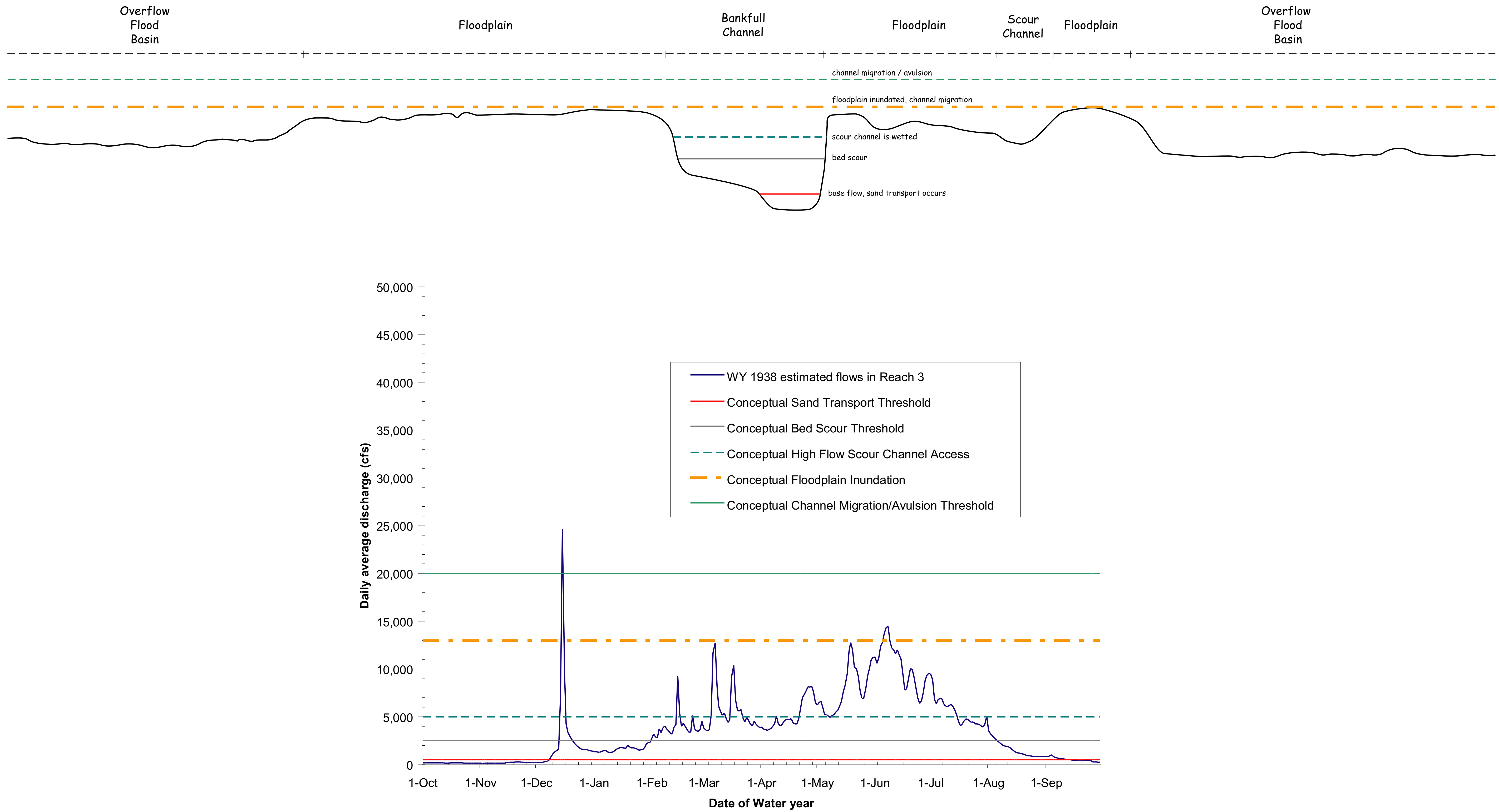


Figure 3-59. Conceptual cross section morphology of Reach 3, showing relationship between hydrograph components, fluvial geomorphic thresholds, and channel morphology. Relationship is purely conceptual, not based on measured data, and is subject to refinement.

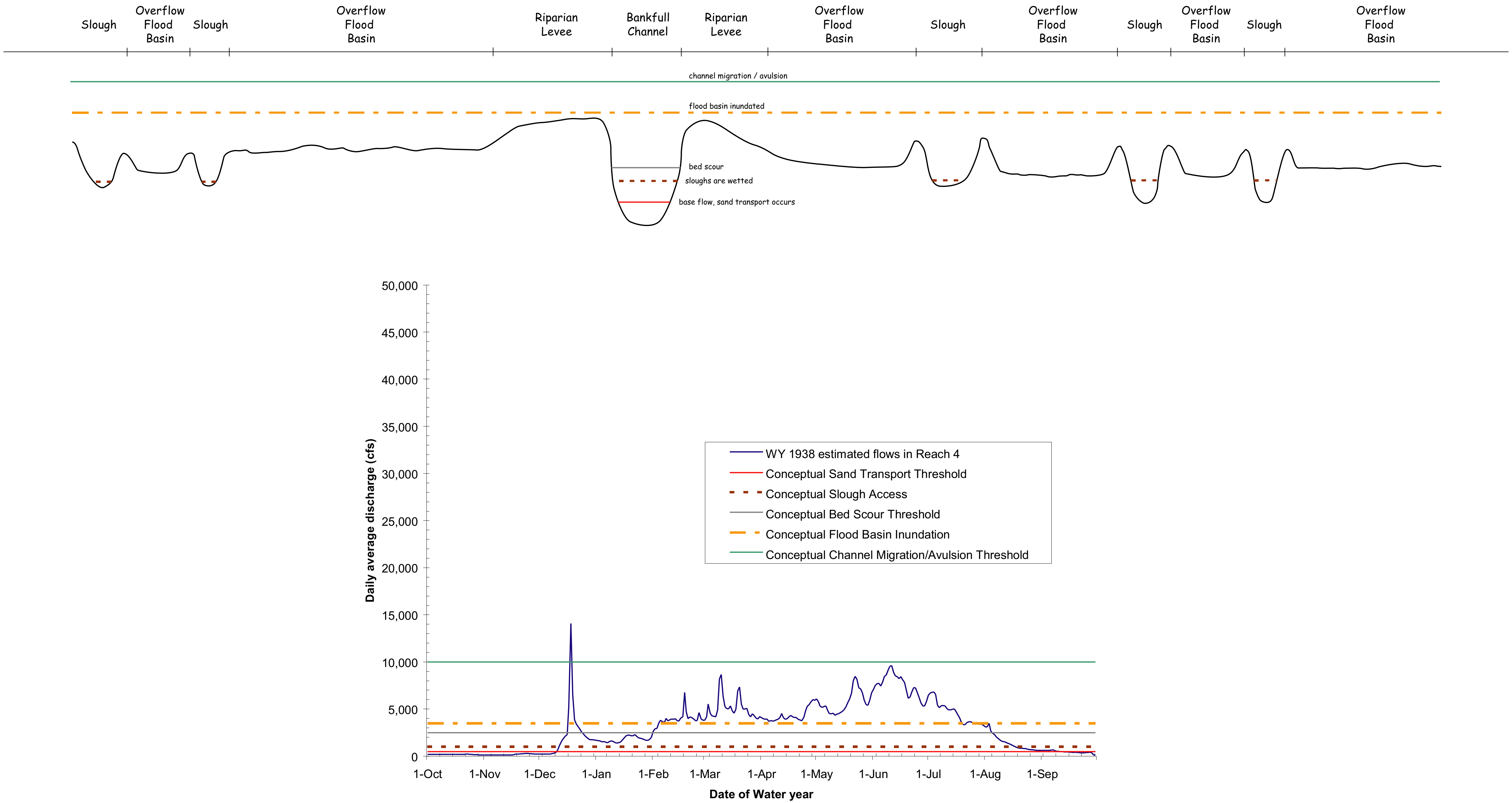


Figure 3-60. Conceptual cross section morphology of Reach 4, showing relationship between hydrograph components, fluvial geomorphic thresholds, and channel morphology. Relationship is purely conceptual, not based on measured data, and is subject to refinement.

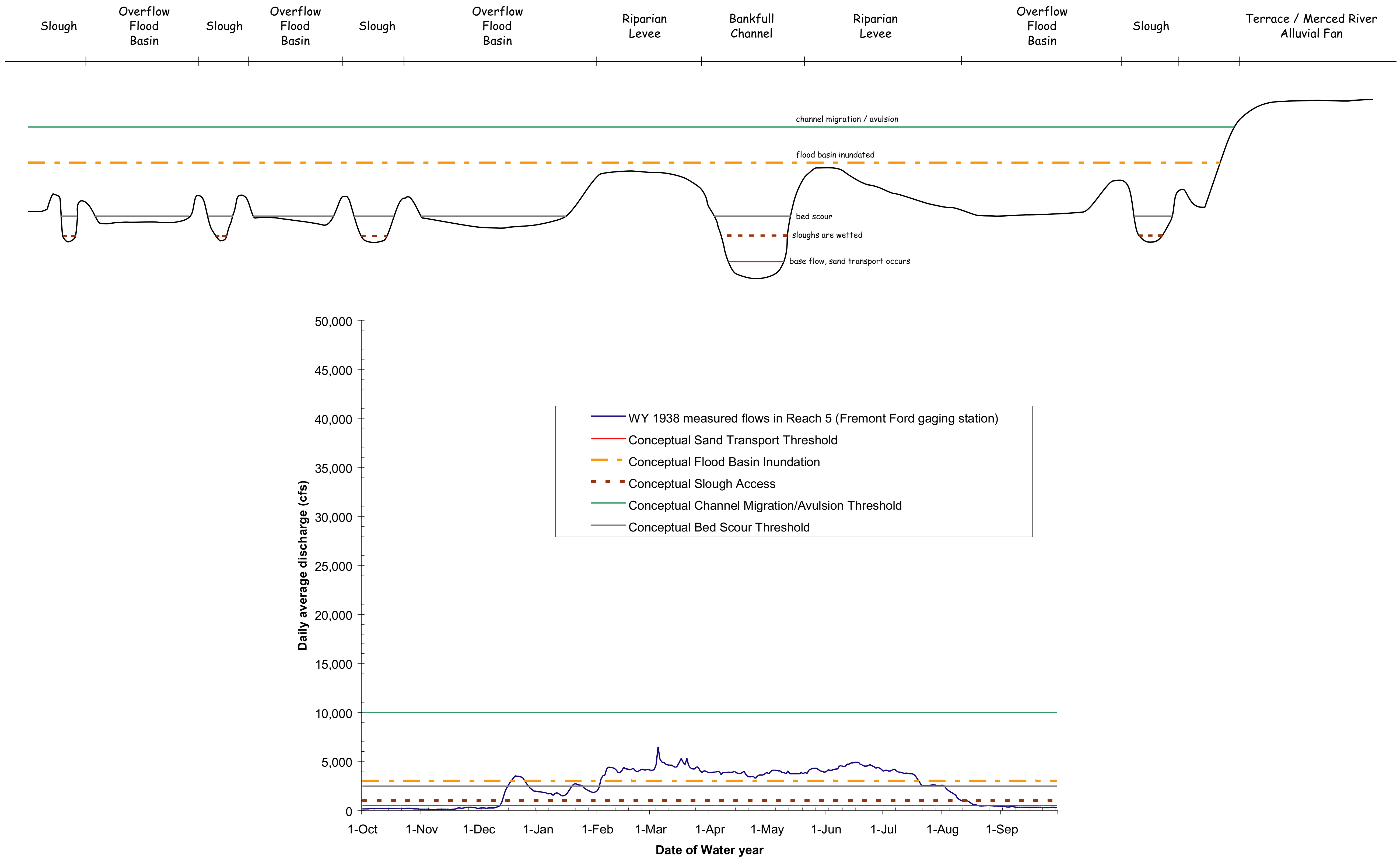


Figure 3-61. Conceptual cross section morphology of Reach 5 showing relationship between hydrograph components, fluvial geomorphic thresholds, and channel morphology. Relationship is purely conceptual, not based on measured data, and is subject to refinement.

