FINAL REPORT

Sacramento and San Joaquin River Basins Comprehensive Study, California

Geomorphic and Sediment Baseline Evaluation of the San Joaquin River from the Delta to the Confluence with the Merced River and Major Tributaries

Watershed Planning Services Contract No. DACW05-98-D-0020
Task Order No. 008

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April 2000

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1. INTRODUCTION

1.1. Background

This reconnaissance-level geomorphic, sediment transport and riparian ecology study of the San Joaquin River between Old River (River Mile 54) and the confluence with the Merced River at Hills Ferry (RM 118), was conducted as part of the Sacramento and San Joaquin River Basins Comprehensive Study, California. This work also considered the lower reaches of the major tributaries to the reach, Stanislaus, Tuolumne, and Merced Rivers. The Sacramento and San Joaquin River Basins Comprehensive Study (Comprehensive Study) was initiated by the Sacramento District of the U.S. Army Corps of Engineers (COE), the Reclamation Board of the State of California (RB), and the California Department of Water Resources (DWR) in cooperation with several other state and federal agencies.

The purpose of the Comprehensive Study is to identify means by which to reduce flood damages along waterways and basins in the Central Valley while restoring environmental resources in these areas. Flood-damage reduction and ecosystem restoration are the two general objectives of the study and measures will be proposed and evaluated to achieve both of these. The feasibility study will examine a full range of structural and nonstructural measures and strategies to ultimately lead to a new master plan for flood management for the Sacramento and San Joaquin River Basins. A complete description of the river system problems and opportunities for ecosystem restoration requires a basic understanding of the geomorphology of the system, its existing stability and sediment transport through the system. To date, little information on the geomorphology, sediment dynamics or riparian ecosystem is available for the project reach or the tributaries. The purpose of the current investigation is to remedy the lack of information for the project reach of the San Joaquin River and its major tributaries.

The project reach of the San Joaquin River is located in Merced, Stanislaus, and San Joaquin Counties, California (**Figure 1.1**). It extends from the Old River at RM 53 to the confluence with the Merced River at RM 118, a distance of 65 river miles. On the Merced River, the study reach extends from its confluence with the San Joaquin River to McSwain Lake, a distance of 35 river miles. The study reach of the Tuolumne River extends from the confluence with the San Joaquin River to Turlock Lake, a distance of 46 river miles. The project reach on the Stanislaus River extends from the confluence with the San Joaquin River to Knights Ferry, a distance of 55 river miles.

1.2. Authorization

This study of the San Joaquin River and its major tributaries was conducted for the Sacramento District, U.S. Army Corps of Engineers by Mussetter Engineering, Inc. (MEI) and Jones & Stokes Associates, Inc. (JSA). The project is part of the Sacramento and San Joaquin River Basins Comprehensive Study, California, and was conducted under the authority of Task Order No. 008, Watershed Planning Services Contract, DACW05-98-D-0020. Mr. Larry Dacus P.E. was the Sacramento District=s project manager. The principal investigators for Mussetter Engineering, Inc. were Michael D. Harvey, Ph.D., P.G. (Geomorphologist) and Robert A. Mussetter, Ph.D., P.E. (Hydraulic Engineer). Mr. Steven J. Chainey (Riparian Ecologist) was the principal investigator for Jones & Stokes Associates, Inc., and Mr. Alan Solbert (JSA) was the contract manager.

Figure 1.1. Map showing the locations of the project reach and subreaches of the San Joaquin River and the major tributaries.

1.3. Study Purposes and Objectives

The primary objectives of this investigation of the lower San Joaquin river and its major tributaries were to:

1. Determine, based on existing information and field reconnaissance, geologic, geomorphic, qualitative sediment transport and channel stability conditions through the study reach,

2. Qualitatively describe current sedimentation and channel stability trends through the study reach, and

3. Describe and explain the role of the existing riparian vegetation on channel stability and sedimentation patterns through the study reach, and qualitatively evaluate the potential for enhancement of riparian habitat.

To meet these objectives, a number of tasks were identified in the Scope of Work (SOW), as follows:

Task 1. Data Collection and Field Reconnaissance,
Task 2. Determination of Basin Geology,
Task 3. Determination of historical and present day Basin Geomorphology,
Task 4. Determination of Basin Sedimentology,
Task 5. Evaluation of Historic and Present Basin Hydrology,
Task 6. Qualitative Evaluation of Basin Hydraulics and Sediment Transport,
Task 7. Qualitative Evaluation of Existing Conditions Riparian Ecology,
Task 8. Qualitative Identification of Trends in Sediment Transport, Channel Stability and Vegetation Distribution, and
Task 9. Reports (Draft and Final).

1.4. Subreach Identification for San Joaquin River and Tributaries

The project reach of the San Joaquin River was subdivided into four subreaches on the basis of hydrological and geomorphic characteristics (Figure 1.1, **Appendix A**) The subreaches are as follows:

Subreach 1. Old River (RM 54) to the Stanislaus River (RM 74.8) - 20.8 miles, **Appendix A.1**
Subreach 2. Stanislaus River (RM 74.8) to Tuolumne River