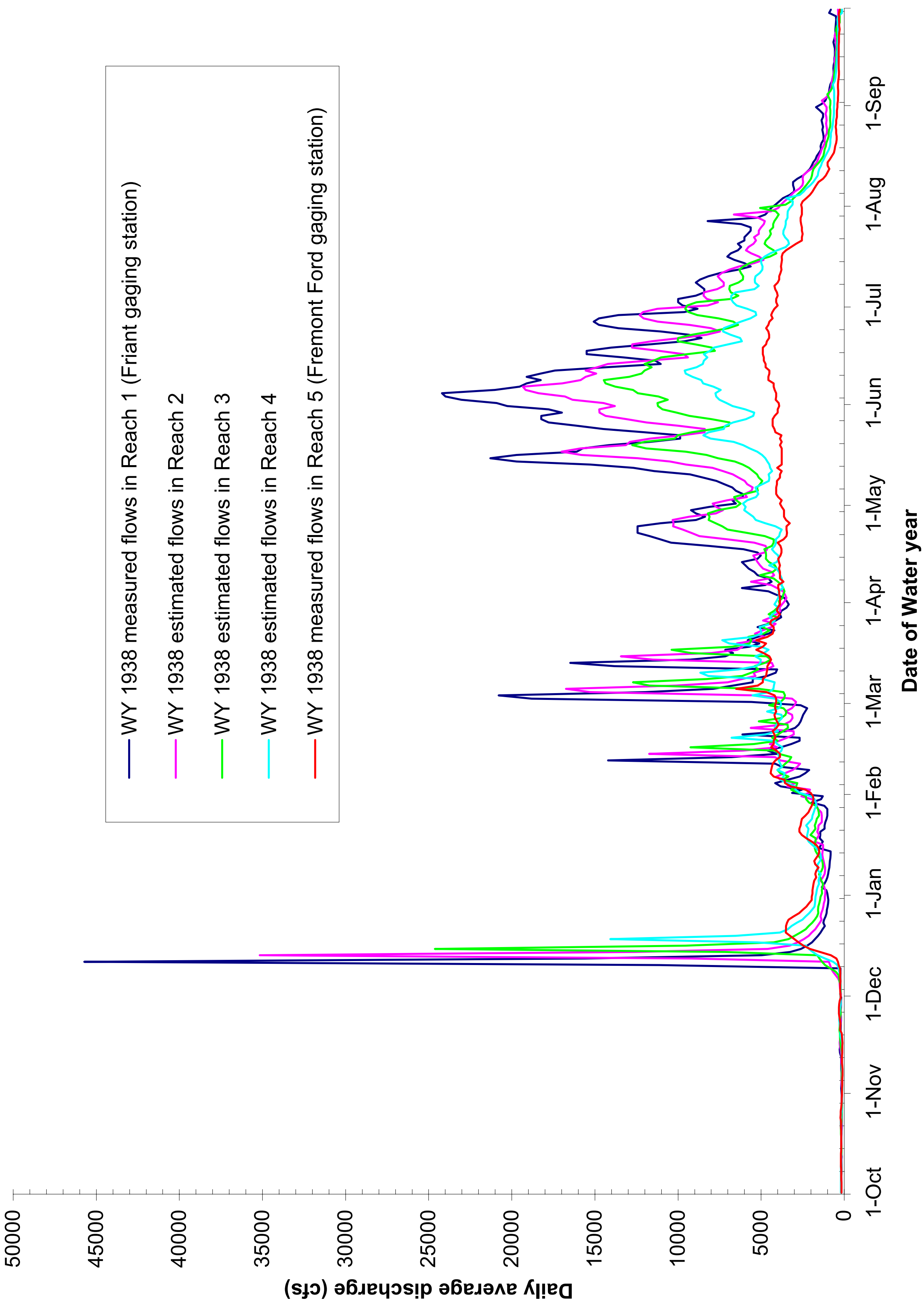


Figure 3-62. Measured 1938 hydrographs at the USGS gaging stations at Friant (Reach 1) and Fremont Ford (Reach 5), with hydrographs in Reaches 2-4 estimated by interpolating between the two USGS gaging stations. Estimated hydrographs are used to help illustrate conceptual relationships between hydrology and channel morphology in the different reaches.

season (week). High flow scour channels and side channels were likely inundated much longer, particularly during the spring snowmelt hydrograph. This prolonged inundation of these channels likely provided high flow refugia habitat for salmonids, as well as high quality rearing habitat. The prolonged inundation of high flow scour channels and gradual draining during the snowmelt hydrograph recession was likely important for natural woody and herbaceous riparian vegetation recruitment in these areas.

3.8.2. Reach 2

Based on the hydraulic modeling results on the 1914 cross sections, 1937 aerial photographs, field observations, pre-Friant Dam hydrology, and general understanding of sand-bedded rivers, a conceptual model of unimpaired channel morphology, geomorphic processes, and hydrograph component relationships was developed (Figure 3-58). This conceptual cross section is located at river mile 223 (Figure 3-7) and is intended to be representative of channel morphology in Reach 2. The cross section illustrates that channel morphology in Reach 2 was comprised of a single primary channel, an inner channel bench with riparian vegetation, and extensive floodplains that were not confined by bluffs. Review of 1937 aerial photographs suggests that the left (south) bank was lower and that high flows spilled overbank and flowed south to Fresno Slough. This reach is sand-bedded, and sand transport likely occurred during high summer baseflows and typical winter baseflows. Correspondingly, moderate bed scour would have occurred during moderate flows by migrating dunes, and greater scour during higher flows. The threshold for initiating channel migration or avulsion in Reach 2 is unknown, but probably occurred during flows equaling or exceeding bankfull discharge (greater than 12,000 to 15,000 cfs as indicated on Figure 3-58). The bankfull discharge begins inundating floodplains and high flow scour channels, and the 1914 cross sections suggest that the bankfull discharge is approximately 12,000 cfs to 14,000 cfs.

Recalling that floodplains on lowland alluvial rivers tend to inundate at flows larger than the 1.5-year flood, the bankfull estimates from the 1914 cross sections can be compared to this conceptual model. The 12,000 cfs to 14,000 cfs bankfull discharge estimate from the 1914 cross sections is slightly smaller than the pre-Friant Dam 1.5-year flood of 10,200 cfs (see Figure 2-5), but tributary accretion downstream of the Friant gage may have increased the magnitude of the 1.5-year flood slightly. Additionally, the bankfull discharge estimates are based on the hydraulic analysis of only a few of the 1914 cross sections. This conceptual figure illustrates that floodplains were also likely inundated for short periods of time during winter floods (days), and a bit longer for the snowmelt peak runoff season (week). High flow scour channels and side channels were likely inundated much longer, particularly during the spring snowmelt hydrograph. This prolonged inundation of these channels may have provided high flow refugia habitat for salmonids, as well as high quality rearing habitat, but this is subject to debate among salmonid biologists. The prolonged inundation of high flow scour channels and gradual draining during the recession of the snowmelt hydrograph was likely important for natural recruitment of woody and herbaceous riparian vegetation on lower benches in Reach 2, but there did not appear to be extensive riparian vegetation on the floodplains based on historical description, the 1914 maps, and the 1937 aerial photographs (see Chapter 8 for more discussion).

3.8.3. Reach 3

The cross section illustrates that channel morphology in Reach 3 was comprised of a single primary channel, an inner channel bench with riparian vegetation, and extensive floodplains that were not confined by bluffs. Review of the 1914 maps and 1937 aerial photographs show that Reach 3 had more abandoned channels (oxbows) and high flow scour channels that were likely accessible during high summer baseflows and typical winter baseflows. This reach is sand-bedded, and sand transport likely occurred during high summer baseflows and typical winter baseflows. Correspondingly, moderate bed scour would have occurred during moderate flows by migrating dunes, and greater scour during higher flows. The threshold for initiating channel migration or avulsion in Reach 3 is unknown, but probably occurred during flows equaling or exceeding bankfull discharge (greater than 12,000 cfs indicated on Figure 3-59). The 1938 hydrograph shown on Figure 3-59 suggests that overbank inundation was short and infrequent; however, this may simply be a relic of the process used to estimate the Reach 3 hydrograph. Flood peak attenuation for flows less than bankfull would have been moderate due to floodplain confinement, and considerable contribution of high flows would likely have been provided by the Kings River via Fresno Slough. Therefore, the hydrograph shown for Reach 3 may be underestimated, which would result in floodplains being inundated for short periods during winter floods (days), and a bit longer for the snowmelt peak runoff season (week) in a similar manner to Reach 2. High flow scour channels and recently abandoned channels were likely inundated longer, particularly during the spring snowmelt hydrograph. This prolonged inundation of these channels may have again provided high flow refugia and rearing habitat for salmonids. The prolonged inundation of high flow scour channels and gradual draining during the recession of the snowmelt hydrograph was likely important for natural recruitment of woody and herbaceous riparian vegetation on Reach 3 floodplains.

3.8.4. Reach 4

The transition from Reach 3 to Reach 4 results in a pronounced change in channel geometry as the Reach 3 floodplains gradually reduce to riparian levees, resulting in extensive tule marshes and sloughs in the flood basin. The representative cross section illustrates that channel morphology in Reach 4 was comprised of a primary channel with several lesser sloughs. Review of the 1914 maps and 1937 aerial photographs show that Reach 4 has numerous anabranching channels (sloughs), such as Santa Rita Slough, Pick Anderson Slough, and others. The 1914 maps illustrate that these sloughs are being used to deliver irrigation water, thus there is uncertainty whether these sloughs conveyed baseflows under unimpaired conditions. The 1914 maps note that the Pick Anderson Slough was dry on October 25, 1915; however, the hand-drawn 1841 map of the Rancho Santa Rita indicates that the Santa Rita Slough and a lesser slough are flowing at some unknown discharge (Figure 3-48). We assume that because the maps showing the sloughs flowing would have been prepared during baseflow period rather than during flood flow period, these slough channels were likely accessible during high summer baseflows and typical winter baseflows. This reach is sand-bedded, and as with upstream sand bedded reaches, sand transport likely occurred during high summer baseflows and typical winter baseflows. Correspondingly, moderate bed scour would have occurred during moderate flows by migrating dunes, and greater scour during higher flows. The threshold for initiating channel migration or avulsion in Reach 4 is unknown, but probably occurred during very rare floods that would breach the riparian levee and scour a new channel location (probably greater than the 10,000 cfs indicated on Figure 3-60). Due to the loss of channel confinement in the upstream portions of Reach 4A, overbank inundation of the flood basin probably occurred most years and was of long duration (months). Because of the loss of confinement and large flood storage available in the flood basin, flood peak attenuation for flows greater than bankfull would have been considerable. Therefore, the hydrograph shown for Reach 3 may overestimate flow magnitude in the lower portions of Reach 4B, which would result in floodplains being inundated for longer periods of time. The prolonged inundation of sloughs and flood basins may have again provided high flow refugia and rearing habitat for salmonids, as well as other native fishes (splittail, delta smelt). The prolonged inundation of the flood basins and gradual draining during the recession of the snowmelt hydrograph was likely important for propagation of the extensive tule marshes, as well as the riparian vegetation on Reach 4 levees along the primary channels.

3.8.5. Reach 5

The low confinement and flood basin morphology of Reach 4 continues into Reach 5. Riparian levees continue to provide a small degree of confinement, with extensive tule marshes and sloughs in the flood basin. Like Reach 4, the representative cross section illustrates that channel morphology in Reach 5 was comprised of a primary channel with several lesser sloughs. Many of the numerous anabranching channels (sloughs) originating from Reach 4 merge with Salt Slough and Mud Slough, rejoining the San Joaquin River in Reach 5. Based on review of the maps, it is again assumed that these slough channels were likely accessible during high summer baseflows and typical winter baseflows. This reach is sand-bedded, and as with upstream sand bedded reaches, sand transport likely occurred during high summer baseflows and typical winter baseflows. Correspondingly, moderate bed scour would have occurred during moderate flows by migrating dunes, and greater scour during higher flows. The threshold for initiating channel migration or avulsion in Reach 5 is unknown, but as with Reach 4, probably occurred during very rare floods that would breach the riparian levee and scour a new channel location (probably greater than the 10,000 cfs indicated on Figure 3-61). Overbank inundation of the flood basin probably occurred in most years and was of long duration (months). The low confinement and large flood storage available in the flood basin continued to attenuate flood peaks for flows greater than bankfull. The prolonged inundation of sloughs and flood basins may have again provided high flow refugia and rearing habitat for salmonids, as well as other native fishes (splittail, delta smelt). The prolonged inundation of the flood basins and gradual draining during the recession of the snowmelt hydrograph were likely important for propagation of the extensive tule marshes, as well as the riparian vegetation on Reach 5 levees along the primary channels.

3.9. BANK EROSION AND SEDIMENT CONTINUITY INVESTIGATIONS

As part of the San Joaquin River Restoration Study, a field reconnaissance was conducted to evaluate channel migration potential through the study reach. This evaluation was a reconnaissance level evaluation, and did not include any predictive modeling, nor did it include a rigorous historic channel analysis to document migration from 1854-1998 maps and air photos. Additionally, the sediment transport analysis conducted between Friant Dam and Mendota Dam (MEI 2000a) and between Mendota Dam and the Merced River confluence (MEI 2000b) is summarized below.

3.9.1. Bank Erosion Investigation

As part of the field reconnaissance of the study area for the San Joaquin River Restoration Study, a qualitative evaluation of channel erosion/migration was undertaken. During the field reconnaissance in 2001, sediment samples were collected along the San Joaquin River and in the bypasses to characterize the sedimentology of the system. Sample locations are indicated by river mile location in Table 3-8. In the upstream reaches, where the bed material was coarser, Wolman pebble counts (Wolman 1954, Leopold 1970) were used to develop bed surface particle size distributions, whereas in downstream reaches, bulk samples were used to develop bed surface particle size distributions.

Along the lower reaches of the San Joaquin River, bank erosion is ubiquitous on the outsides of bends. Bank erosion rates are locally high during high flow events in areas where the toes of the eroding banks tend to be composed of cohesionless sands (Reach 2 and 3). The highly contorted shape of many of the bends in both the San Joaquin River and the sloughs is a result of differential erodibility of the floodplain sediments. More erosion-resistant, cohesive flood basin sediments in Reach 4 and 5 are eroded by mass wasting processes rather than by fluvial entrainment. The bank erosion appears to be a meaningful source of sediment that is deposited on the floodplain during larger flood events, such as in 1997.

Erosion of agricultural fields that border the channel is a meaningful source of sediment for the river and sloughs. Downstream transport of sediment is greatly complicated by the control structures that are used to split floodflows between the mainstem San Joaquin River and the Chowchilla Bypasses. Because the majority of sediment in transport is sand-sized and finer, the sediment is probably distributed in proportion to the flows at the bifurcation points.

The locations of bank erosion are controlled to a large extent by the local flow magnitude at any given reach. Downstream of Sack Dam, where the channel is dry most of the time, the distribution of the sediment, derived primarily from upstream bank erosion, is dependent on the duration of floodflows. Upstream of Sack Dam, the sand-sized sediment derived from bank erosion can be conveyed downstream via the river by the 500 cfs to 600 cfs of Delta-Mendota Canal flows released into Reach 3. Riparian vegetation is well established in the reach because of the perennial flows and, where present, it increases the resistance to erosion of the banks. A considerable amount of sediment is diverted from the San Joaquin River upstream of Mendota Dam at the Chowchilla Bifurcation Structure. This loss of sediment, combined with the sediment-free water contributed to Reach 3 by the Delta Mendota Canal, results in a rate of erosion of nonvegetated banks in Reach 3 that is probably larger than if upstream sediment supply were not diverted into the Chowchilla Bypass. General bed degradation, as seen from the comparative surveys of the reach (Table 3-5), may be a result of the clear water releases from Mendota Dam. Wherever hydraulic energy in the reach is reduced, either as a result of backwater generated by a sharp radius of curvature bend or by a flow expansion zone, sediment is deposited in the channel or in the overbank areas.

Upstream of Mendota Dam, the high-amplitude meander bends store a considerable volume of sediment. The combined effects of the Chowchilla Bifurcation Structure and the low channel slope associated with the high channel sinuosity are likely responsible for the aggradation in the reach immediately upstream of the Chowchilla Bifurcation Structure.

Bank erosion is the primary source of sediment upstream of the Chowchilla Bifurcation Structure. Considerable volumes of sediment are stored in the bed of the channel upstream of the Chowchilla Bifurcation Structure (up to 500,000 yd^3/mile of channel). It has been estimated that the sediment retention basin at the head of the Chowchilla Bypass (with a capacity of about 200,000 yd^3) fills up with sediment every 2 to 3 months during a high flow event (Hill pers. comm.).

Upstream of Gravelly Ford, the bed material in the channel of the San Joaquin River becomes coarser. The coarser bed material is probably derived from bank erosion and, to some extent, residual sediment contributed by Little Dry Creek prior to aggregate extraction at the mouth of Little Dry Creek. Perennial flow releases from Friant Dam have caused riparian encroachment along the low flow channel, armoring the banks and discouraging channel migration.

3.9.2. Sediment Continuity Modeling

Empirical measurements of sediment transport rates have not been collected. In order to generate a rough understanding of sediment transport capacity in the study area, a sediment continuity model was developed for the reach from Friant Dam to Mendota Dam (MEI 2000a) and for the reach from Mendota Dam to the Merced River confluence (MEI 2000b). The sediment transport analysis of the study area describes sediment transport capacity, and patterns of aggradation and degradation of the San Joaquin River. Understanding these physical processes is an important part of developing a river restoration plan and for evaluating salmonid spawning gravel availability and quality.

An important clarification of model output needs to be made in order to avoid misinterpretation of results: The sediment transport capacity predicts <u>possible</u> sediment transport rates if upstream supply is not limiting and other sediment transport discontinuities (e.g., instream aggregate pits) are negligible. While this is not the case in the San Joaquin River, the model provides a useful comparison of hydraulic transport capability between the different reaches. Therefore, results should not be interpreted literally or with any precision, but merely as a means to compare the potential sediment transport capacity between the reaches. The following analyses are fundamentally derived from hydraulic models, which in turn are based on moderately accurate topographic surveys (this is not to say that the topographic surveys are faulty, just that their level of accuracy influences the hydraulic and sediment transport capacity predictions). Additionally, the sediment transport capacity modeling results for several segments were based on only one or two sediment samples from each segment, which may introduce some substantial uncertainty into modeling results in reaches that have a large amount of variability in particle size (e.g., Reach 1). Local particle size adjusts to local hydraulic conditions; therefore, using average particle size for many cross sections in a reach with diverse particle size may add to variability in model predictions. Sediment transport is moderately sensitive to local particle size, so a small number of sediment samples may reduce the accuracy of model predictions. Therefore, it must be clearly stated that modeling results are simply predictions of sediment transport capacity, are not to be interpreted as absolute predictions, and have not been calibrated or validated with empirical field measurements.

On the basis of geomorphic, hydrologic, and hydraulic criteria, the five reaches of the study area were further subdivided into six hydraulic modeling segments for Reaches 1-2 and nine segments for Reaches 3-5 (MEI 2000a, MEI 2000b) (Figure 3-2, Table 3-10). For Reaches 3-5, a single representative particle size gradation was developed from samples S1 through S6 for use in the sediment transport computations. This gradation had D_{84}, D_{50} and D_{16} sizes of 0.78 mm, 0.45 mm, and 0.2 mm, respectively (Table 3-8). For Reaches 1 and 2, a combination of individual samples and averaged samples were used for sediment transport capacity computations (Table 3-11). The sediment transport capacity analysis for existing conditions was carried out for the mean daily flow analysis period (1986–1999) and for the hydrographs developed for the spring 1986 and 1995 flows. For further details on the modeling methods, see MEI 2000a and MEI 2000b.

Table 3-10. Reach limits of hydraulic modeling segments used in the hydraulic model and sediment transport capacity analysis.

Hydraulic Modeling Segment	Reach	Upstream Limit Station (feet)	Upstream Limit River Mile	Downstream Limit Station (feet)	Downstream Limit River Mile	Length Feet	Length Miles	Description
Between Friant Dam and Mendota Dam								
1A.1	1A	331,050	267.5	266,540	255.2	64,510	12.2	Friant Dam to SR 41 Bridge (SR 41)
1A.2	1A	266,540	255.2	204,220	243.2	62,320	11.8	SR 41 Bridge (SR 41) to Herndon (SR 99)
1B.1	1B	204,220	243.2	146,500	232.8	57,720	10.8	Herndon (SR 99) to RM 232.8
2A.1	2A	146,500	232.8	105,020	225.0	41,480	7.9	RM 232.8 to end LB levee
2A.2	2A	105,020	225.0	59,200	216.1	45,820	8.7	End LB levee to Bifurcation Structure
2B.1	2	59,200	216.1	–	204.8	59,200	11.2	Bifurcation Structure to Mendota Dam
Total						331,050	62.7	

Table 3-10. cont.

Hydraulic Modeling Segment	Reach	Upstream Limit Station (feet)	Upstream Limit River Mile	Downstream Limit Station (feet)	Downstream Limit River Mile	Length Feet	Length Miles	Description
Between Mendota Dam and the Merced River								
3.1	3	456,330	204.7	406,910	195.2	49,420	9.4	Mendota Dam to Avenue 7-1/2 (Firebaugh)
3.2	3	406,910	195.2	338,290	182.0	68,620	13.0	Avenue 7-1/2 to Sack Dam
4A.1	4A	338,290	182.0	295,640	173.9	42,650	8.1	Sack Dam to SR 152 (Santa Rita Bridge)
4A.2	4A	295,640	173.9	266,620	168.5	29,020	5.5	SR 152 (Santa Rita Bridge) to Sand Slough Control Structure
4B.1	4B	266,280	168.5	206,210	157.3	60,070	11.4	Sand Slough Control Structure to Turner Island Bridge
4B.2	4B	206,210	157.3	155,080	147.6	51,130	9.7	Turner Island Bridge to the Mariposa Bypass
4B.3	4B	155,080	147.6	93,840	135.9	61,240	11.6	Mariposa Bypass to Bear Creek
5.1	5	93,840	135.9	65,030	130.4	28,810	5.5	Bear Creek to the downstream limit of State Project levee on west side
5.2	5	65,030	130.4	180	118.3	64,850	12.3	Downstream limit of State Project levee on west side to the Merced River
Total						455,810	86.3	

Table 3-11. Summary of representative bed material size gradations for the San Joaquin River, by hydraulic modeling segment between Friant Dam and Mendota Dam

Hydraulic Modeling Segment	**Representative Particle Size**			
	D_{16} (mm)	**D_{50} (mm)**	**D_{84} (mm)**	**Remarks**
1A.1	27.8	64.0	112.2	Based on average of Samples WC-1 and WC-6
1A.2	26.9	47.6	73.4	Based on average of Samples WC-2 and WC-3
1B.1	14.0	27.0	49.0	Based on average of Samples WC-4 and WC-5
2A.1	0.60	2.6	20.1	Based on Sample S-9
2A.2	0.62	1.7	12.7	Based on Sample S-8
2B.1	0.21	0.65	2.5	Based on Sample S-7

3.9.2.1. Friant Dam to Mendota Dam

The three upstream-most hydraulic modeling segments below Friant Dam have bed material that is coarser than downstream segments because Reach 1 is gravel-bedded, and locally armored due to impacts of flow and sediment regulation by upstream dams. In-channel and floodplain aggregate mining has affected the morphology and hydraulics of these upstream modeling segments, which has had a very disruptive effect on the continuity of coarse sediment transport. As a result of the elimination of the upstream coarse sediment supply, the primary supply of coarse sediment to the river is from the bed itself and a small number of locations where bank erosion of floodplains and terraces occur. However, operation of Friant Dam for flood control purposes has greatly reduced peak discharges and, consequently, reduced the amount of bank erosion as well. Elimination of frequent flood flows and maintenance of base flows have caused riparian encroachment between Friant Dam and Gravelly Ford (see Section 3.10.5). This vegetation has, through root reinforcement of the sediments, further reduced the availability of sediment (Cain 1997).

The bed of the channel is armored for the range of commonly occurring flows in the gravel- and cobble-bed portion of Reach 1. At the highest flows associated with the existing operating rules for Friant Dam, some local reworking of the bed occurs, but substantial reworking and gravel recruitment does not appear to occur.

Table 3-12 summarizes the results of the sediment continuity calculations for existing conditions. The results show that the computed transport capacities of hydraulic modeling segments 1A.1–1B.1 are negligible, attributable largely to the coarse bed material in this portion of the river and the controlled releases from Friant Dam. These results are consistent with the incipient motion analysis that showed that shear stresses necessary to mobilize the bed material are exceeded only in localized areas at discharges larger than 12,000 cfs to 16,000 cfs (or greater). The coarse sediment that is mobilized is transported over relatively short distances and does not constitute a large volume of sediment movement through the segments. In addition, in-channel gravel pits in this portion of the river capture all coarse sediment load that is transported. The coarse sediment supply to the upstream end of Reach 1 was eliminated with the closure of Friant Dam in 1944, which has contributed to the coarsening of the bed material in the river below Friant Dam. There are also two tributaries that can theoretically contribute sediment to the upper portion of Reach 1: Cottonwood Creek and Little Dry Creek. Both tributaries enter into the hydraulic model segment 1A.1. Cain (1997) provides estimates of the potential coarse sediment supply from these tributaries, which range from about 55 yd^3/year for Cottonwood Creek and from about 335 yd^3/year for Little Dry Creek, assuming the coarse sediment load is 10% of total sediment load. Gravel pits near the downstream end of Little Dry Creek may limit the sediment supply from this source. A large portion of the sediment supply from Little Dry Creek and Cottonwood Creek is fine sand and silt, which may move through the upper hydraulic modeling segments between the gravel pits as wash load during high flows. This finer material may be captured by the pits along with any other transported coarser bed material load, with very little bed material-sized sediment being delivered to downstream segments of the river. Comparison of available spawning gravel areas between 1957 and 1996 (Cain 1997) indicates that there has been an order-of-magnitude decrease, which tends to support the observation that the supply of gravel-sized material to the river has been reduced.

Because of finer material in the bed of the channel in Reach 2, the transport capacities of hydraulic modeling segments 2A.1–2B.1 are much higher than the reaches upstream. The transport capacity of hydraulic modeling segment 2A.1 is the highest in the overall study reach, which is consistent with the high main-channel velocities computed for this segment. Because of the low coarse sediment supply from upstream, this result indicates that hydraulic modeling segment 2A.1 has a sediment deficit. In the absence of geological controls or coarse sediment armoring, the segment should respond to the deficit by degradation or by channel widening. The computed sediment deficit for average annual conditions (about 32,500 tons/year) corresponds to about 0.09 feet/year of average degradation for the entire segment, or about 0.7 feet/year of channel widening (assuming an average bank height of 20 feet). These numbers are quite low, which is consistent with historical data (JSA and MEI 1998) that show that only minor amounts of degradation (an average of about 2 feet except in the vicinity of gravel pits) and little or no overall channel widening have occurred since 1914.

The transport capacity of hydraulic modeling segment 2A.2 is lower than hydraulic modeling segment 2A.1, indicating a potential for channel aggradation. This is consistent with evidence of bed aggradation above the Chowchilla Bifurcation Structure. The computed average annual aggradation (about 13,400 tons/year) corresponds to an average aggradation rate for the entire segment of about 0.02 feet/year. As the aggradation is not uniform, greater amounts will occur in some areas (such as the segment just above the Chowchilla Bifurcation Structure). Based on the flow split at the Chowchilla Bifurcation Structure, about 9,300 tons/year of bed-material load is diverted into the Chowchilla Bypass, with the remainder (about 9,800 tons/year) being delivered to the river downstream from the bypass. The volume of bed material diverted into the bypass on an average annual basis (approximately 160,000 yd^3) is large enough to fill a large portion of the approximately 200,000 yd^3 capacity sediment detention basin just downstream of the diversion point. The volume of bed-material sediment diverted during individual storm events can be even greater than the average annual estimate (about 280,000 yd^3 for the 1986 release hydrograph, and about 510,000 yd^3 for the 1995 release hydrograph), filling the basin in a single event. Also, at least a portion of the finer material that was considered to be wash load, and therefore not considered in the sediment continuity analysis (less than 0.5 mm), would settle in the detention basin, further shortening the filling time.

The low transport capacity of hydraulic modeling segment 2B.1 results in about 6,700 tons/year of aggradation. This corresponds to about 0.01 feet per year if the aggradation were uniform throughout the segment. Again, higher rates exist locally (such as in Mendota Pool) because the aggradation is not uniform.

Table 3-12 shows that the predicted sediment transport capacity for the 1986 and 1995 flow release hydrographs are higher (about 50% higher for the 1986 hydrograph and about 140% to 170% higher for the 1995 hydrograph) than the average annual sediment transport capacity estimates. Examination of recorded releases from Friant Dam shows that flows are very low in most years, with occasional years of high flows similar to those that occurred in 1986 and 1995. The bulk of the sediment that is carried by the river is carried during the high flow years, with little or no transport during the dry years.

3.9.2.2. Mendota Dam to Merced River

The same analysis as above was conducted for the modeling segments between Mendota Dam and the Merced River confluence. Table 3-12 summarizes the results of the sediment transport capacity calculations for existing channel conditions. The results predict that hydraulic modeling segments 3.1 and 3.2 downstream of Mendota Dam are degradational, with a computed sediment deficit for average annual conditions ranging from about 2,300 tons/year to 2,700 tons/year. These estimates are quite low, corresponding to less than 0.01 feet/year of average degradation for each segment. Historical surveys suggest that general bed degradation has occurred in this reach of the river (JSA and MEI 1998), although valley floor subsidence may be responsible for a majority of this observed trend. Bridge inspection reports obtained from Caltrans for the 7½ Avenue Bridge in Firebaugh indicate that scour has occurred at the bridge during the last decade, although the reports are not conclusive as to whether the observed scour indicates general bed degradation. The computed slight

Table 3-12. Summary of sediment transport capacity modeling results for existing channel conditions.

Hydraulic Modeling Segment	Average Annual (1986-1999)		1986 Hydrograph		1995 Hydrograph	
	Sediment transport capacity (tons/year)	**Sediment transport capacity surplus (+) or deficit (-) (tons/year)**	**Sediment transport capacity (tons)**	**Sediment transport capacity surplus (+) or deficit (-) (tons)**	**Sediment transport capacity (tons)**	**Sediment transport capacity surplus (+) or deficit (-) (tons)**
1A.1	0	0	0	0	0	0
1A.2	0	0	0	0	0	0
1B.1	3	-3	1	-1	4	-4
2A.1	32,500	-32,600	49,400	49,400	87,100	87,100
2A.2	19,100	13,400	29,700	19,700	51,900	35,200
Supply to 2B.1[a]	9,800	--	13,200	--	22,300	--
2B.1	2,700	6,600	4,970	11,500	7,900	21,700
3.1	5,000	-2,300	15,500	-10,500	18,300	-10,500
3.2	7,700	-2,700	22,300	-6,800	27,300	-8,950
Split to Arroyo Canal[a]	2,100	--	2,000	--	2,170	--
4A.1	6,300	-570	22,900	-2,600	28,000	-2,900
4A.2	2,900	3,400	16,000	6,850	17,800	10,300
Split to Eastside Bypass[a]	2,200	--	14,700	--	16,000	--
4B.1	60	600	54	1,250	56	1,650
4B.2	14	44	10	44	9	47
Mariposa Bypass[b]	5,900	--	10,900	--	14,300	--
4B.3	5,900	0	10,900	0	14,300	0
Bear Creek[b]	56,100	--	111,000	--	147,000	--
5.1	62,000	0	122,000	0	162,000	0
5.2	23,100	38,900	33,600	88,800	42,300	119,000

[a] Transport capacity is the volume of sediment exported out of river based on the flow split at the junction.

[b] Estimated supply assuming equilibrium in mainstem reach just downstream.

degradational tendency of hydraulic modeling segments 3.1 and 3.2 is attributable in part to diversion of sediment from the San Joaquin River into the Chowchilla Bypass at the Chowchilla Bifurcation Structure. This degradational trend could indicate the possibility of increased bank erosion. However, sustained flows from imported Delta Mendota Canal releases from Mendota Dam have contributed to the maintenance of well-established riparian vegetation along the channel banks in this reach of the river (JSA and MEI 1998). Where present, the vegetation roots increase the resistance of the banks to erosion, which may limit any increased bank erosion that would occur as a result of the computed sediment deficit.

The sediment transport capacity computations predict that hydraulic modeling segment 4A.1, downstream of Sack Dam, is nearly in equilibrium, predicting only very small sediment deficit. The sediment transport capacity computations predict that hydraulic modeling segment 4A.2, upstream of the Sand Slough Control Structure, is aggradational under existing conditions, with a predicted average annual aggradation of about 3,400 tons per year, which corresponds to about 0.01 foot/year if the aggradation were uniform throughout the segment. Higher rates may exist locally (e.g., the area just above the entrance to the Sand Slough Control Structure) because the aggradation is not uniform. The predicted aggradation in this segment is supported by field observation and bridge inspection reports for the SR 152 Bridge (Santa Rita Bridge) at the upstream end of the segment (JSA 1998). The computed aggradation is the result of backwater caused by high bed elevations in the Eastside Bypass near the junction with the San Joaquin River. This portion of the Eastside Bypass has had a historical aggradational problem because of erosion of the bed of the bypass channel upstream (ACOE 1993). The sediment transport capacity computations predict an average of 2,200 tons/year diverted into the Eastside Bypass from the San Joaquin River via the Sand Slough Control Structure.

Predicted sediment transport capacities of hydraulic modeling segments 4B.1 and 4B.2 are negligible compared to other sections of the river, the result of all of the river flow being diverted into the Eastside Bypass at the upstream end of Reach 4B. The small amount of bed-material load that would theoretically enter Reach 4B at the Sand Slough Control Structure would be trapped by vegetation growing in the channel bed; however, the headgates controlling flow into Reach 4B have not been opened in the recent past, so these predicted result would not apply unless headgates were opened in the future. Inflows from the Mariposa Bypass and Bear Creek (Eastside Bypass) increases sediment transport capacities of hydraulic modeling segments 4B.3 and 5.1. The assumption of zero aggradation/degradation for these segments, used to estimate the existing conditions of bed-material/sediment supplies from the Mariposa Bypass and Bear Creek, was based on the assumption of overall stability of this portion of the river under existing conditions. The computed transport capacity of segment 5.2 is less than segment 5.1, with a computed aggradation of about 38,800 tons/year on an average annual basis. This corresponds to about 0.06 foot/year if the aggradation was uniform throughout the segment. Segment 5.2 covers the portion of river below the end of the State Water Project levee on the west side (RM 130) of the river where high flows are able to spread out into the historical anabranched channels. While anabranched river systems are not typically aggradational (Nanson and Huang 1997), the computed net aggradational trend in this segment may be the result of proportionally larger reductions in transport capacity (compared to historical conditions) resulting from reduced flood flows (assuming upstream sediment supply remained constant). However, upstream sediment supply may have increased over historical conditions due to erosion of the Eastside Bypass, which may further cause aggradation in downstream reaches.

Table 3-12 shows that the computed sediment transport capacity for the 1986 and 1995 hydrographs are higher than the average annual estimates, with the largest volumes occurring during 1995, which had a longer duration of high flows (larger runoff volume). Hydraulic modeling segments 4B.1 and 4B.2 are exceptions, where computed sediment transport capacity is similar (very small) for each case, the result of the flow limitation caused by the operation of the Sand Slough Control Structure.

The bulk of the predicted sediment transport capacity in the river occurs during the high flow years, with little or no predicted transport during the dry years. Thus, changes in the river as a result of erosion and deposition of sediment would be expected to occur only during years with larger than normal flood flows.

3.10. HUMAN CHANGES TO THE CHANNEL AND ASSOCIATED IMPLICATIONS

This section provides a description of the human modifications to the San Joaquin River and its floodplain. Most modifications have been made to provide:

- transportation pathways (highways, bridges, and culverts),
- water supply infrastructure elements (dams, canals, and diversions),
- flood control (state project levees, nonproject levees, flow bifurcation structures, flood bypasses), and
- sand and gravel materials for construction.

In contrast to other Central Valley rivers draining the Mother Lode of the Sierra Nevada, gold mining activities have had a minimal impact on the San Joaquin River. Although some placer mining did occur at the Friant townsite, Temperance Flat adjacent to the mainstem above Friant, Fine Gold Creek, and Big Dry Creeks (Gudde, 1975), these resulted in small amounts of sediment delivery to the San Joaquin River. More importantly, the San Joaquin River was spared the extensive dredging of floodplains in the gravel-bedded reaches exiting the foothills of the Sierra Nevada (e.g., compare with the Yuba River or Merced River).

Other secondary impacts from human manipulations to surface and groundwater hydrology have caused the following impacts:

- Riparian encroachment along the low flow channel margins, and
- Excessive groundwater withdrawal since the 1920s has caused over 30 feet of subsidence in portions of the San Joaquin Valley (Poland et al. 1975, Basagaoglu et al. 1999), and impaired riparian vegetation regeneration and survival in Reach 2 (JSA and MEI 1998).

The impact of groundwater withdrawal is discussed in Chapter 5 and Chapter 8; a summary of the process of riparian encroachment and associated impact is provided in a following section. The natural flow character and channel morphology of the San Joaquin River have been affected by five main categories of human impact (JSA, 2002):

- transportation pathways (highways, bridges, and culverts);
- water supply infrastructure (dams, canals, and diversions);
- flood control initiatives (state project levees, non-project levees, flow bifurcation structures, flood bypasses);
- mining for construction aggregates (sand and gravel)
- groundwater abstraction above groundwater recharge rates

The direct effects of these major human impacts are varied. Some bridges and culverts cause flows to backwater and in-channel sediment deposition, whereas other culverts are probably washed out at high flows after causing temporary effects on the ascending limb of the high flow hydrograph (JSA, 2002). The major water supply impact is from Friant Dam, which supplies water to the Friant-Kern Canal and Madera Canal. Consequently, flow reductions in the San Joaquin River cause the mainstem to be generally dry between Gravelly Ford (RM 229) and Mendota Pool (RM 206) except during flood events. Imported flows from the Delta Mendota Canal ensure water between Mendota Dam (RM 204.6) and Sack Dam (RM 182.1), but downstream flows are again generally absent downstream to the Sand Slough Control Structure (RM 168.5) whereupon irrigation return discharges provide some flow. Friant Dam also reduces the magnitude of the flood flows and eliminates the supply of coarse sediment to downstream reaches (see Chapter 2).

Elsewhere, between Mendota Dam (RM 204.6) and the Sand Slough Control Structure (RM 168.5) canals bordering the river serve to reduce the effective width of the floodplain. Constructed bypasses on the east side of the San Joaquin River (Chowchilla, Eastside, and Mariposa Bypasses) and nearly 200 miles of associated levees alter the natural flood inundation and routing processes, and isolate approximately 240,000 acres of floodplain from the river (ACOE 1993) as part of the San Joaquin River Flood Control Project. Other impacts include the in-channel and floodplain mining of sand and gravel construction aggregate between Friant Dam (RM 267.5) and Skaggs Bridge (RM 234.1), which since the early 1940s has caused local channel degradation (see Section 3.7.1.2). Larger-scale channel degradation has only been limited by the presence of bedrock outcrops close to the channel bed in Reach 1A (Cain 1997) and the low sediment transport rate resulting from the low slope in Reach 1A and 1B. As a result, historic channel floodplains are now terraces in locations that have not been mined for aggregate or disrupted by agricultural land conversion. Overall, the channel in much of Reach 1 is a "hydraulically disrupted flood conveyance system composed of single channel segments, multi-channel segments, and breached pits" (JSA, 2002). The aggregate pits trap sediment transported from upstream reaches, resulting in headcutting on the upstream side of the pit and channel degradation downstream of the pit due to loss of sediment supply (Figure 3-62). In downstream portions of Reach 1B and portions of Reach 2, aggregate extraction has been smaller scale, and focused within the active floodway. While impacts in these reaches have not been as severe as in Reach 1A and the upper portion of Reach 1B, these smaller scale extraction operations reduces sediment supply to downstream reaches.

3.10.1. Transportation Pathways

Between Friant Dam and the Merced River, a number of bridges and culverts have been constructed for vehicular and railroad crossings of the San Joaquin River (Table 3-13). Some of the bridges cause backwater effects at higher flows, which changes upstream water surface elevations and causes sediment deposition in the channel. Most of the culvert crossings are probably washed out at high flows, but they do cause some backwater and upstream ponding at lower flows, which has implications for both flow routings, and possibly water temperatures as well. These bridges and culverts that constrict the river cause discontinuities in the longitudinal distribution of energy of the river, such that some areas are severe depositional areas, and some areas are higher energy scour areas. Unimpaired channels distribute the energy dissipation more gradually, and important channel processes (bedload transport, gravel cleansing) occur in a more consistent basis throughout the river channel.

Comparison of channel bed elevation data collected for the National Bridge Safety Inspection Program by Caltrans indicates that the bed has lowered between Friant Dam and Skaggs Bridge (SR 145), most likely as a result of sand and gravel mining (Cain 1997, JSA and MEI 1998). Although there has been about one foot of bed lowering at the Avenue 7½ Bridge at Firebaugh, it is not clear whether there has been degradation or whether the difference in elevations is caused by local subsidence (MEI 2000b). At the Santa Rita Bridge (SR 152), there is little doubt that there has been aggradation, probably as a result of backwater caused by a narrow channel section downstream. Within the Eastside Bypass, the SR 152 bridge crossing shows clear evidence of up to 3.5 feet of degradation between 1972 and 1997. The degradation of the Eastside Bypass channel near State Route 152 is responsible for aggradation and loss of hydraulic capacity in the bypass immediately downstream of the Sand Slough Control Structure. In the lower reaches of the San Joaquin River, there is no clear evidence for either aggradation or degradation of the channel associated with road crossings. Comparative survey data at the SR 165 Bridge indicate no change between 1972 and 1997, but the comparative data at the SR 140 Bridge show about 1.6 feet of degradation in the same time period.

Table 3-13. Listing of bridge and culvert crossings of the San Joaquin River between Friant Dam and the Merced River.

Transportation Element	Location (River Mile)	Comments
North Fork Road Bridge	266.7	
Ledger Island Bridge	262.2	
Culvert	258.5	Probably washed out at high flows, causes backwater at lower flows
SR 41 Bridge (Lane's Bridge)	255.3	Recently replaced with bridge with greater conveyance capacity. 5.4 feet of channel degradation between 1940 and 1997 (Cain 1997).
Culvert	252.8	Probably washed out at high flows, causes backwater at lower flows
AT & SF Railroad Bridge	245.1	
SR 99	243.2	5.6 feet of channel degradation between 1970 and 1997 (Cain 1997)
SR 145 (Skaggs Bridge)	234.1	Causes some backwater at higher flows
Bifurcation Structure	216.1	Causes backwater at higher flows
Concrete Dip Crossing at San Mateo Road	211.8	Barrier to fish passage at low flows
Avenue 7½ Bridge, Firebaugh	195.2	Two bridge openings. 2.2 feet of channel degradation between 1970 and 1997 (JSA and MEI 1998)
SR 152 Bridge (Santa Rita Bridge)	173.9	3.3 feet of channel aggradation between 1972 and 1997 (JSA and MEI 1998)
Culvert	163.1	Probably washed out at high flows
Turner Is. Road Bridge	157.2	
Culvert	153.4	Probably washed out at high flows, causes backwater at lower flows
SR 165 Bridge (Lander Avenue)	132.9	Causes some backwater at higher flows
SR 140 Bridge (Freemont Ford)	125.1	Causes some backwater at higher flows; 1.6 feet of channel degradation between 1972 and 1997 (JSA and MEI 1998)

Bridge and culvert crossings that constrict flow tend to have the following impacts to fluvial processes and channel form (Figure 3-63):

- Channel constrictions cause backwater effects upstream of the constriction, encouraging sediment deposition at the upstream extent of the backwater,
- The channel constriction elevates water surface elevation and increases velocity, causing local scour at the constriction,
- Flow expansion downstream of the constriction causes sediment deposition, such that splayed bars often form immediately downstream of the constriction,
- Fill associated with bridge or culvert abutments eliminates large portions of function floodplain and reduces flood conveyance capacity.

Cumulatively, constrictive road crossings impair sediment routing through the reach, and cause dramatic changes in the local slope. Figure 3-20 illustrates these impact on the longitudinal thalweg profile, as well as impacts on the water surface profile at high flows. Bridges that do not constrict the floodway tend to have few impacts on sediment routing and the longitudinal profile.

3.10.2. Water Supply Infrastructure

Water-supply infrastructure elements along the San Joaquin River between Friant Dam and the Merced River include dams, diversions, and canals. Table 3-14 identifies the locations of the major structures in the study area.

Table 3-14. Summary of major water-supply elements between Friant Dam and the Merced River that may influence fluvial processes and channel form.

Element	Location (River Mile)	Comments
Friant Dam	267.5	Millerton Lake has 530,000 acre-ft of storage, 170,000 acre-ft is be reserved for flood control during the winter months. Reservoir eliminates sediment supply to the study area from the upper watershed. Most stored water is delivered via Friant-Kern and Friant-Madera Canals. Barrier to upstream fish passage.
Big Willow Unit Diversion	261.3	Cobble and rock weir structure diverts flow to the CDFG fish hatchery
Rank Island Diversion	260	Cobble weir structure diverts about 5 cfs
Unnamed Diversion	247.2	Rock weir provides head for a pump upstream
Unnamed Diversion	228.2	Sand and gravel berm constructed to provide head for upstream pump, extends across most of river and forces river flow through narrow slot on right bank.
Mendota Dam	204.6	Low-head dam that provides the headworks for distributing water brought into the system through the Delta Mendota Canal. Mendota Pool has no flood storage capacity. Barrier to upstream fish passage at all flows with boards installed and without replacing old fish ladder.

Table 3-14. cont.

Element	Location (River Mile)	Comments
Sack Dam	182.0	Low-head earth and concrete structure with wooden flap gates that diverts Delta Mendota Canal flows into the Arroyo Canal. Fish ladder could be easily modified to permit fish passage. Sack Dam likely has small to no impact to sediment routing over the long-term
Columbia Canal	206-183	Right bank canal that borders the river, dissecting the historic floodplain and confines high flows
Helm Ditch	204.6-197.5	Left bank canal that borders the river, dissecting the historic floodplain and confines high flows
Poso Canal	194-176.3	Left bank canal that borders the river, dissecting the historic floodplain and confines high flows
Riverside Canal	176.3-168.5	Left bank canal that borders the river, dissecting the historic floodplain and confines high flows
Arroyo Canal	182.1	Left bank canal conveys DMC water, does not border the river, thus has no direct impact on high flows.

The major water-supply-related impacts on the San Joaquin River are caused by Friant Dam. Because most of the runoff stored in Millerton Lake is diverted from the San Joaquin River system via the Friant-Kern and Madera Canals, the bed of the river is usually dry in most years between Gravelly Ford (RM 229) and Mendota Pool (RM 206). Water imported via the Delta Mendota Canal provides flows to the San Joaquin River between Mendota Dam (RM 204.6) and Sack Dam (RM 182.1), but the bed of the river is again dewatered as far downstream as the confluence of the Mariposa Bypass (RM 147.2) in most years. Agricultural tailwater conveyed to the San Joaquin River via drains provides some flow in the river downstream of the Mariposa Bypass confluence. Smaller infrastructure associated with riparian diversions (pumps, gravel berms) does not have significant geomorphic impacts to the river, unless there is rip-rap protection of the infrastructure that could impair the ability of the channel to migrate.

The canal embankments that border both sides of the San Joaquin River between Mendota Dam (RM 204.6) and the Sand Slough Control Structure (RM 168.5) effectively form a set of nonproject levees that have greatly reduced the width of the floodplain, primarily on the east side of the river. In addition to the direct impact of dissecting the historic floodplain from the San Joaquin River, the confinement of the canal embankments increases water depths and velocities during infrequent periods of high flow, which increases sediment transport capacity. Combined with the reduction in sediment supply by upstream dams, the cumulative impacts of the confinement and reduced sediment supply can result in accelerated channel incision, bed armoring, and channel simplification (McBain and Trush, 1998). Canal embankments and associated bank protection also halts channel migration and avulsion processes, which reduces or eliminates floodplain and oxbow formation processes. Elimination of floodplain and oxbow formation processes can have negative impacts on species that depend on these large-scale formative processes for habitat creation (Greco 1999).

3.10.3. Flood Control Projects

The State of California constructed the Eastside Bypass project from the Merced River upstream to the head of the Chowchilla Bypass between 1959 and 1966. The bypass system and its associated levees isolated about 240,000 acres of floodplain from the river (ACOE 1993). The bypass system consists primarily of human-made channels. The Chowchilla Bifurcation Structure diverts most flood

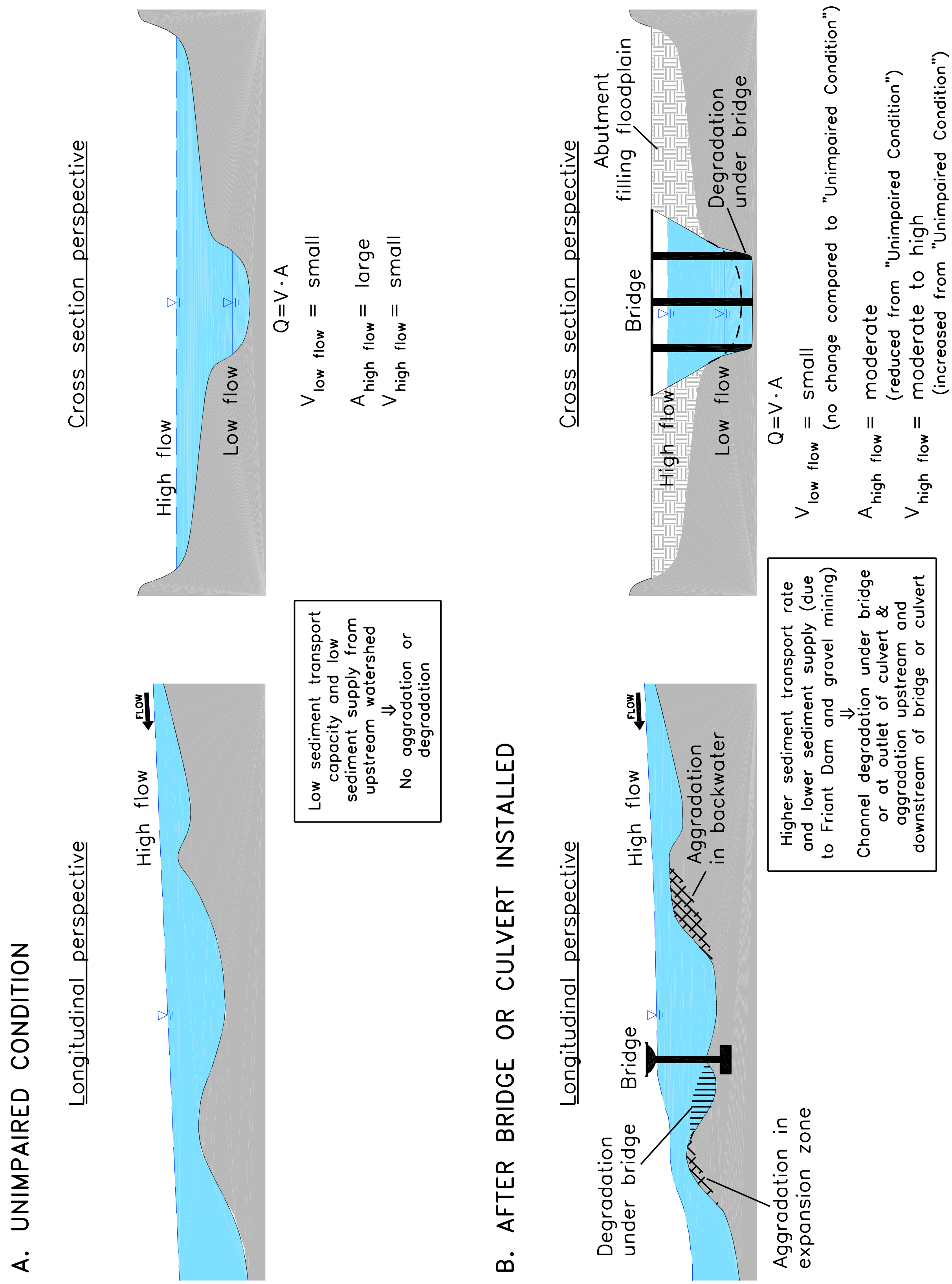


Figure 3-63. Conceptual impacts of local floodway constrictions (bridges and culverts) to hydraulics, local bed scour/degradation, and local bed deposition/aggradation.

flows and sediment from the San Joaquin River at the Reach 2A/2B boundary into the Chowchilla Bypass. The Sand Slough Control Structure again diverts flood flows and sediment from the San Joaquin River at the Reach 4A/4B boundary into the Eastside Bypass. The Mariposa Bifurcation Structure is located within the Eastside Bypass, and diverts a portion of flood flows and sediment load in the Eastside Bypass back into the San Joaquin River via the Mariposa Bypass (Figure 3-2). The San Joaquin River Flood Control Project consists of about 193 miles of levees, several control structures (Chowchilla Bifurcation Structure, Sand Slough Control Structure, Mariposa Bifurcation Structure) and other appurtenant facilities (Mariposa Bypass Drop Structure, Ash Slough Drop Structure). The system was designed to provide a 50-year level of protection (Hill pers. comm.).

Nonproject levees have been constructed on both sides of the river by local landowners from the Chowchilla Bifurcation Structure (RM 216.1) to Mendota Pool (RM 206) and from Mendota Dam to the Sand Slough Control Structure (RM 168.5). Local levees also border the channel between Sand Slough Control Structure and the downstream end of the Mariposa Bypass where the project levees begin (RM 147.2)

During flood periods, additional flood flows enter Mendota Pool from the Kings River North via James Bypass and Fresno Slough. Flows in the Kings River North are controlled by the operation of Pine Flat Dam, where a weir directs flows to the north up to the channel capacity of the James Bypass and then directs any additional flows into the south channel into the Tulare Lake area. Although early studies indicated that the capacity of the Kings River North was about 4,500 cfs, flows up to 6,000 cfs have passed through the reach (ACOE 1993). Under impaired conditions, the flow contribution from the Kings River North and Fresno Slough to the San Joaquin River was likely considerably more than present conditions; thus, flood control operations on the Kings River (as well as Fresno River, Chowchilla River, and other tributaries) has reduced the high flow contribution to Reaches 3-5 of the San Joaquin River.

The Sand Slough Control Structure, located at RM 168.5, controls the flow split between the mainstem San Joaquin River and the Eastside Bypass. There are no published operating rules for the structure during low flows, but the rules theoretically limit high flows routed to Reach 4B to the design discharge of 1,500 cfs. However, the headgates controlling flows into Reach 4B have not been opened recently, which causes all flows to be diverted into the Eastside Bypass. Even if the headgates were opened during high flows, the present capacity of portions of Reach 4B is limited, and the channel could only convey 300 to 400 cfs (MEI 2000b).

The State of California also has a designated floodway program that is administered by the Reclamation Board. The designated floodway provides a nonstructural means of reducing potential flood damages by preventing encroachments into flood-prone areas. Designated floodways are located along the Kings River North, and between Friant Dam and the head of the project levees (RM 227), as well as between Salt Slough confluence (RM 168) and the Merced River confluence (RM 118.3). Regulatory requirements of the Reclamation Board require that the San Joaquin River Levee District maintain the capacity of the designated floodway. “Maintenance” includes periodically removing riparian vegetation and removal of large wood debris that may impair flood conveyance.

Hydraulic capacities of the leveed reaches, without regard to freeboard requirements or to the stability of the levees, were estimated with 1-D hydraulic models (HEC-2) (MEI 2000a, MEI 2000b). Upstream of the Chowchilla Bifurcation Structure (RM 216.1), the project levees extend as far as RM 225 on the left (south) bank and RM 227 on the right (north) bank. The maximum levee capacity predicted from the hydraulic models without any freeboard is about 16,000 cfs in this reach (see Figure 5-7). The ACOE criteria provide 3 feet of freeboard, with a maximum design capacity of 8,000 cfs. However, San Joaquin River Levee District staff have observed piping and seepage problems well before the design flow of 8,000 cfs. Eleven levee breaks occurred in this reach during the 1997 flood as a result of piping failure (See Figure 5-6). Because of aggradation in the channel as a result of the levee confinement and the backwater generated by the Chowchilla Bifurcation Structure, the bed of the channel in the downstream portion of Reach 2A is elevated above some of the orchard lands adjacent to the levees in the lower part of the reach. Periods of sustained high flows in the river result in seepage damage in the orchards (Hill pers. comm.).

Between the Chowchilla Bifurcation Structure (RM 216.1) and Mendota Pool (RM 206), the San Joaquin River is bounded by nonproject local levees. Current operating rules for the flood control system limit flows in the river to 2,500 cfs when the discharge in the river upstream of the Bifurcation Structure is 8,000 cfs. When the discharge in the river upstream of the Bifurcation Structure reaches 12,000 cfs, the release into the river is increased to 6,500 cfs. Water-surface profiles predicted from hydraulic models (see Figure 5-7) indicate that about 4,500 cfs could be released into the river without overtopping of the nonproject levees. At higher discharges, a number of the levees would be overtopped. However, even if the levees were not overtopped, it is likely that they would fail as a result of piping. Seepage problems are reported to occur in Reach 2B at discharges in excess of 1,300 cfs (White pers. comm).

Between Mendota Dam (RM 204.6) and the Sand Slough Control Structure (RM 168.5), the San Joaquin River is bordered by canal embankments that act as nonproject levees. The hydraulic capacity of the channel between these levees, without any freeboard considerations or taking into account the stability of the levees themselves, was determined with an HEC-2 model (MEI 2000b). Between Mendota Dam and Avenue 7½ Bridge at Firebaugh (RM 195.2), the channel capacity is on the order of 8,000 cfs, except for a short reach where the capacity is closer to 6,000 cfs (see Figure 5-8). The design discharge for the reach is 4,500 cfs, which was set to minimize flooding of agricultural lands between the canals (Hill pers. comm.). Between Avenue 7½ Bridge and Sack Dam (RM 182.1), the channel capacity is about 8,000 cfs (see Figure 5-8). Between Sack Dam and SR 152 (RM 173.9), the channel capacity is also about 8,000 cfs (Figure 3-44). Between SR 152 and the Sand Slough Control Structure (RM 168.5), the channel capacity is also about 8,000 cfs (Figure 3-44).

Between the Sand Slough Control Structure and Turner Island Road (RM 157.2), the channel is bounded by local levees, and the capacity is about 600 cfs (Figure 3-45). Design discharge for this reach of the river is 1,500 cfs, but because of agricultural encroachments in the channel and extensive riparian vegetation, the effective capacity is much less. In recent years, the headgates controlling flows into Reach 4B at the Sand Slough Control Structure have not been opened. Between Turner Island Road and the start of the project levees upstream of the Mariposa Bypass (RM 151), the capacity is between 600 and 1,000 cfs. Within the project levees, the capacity increases to more than 1,500 cfs (Figure 3-46). From the Mariposa Bypass confluence (RM 147.2) to the Eastside Bypass confluence (RM 136), the channel capacity is in excess of the 10,000-cfs design flow (Figure 3-46). Between Eastside Bypass confluence and the downstream end of the project levee on the left bank of the river, the capacity is in excess of the 26,000-cfs design flow level (Figure 3-53). In the floodway section from the downstream end of the project levee to the Merced River confluence, the capacity is about 26,000 cfs (Figure 3-53).

In addition to the direct impact of dissecting the historic floodplain from the San Joaquin River, the structural confinement caused by nonproject dikes and San Joaquin River Flood Control Project levees increase water depths and velocities during infrequent periods of high flow, which increases sediment transport capacity. Combined with the reduction in sediment supply by upstream dams, the cumulative impacts of the confinement and reduced sediment supply can result in accelerated channel incision, bed armoring, and channel simplification (McBain and Trush, 1998). Levee, dikes, and associated bank protection also halts channel migration and avulsion processes, which reduces or eliminates floodplain and oxbow formation processes. Elimination of floodplain and oxbow formation processes can have negative impacts on species that depend on these large-scale formative processes for habitat creation (Grecco 1999, McBain and Trush 1998).

3.10.4. Sand and Gravel Mining

Between Friant Dam (RM 267.5) and Skaggs Bridge (RM 234.1), there has been considerable in-channel and channel-margin (floodplain and terraces) mining for sand and gravel. The mining began in earnest in the early 1940s. For Reach 1A, Cain (1997) estimated that 1,562,000 yd^3 were removed from the active channel of the San Joaquin River between 1939 and 1989, and 3,103,000 yd^3 were removed from the floodplain and terraces. Reach 1B does not have nearly the level of aggregate extraction, with 107,000 yd^3 removed from the active channel, and 72,000 yd^3 removed from floodplains and terraces. Based on comparative cross sections, it is apparent that the channel has locally degraded since 1939 (Table 3-5) and that channel degradation may well have been greater from the combined effects of the sand and gravel mining and elimination of the upstream sediment supply by Friant Dam had it not been for the presence of bedrock outcrops in the bed of the channel in Reach 1A (Cain 1997). The bed of the channel has degraded in many locations, with former floodplains now functional terraces in reaches where the historic floodplain has not been mined or modified by agricultural activities.

The captured pits and floodplain pits provide some flood peak attenuation benefits, but have had negative impacts on the continuity of sediment transport and routing (Figure 3-64), availability of spawning gravels, and potentially elevated water temperatures (Kondolf and Swanson, 1993). Table 3-15 summarizes the total mined area along the river, including the breached pits through which the river currently flows, and Table 3-16 identifies the specific locations where the river has captured the pits. Based on the available data, it appears that under existing conditions about 3.3 miles of channel (17,424 feet) would have to be reconstructed to provide a single continuous channel and fully restore sediment routing through Reach 1.

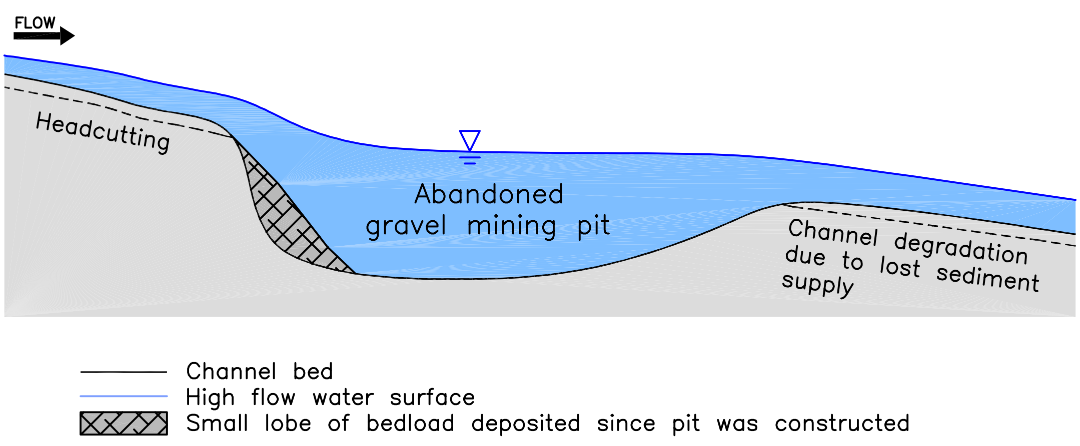


Figure 3-64. Conceptual impact of instream gravel pit or captured "off-channel" gravel pit on bedload routing through Reach 1 of the San Joaquin River. Upstream sediment supply and transport is so small that it would take centuries for the river to naturally fill these large pits.

Table 3-15. Aggregate mining areas along the San Joaquin River between Friant Dam and Skaggs Bridge.

Reach	Total area of mining pits (acres)	Area of pits captured by river (acres)	Percentage of pits captured
Friant Dam (RM 267.5)—SR 41 (RM 255.2)	494.5	7.5	1.5
SR 41 (RM 255.2)—SR 99 (243.2)	784.4	155.4	19.8
SR 99 (RM 243.2)—Skaggs Bridge (232.8)	76.2	26.8	35.1
Total	1,355.1	189.7	14.0

Table 3-16. Locations of captured mining pits captured along the San Joaquin River between Friant Dam and Skaggs Bridge.

Location (RM–RM)	Pit/channel length (feet)	Pit area (acres)
258.5–258.8	1,584	7.7
253.4–254.2	4,224	67.3
252.8–253.4	3,168	23.7
252.3–252.8	2,640	42.5
246.3–246.5	1,056	9.2
243.9–244.1	1,056	2.8
243.8–243.9	528	9.9
240.9–241.3	2,112	11.3
233.2–233.4	1,056	15.5
Total	17,424	189.7

Some sand mining by local landowners occurs in Reach 2 within the levees. However, even though the pits are sometimes as deep as 10–15 feet, they appear to be filled during a single flood control release from Friant Dam. A 200,000 yd^3 sediment detention basin is located in the upstream section of the Chowchilla Bypass, and it was designed to store about 1.5 times the project storm bedload yield. Sediment continuity analyses indicate that the trap will fill within a 2 to 3-month period (MEI 2000a). Additionally, aggradation is occurring in the Eastside Bypass immediately downstream of Sand Slough Control Structure, and this sediment is periodically removed because of the ongoing aggradation problem and its impacts on the conveyance capacity of the bypass (ACOE 1993). Most of the deposited sediment is derived from erosion of the bed of the Eastside Bypass (JSA and MEI 1998). Subsidence-induced sediment deposition required the Corps to remove about 1 million cubic yards of deposited sand from the lower 1.5 to 2 miles of the Eastside Bypass in 1985 because the bypass capacity had been reduced from about 16,500 cfs to 6,000 to 7,000 cfs (ACOE 1993).

3.10.5. Subsidence

The geologic evidence indicates that the San Joaquin Valley has been undergoing almost continuous deformation since the Mesozoic age (Davis and Green 1962, Bull and Miller 1975). Geologically driven subsidence of the valley is ongoing and is on the order of 0.25 mm per year (Janda 1965, Ouchi 1983). The combination of excessive groundwater pumping and hydrocompaction of lands adjacent to the San Joaquin River due to irrigation and agriculture has led to accelerated subsidence in and around Los Banos–Kettleman City since the 1920s (Poland et al. 1975, Bull 1964, Basagaoglu et al. 1999), resulting in levee subsidence and possible impairment sediment routing through Reach 2 and 3. Maximum amounts of subsidence (about 30 feet since the 1920s) have occurred in the Los Banos–Kettleman City area, but from 1 to 6 feet of subsidence have occurred along portions of the San Joaquin River between Mendota and about Los Banos, a rate of 35 to 45 mm/year (Ouchi 1983). Levee subsidence and sediment accumulation had reduced flood capacity of the lower 1.5 to 2 miles of the Eastside Bypass to about 6,000 to 7,000 cfs from the design capacity of 16,500 cfs (ACOE 1993). To correct the problem, the ACOE removed about 1 million cubic yards of sediment, and the Lower San Joaquin Levee District (LSJLD) raised the levee height by 3 feet. Subsidence is discussed in more detail in Chapter 5; no quantitative evaluation of the effect of subsidence on sediment routing has been performed to date.

Comparison of thalweg elevations at cross sections that were originally surveyed by the ACOE (1917) in 1913/1914 with 1998 ACOE survey data indicate that there has been general bed lowering in Reaches 4A and 3 (JSA and MEI 1998). The bed has lowered from 1.5 to 10.8 feet, with the higher values of bed lowering being recorded closer to Mendota, where the recorded subsidence has been on the order of 6 feet. However, because of the subsidence, it is not known whether the apparent degradation is a result of subsidence or is attributable to human-induced changes to sediment supply and hydrology. As part of the Sacramento and San Joaquin River Basins Comprehensive Study, the ACOE is running first order cross valley survey traverses to determine the degree and extent of subsidence in the valley. Until these traverses are completed, it will not be possible to resolve many of the apparent datum problems in the valley or to determine whether the San Joaquin River has truly degraded downstream of Mendota Dam.

3.10.6. Riparian Encroachment

Riparian levees are naturally found along rivers and streams (Russel 1902), and are often caused by riparian-induced roughness above the bankfull margins (e.g., historical conditions in Reach 4 and 5). In an unregulated river, these berms often mark the transition from coarse mobile alluvial deposits in the active channel to fine-grained floodplain deposits, typically near the edge of the bankfull channel. Shear stresses within the bankfull channel are usually sufficient to scour riparian seedlings under unimpaired flow and sediment conditions, such that exposed sand and gravel bars are maintained relatively free of riparian vegetation. However, the reduction of the high flow regime initiates a riparian encroachment process. This process is illustrated from conceptual drawings of the riparian encroachment process on the Trinity River, in northern California, from Bair (2001) (Figure 3-65):

- Under unimpaired conditions, initiating riparian plants on lower bar surfaces in the summer months would be scoured away by large winter floods or snowmelt peaks in the coming year(s)
- Woody riparian plants germinate along the low flow edge of exposed sand and gravel bars. Once flow regulation begins, the frequency of large winter floods and snowmelt peaks decrease, allowing riparian vegetation to establish and grow. The first woody plant to establish along the low flow channel is typically narrowleaf willow (*Salix exigua*), a willow shrub that tends to form dense monotypic stands (Pelzman 1973).
- As the plants grow, they begin to influence hydraulics during those infrequent periods when fine sediment is transported, causing deposition of fine sediment along these rougher areas along the low flow channel. Narrowleaf willow shrubs typically have a high stem density,

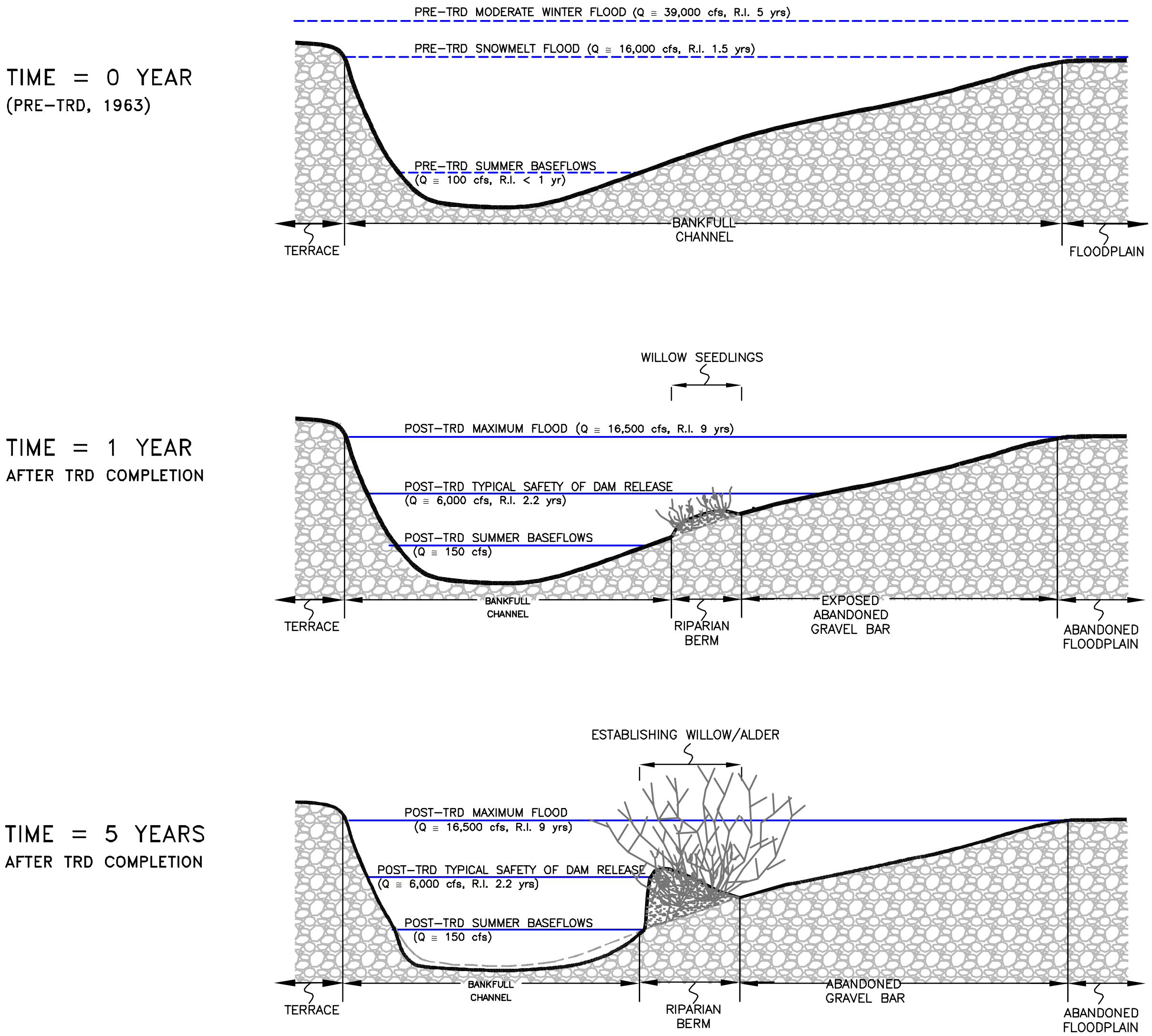


Figure 3-65. Riparian encroachment process on an alluvial river resulting from severe flow regulation (Bair 2001).

which reduce water velocities and facilitates coarse sand deposition. A small sand berm quickly develops within the narrowleaf willow stands (Ritter 1968), and with time and infrequent high flows, the riparian berm grows in width and elevation. As fine sediments deposit, more seedlings establish in the favorable seedbeds, and a self-perpetuating process begins (more riparian vegetation inducing more sediment deposition). As narrowleaf willow stands develop, white alder (*Alnus rhombifolia*) seed deposits in the sandy berm. These seeds germinate and an overstory of white alder becomes established.

- Within 5-10 years, the riparian vegetation is sufficiently large that the post-dam flood flow regime can no longer remove the plants. If an adequate fine sediment supply is available, the berms can continue to grow in height and width until they reach a height where post-dam floods rarely overtop them.

Sediment captured by mature riparian woody plants creates berms that may reach heights of 15 feet from the channel bed (McBain and Trush 1997, Peltzman 1973). The degree of berm development depends on the magnitude of the fine sediment supply and the high flow regime. Riparian encroachment on the San Joaquin River occurs, but the degree of berm development does not appear as severe as on the Trinity River. In some cases, the riparian encroachment process increases the amount of riparian vegetation on larger gravel bedded rivers compared to unimpaired conditions; in other cases, the riparian vegetation on historic floodplains eventually die off, such that there is a net decrease in riparian vegetation. There are also many geomorphic and ecological impacts of riparian berms. The riparian berms confine the river during moderate flows, increasing shear stress fields and sediment transport compared to the channel if no berm was in place. Because upstream dams eliminate sediment supply from the upper watershed, the combination of reduced sediment supply and higher transport rate due to channel confinement accelerates channel incision and/or armoring (McBain and Trush 1997, McBain and Trush 1998). Furthermore, the riparian vegetation armors the bars to the point where sediment stored in the bars is functionally taken out of production for use as aquatic habitat. Riparian encroachment also eliminates channel migration. Ecologically, there are benefits to avian and mammal habitat by the increased riparian vegetation. However, there are negative impacts to salmonids by the change in channel morphology caused by the riparian berms (USFWS 1999). The fossilization of alluvial deposits by riparian vegetation, and corresponding confinement-induced changes to sediment transport rates, tends to simplify channel morphology and associated aquatic habitat. Gently sloping gravel bars, backwater channels, median bars, and other formerly dynamic and complex alluvial features are lost, replaced with a simplified, rectangular channel morphology (USFWS 1999).

3.11. SUMMARY

The unimpaired fluvial processes and resulting channel form created a complex river ecosystem along the San Joaquin River that supported a wide range of aquatic and terrestrial species. The unimpaired conditions provided reach-specific channel complexity (bars, backwaters, side channels, etc.), as well as longitudinal changes in channel morphology (e.g., gravel-bedded reach to sand bedded reaches to flood basins). Cumulative changes from flow and sediment management, land use, and infrastructure have reduced both types of complexity, making the five reaches more similar to each other than under unimpaired conditions. Based on review of historical information, the following major points can be made about historical channel form and processes of the San Joaquin River:

- Unimpaired sediment supply to Reach 1 from the upper watershed was low compared to other comparable Central Valley rivers exiting the Sierra Nevada.
- Reach 1 has an unusually low gradient compared to other comparable Central Valley rivers exiting the Sierra Nevada, which results in low predicted sediment transport rates and large predicted discharges for bed mobility (12,000 cfs to 16,000 cfs or greater)
- Channel migration rates and avulsion frequency appeared to be low in most reaches, with the largest amount of lateral movement occurring in Reaches 2 and 3.
- Sediment supply decreased in the downstream direction as sediment deposited in Reaches 1, 2, and 3. The low sediment supply in Reach 4 and 5, combined with the backwater effect of the Merced River alluvial fan, created the flood basin morphology characteristic of Reach 4 and 5. The low sediment supply in Reach 4 and 5 resulted in small (compared to other Central Valley rivers) natural levees along the primary and secondary channels, which was the primary establishment location for woody riparian vegetation.

The cumulative effects of flow and sediment regulation, aggregate extraction and agricultural conversion of adjacent floodplains, local dikes, and infrastructure of the San Joaquin River Flood Control Project have (1) reduced floodway width and area, (2) simplified channel morphology on a reach-specific scale, and (3) simplified channel morphology on a river-wide scale (loss of longitudinal diversity in channel morphology). Furthermore:

- Instream and floodplain aggregate extraction has had a major impact on channel form and processes in Reach 1 (and lesser impact on Reach 2), extracting much greater volumes of sediment than would have been delivered to the San Joaquin River under unimpaired conditions. This impact is even greater now that Friant Dam blocks all sediment supply from the upper watershed. Instream pits or breached floodplain pits have eliminated riparian habitat, destroyed natural channel form, interrupts coarse sediment continuity through the river, and provides habitat for fish species that prey on juvenile salmonids.
- Friant Dam has eliminated sediment supply from the upper watershed, which has likely reduced coarse sediment storage in Reach 1 and silt supply to all reaches. The impact of this reduced coarse sediment supply is mitigated to a large degree by the huge reduction of peak flows capable of transporting sediment and by the naturally low slope in Reach 1 (small coarse sediment transport capacity).
- Associated channel aggradation and degradation has been locally variable, with most significant degradation (incision) associated with instream aggregate extraction, and most significant aggradation associated with the backwater effect of the Chowchilla Bifurcation Structure in the lower portion of Reach 2A.
- The extensive tule marshes in Reaches 3, 4, and 5 have been largely eliminated. While the bypass still provides some “overbank” flow, the prolonged flooding of flood basins and floodplains rarely occurs. In addition, the confinement of the river channel and bypasses by levees provides varying levels of protection to agricultural lands; however, the levees tend to reduce the flood peak attenuation benefits of the historic flood basins and floodplains, as well as reducing inundated riparian/wetland habitats.
- Channel migration and avulsion functionally no longer occurs; in limited areas where it does occur (primarily Reach 2), waste concrete is often placed along the banks in an attempt to cease migration.
- The width of the floodway and extent of functional floodplain has been greatly decreased by levees, dikes, bypasses, and agricultural reclamation.
- Sediment routing through Reach 2 is largely diverted into the Chowchilla Bypass, and remaining sediment supply into Reach 3 is periodically impaired by Mendota Dam.

The following sections summarize historical/unimpaired conditions, characterize changes from these historical/unimpaired conditions, and summarize associated opportunities and constraints to future restoration efforts.

3.11.1. Sediment Regime

The unimpaired sediment regime changes longitudinally through the study reach. Unimpaired sediment supply to Reach 1 includes a wide range of grain sizes (cobbles to silts), which results in the gravel-bedded channel morphology in Reach 1. As slope and confinement decreases between Reach 1 and Reach 2, coarser sediments have been deposited in Reach 1, such that Reaches 2 through 5 are sand-bedded. The magnitude of the sand supply to downstream reaches continues to decrease with decreasing slope and absence of tributaries contributing sediment. The longitudinal reduction of sediment supply had implications on channel morphology. By Reach 4, the sediment supply has been reduced to the point where floodplains were replaced with flood basins, and sediment deposition is concentrated along riparian levees along the primary channels. The flood basin and low slope prevents tributary streams (e.g., Chowchilla River, Fresno River) from contributing sediment to the mainstem San Joaquin River in downstream reaches. Only at the confluence of the Merced River does sediment supply rapidly increase.

The unimpaired sediment supply from the upper watershed is most likely small compared to other Central Valley rivers. Upstream dams have eliminated this small sediment supply from the upper watershed. Loss of coarse sediment (cobbles and gravels) from the upper watershed, combined with large-scale aggregate removal from the channel, floodplain, and tributaries (Little Dry Creek), has reduced the amount of coarse sediment storage in Reach 1 and likely caused local channel incision and armoring of the channel bed. The loss of coarse sediment supply has likely reduced spawning habitat in Reach 1 and contributed to the reduced magnitude, duration, and frequency of geomorphic processes (bedload transport, channel migration, floodplain formation). Additionally, the loss of fine sediment supply (silts) from the upper watershed, combined with the reduced magnitude, duration, and frequency of overbank flows, may impair floodplain formation processes and riparian regeneration success in all reaches.

Field observations in the late 1800s and 1937 aerial photographs suggest that in-channel sand storage in Reach 1 was large even under unimpaired conditions; reduction of the high flow regime by upstream dams and continued contribution of fine sediment from Cottonwood Creek and other sources caused in-channel storage of sand to remain large. Quantitative estimates of contemporary sand storage in Reach 1 have not been performed, but qualitative observations show extensive storage of sand on bars, in pools, in long runs, and in some riffles. Additionally, quantitative estimates of sand sources and the relative volumes contributed by each source has not been performed, and should be an important consideration for future restoration efforts of salmonid spawning and rearing habitat. This extensive sand storage in Reach 1 may represent a significant constraint on future salmonid production, as well as negating many of the benefits of salmonid spawning and rearing habitat restoration efforts (e.g., large sand supply reversing restoration efforts). Lastly, the transition from gravel-bedded channel to sand-bedded channel under unimpaired conditions likely occurred in the lower portions of Reach 1B downstream to Gravelly Ford. The reduction of the high flow regime and maintenance of fine sediment supply by tributaries and land use downstream of Friant Dam have likely functionally moved the gravel-bed-to-sand-bed transition upstream. No specific location of this new transition zone has been estimated.

Human structures in the floodway have also impacted the sediment regime on the San Joaquin River. The Chowchilla Bifurcation Structure is operated to divert most flood flows from the San Joaquin River into the Chowchilla Bypass. Because sediment transporting and routing is roughly proportional to the volume of flow, most sediment transported in Reach 2A is routed into the Chowchilla Bypass, resulting in large-scale deposition of sediment in the bypass, and associated large-scale removal of sediment supply to Reach 2B. The sediment supply and transport capacity in Reach 2B have been reduced by how the Chowchilla Bifurcation Structure is operated. Sediment that is transported in Reach 2B during high flows deposits in Mendota Pool if the boards in Mendota Dam are not removed during the high flow. Storage volume in Mendota Pool is low, and review of historic longitudinal profiles in Mendota Pool indicate that sediment is not filling the pool; thus it must be routing through the pool when the boards are pulled during high flows, or when the pool is periodically drained for inspection. Nonetheless, the Chowchilla Bifurcation Structure removes a large portion of sediment supply to Reach 3 and may represent a future constraint in restoring sediment supply to downstream reaches.

3.11.2. Fluvial Processes

Review of historical maps and aerial photographs suggests that rates of channel migration and frequency of channel avulsion were historically low, but did occur based on a moderate number of oxbows in Reaches 3 and 5, side channels and scour channels in Reach 1, and anabranching channels in Reaches 4 and 5. Small amounts of channel migration may have occurred in Reach 2, with more channel movement within the meander planform, rather than the meander planform migrating. The low migration rates in Reaches 4 and 5 were likely due to a combination of flows spreading out across the flood basin, low sediment supply, and cohesive bank sediment (JSA and MEI 1998); this condition of low migration rates is expected to continue in the future. Channel migration still occurs at local locations in Reaches 1, 2, and 3, but the rates are small. Restoring channel migration and avulsion processes in Reaches 1, 2, and 3 is constrained by local dikes and project levees. However, levee setbacks and removal of associated bank protection to improve flood control conveyance will also provide opportunities for restoring modest amounts of channel migration.

The channel slope in the reaches of the Tuolumne River, Merced River, and Stanislaus River exiting the Sierra Nevada foothills is steeper (0.0015) than Reach 1 of the San Joaquin River (0.00065). While the channel morphology between the San Joaquin River and these tributaries to the lower San Joaquin River is similar, the low slope of Reach 1 makes achieving fluvial geomorphic processes more difficult under the contemporary highly regulated flow and sediment regime downstream of Friant Dam. Modeling and empirical data suggest that under the existing particle size distribution in Reach 1A, flows exceeding 12,000 to 16,000 cfs would be needed to initiate mobilization of the gravel/cobble-bed surfaces. Modeling conducted to evaluate bed mobility thresholds have predicted that different combinations of (1) reduced particle size via gravel introduction, (2) reconstruction of channel geometry, (3) different assumptions on bed mobility model parameters, and (4) slope variations within Reach 1A could lower the discharge required to mobilize the bed surface, but discharges exceeding 12,000 cfs would still be required to mobilize the bed surface in portions of Reach 1 with the lowest slopes. Therefore, the low slope of Reach 1A is a major constraint in achieving fluvial geomorphic thresholds, even with extensive manipulation of channel geometry and gravel introduction.

3.11.3. Channel Morphology

Channel morphology under unimpaired conditions varied longitudinally from Reach 1 to Reach 5. Reach 1 was a predominately a gravel-bedded reach, with variable meanders and side channels. Bedrock control occurred in portions of Reach 1A, but all downstream reaches were purely alluvial. Floodplains and terraces occurred between moderately confining bluffs in Reach 1, with floodplains inundated by 1.5-year and less frequent floods (>10,000 cfs). Progressing downstream, the confining bluffs and terrace fall away from the river corridor in Reach 2. Extensive floodplains occurred in Reaches 2, 4, and upstream portions of Reach 4A; however, extensive tule marsh-dominated flood basins occurred downstream of Reach 3. Riparian levees provided some confinement to the primary channels in Reaches 4 and 5, but overbank flow occurred in most years, with flows greater than 2,000 to 4,000 cfs overtopping the levees and flooding the flood basins behind the levees.

Levees along the San Joaquin River, the bypass system, aggregate extraction, and agricultural land conversion have greatly reduced the surface area of functional floodplains and flood basins. Surface acreages of floodplain and flood basin loss have not been quantified in this report, but floodplain and flood basin widths have been reduced from 1,000’s of feet (Reach 1) to miles (Reaches 2-5) to as low as zero in many reaches (e.g., Reach 4). Efforts to increase the width and area of functional floodplains will be constrained by the infrastructure of the flood control system, as well as agricultural use on former floodplains. The narrow width of the floodway in Reach 4 represents a constraint to increasing floodway width, and the reduced hydrology of the system will make restoration of the historic tule marshes difficult. While restoring tule marshes in Reach 4 may face similar constraints, the wider floodway widths in the lower portions of Reach 4B downstream of the Mariposa Bypass and in Reach 5 may represent opportunities for local restoration of tule marsh and riparian habitat. However, restoration of tule marsh in these reaches will require some restoration of the hydrology that historically supported it. Lastly, the upstream portion of Reach 4B from the Sand Slough Control Structure to the Mariposa Bypass no longer receives flows from Reach 4A. This reach has a rated channel capacity for the San Joaquin River Flood Control Project of 1,500 cfs, so restoring this rated channel capacity in the upstream portion of Reach 4B represents an opportunity for restoring channel morphology and floodplains. Restoration of floodplains in these downstream reaches will be constrained by agricultural uses on these floodplains; however, as described in Chapter 10, opportunities for floodplain restoration is highest on lands farmed for lower value row crops, and those lands of marginal value due to poor soils or frequent flooding.

The extensive aggregate extraction in Reach 1 provides both restoration opportunities and constraints. While extensive aggregate extraction has occurred in many portions of Reach 1, this reach provides a floodplain restoration opportunity in that infrastructure encroachment into the former floodway is minor (due to periodic flood control releases from Friant Dam), the land purchase price is low because the valuable aggregate has been removed, and the societal conflicts to purchase mined lands is low. However, the cost of restoring these mined lands can be very high, up to several million dollars per mile based on recent restoration efforts on the Merced and Tuolumne rivers, and represents a large financial constraint.

Recreating a dynamic alternate bar morphology in Reach 1 is primarily constrained by the impaired high flow regime, but (1) lack of coarse sediment supply, (2) the naturally low slope of the reach, (3) infrastructure in the channel, and (3) frequent instream aggregate pits that function as bedload traps during infrequent periods of high flow sufficient to transport coarse sediment also constrain rehabilitation of this desirable morphology. Restoring bedload transport continuity through Reach 1 will be expensive due to the large number and volume of instream aggregate pits, and even if these pits are filled, flows greater than 7,600 cfs to 16,000 cfs will be required to begin mobilizing coarse sediments that create and maintain channel morphology. Therefore, efforts to restore dynamic alluvial features (bars, riffles, sidechannels) will be constrained by the risk of fossilization by encroaching riparian vegetation.

3.11.4. Floodplain Inundation Patterns

Based on 1914 maps and cross sections by the ACOE (1917), historic channel geometry was moderately confined by bluffs and terraces in Reach 1, less confined by floodplains in Reaches 2 and 3, and unconfined in Reaches 4 and 5. While the surveys that form the basis of these maps and cross sections occurred over 60 years after the first Euro-American manipulation of the river corridor, the inundation trends most likely reasonably represent unimpaired conditions (the primary change since 1850s being canal confinement in Reach 3 and 4A). Overbank flows in Reaches 1, 2, and 3 were moderately infrequent (> 10,000 cfs, approximate pre-Friant Dam 1.5-year flood) and of short duration (days during winter storms, week during snowmelt peaks). Overbank flows in Reaches 4 and 5 were more frequent (2,000 to 4,000 cfs, probably occurred on nearly a yearly basis with Fresno Slough flow contribution from the Kings River) and of long duration (a week during winter storms, weeks to months during snowmelt runoff). This pattern of inundation has dramatically changed with the San Joaquin River Flood Control Project. The combination of upstream dams, levees and dikes along the river, and the bypass system, has greatly reduced the magnitude, duration, and frequency of overbank flow in all reaches. Flows necessary to inundate floodplains in Reaches 1, 2, and 3, rarely occur, and while the duration of these higher flood control releases from Friant Dam can still be of long duration (days to weeks), the duration is still much less than unimpaired conditions (see Chapter 2).

Restoring floodplain inundation may require a combination of modifications to the high flow regime, levee setbacks, and/or mechanical restoration of floodplains. Additionally, mechanically creating floodplains in Reach 1 by lowering pre-dam gravel bars and floodplains can generate large quantities of gravel and cobbles, which could be screened and used for gravel introduction projects in Reach 1. The large monetary and land cost of restoring floodplains represents a constraint; however, existing flood control infrastructure is inadequate in most reaches to safely convey the 100-year flood (ACOE 1998), so a combined effort of floodplain restoration and floodway expansion represents an opportunity to achieve the multiple objectives of restoration and improved flood protection.

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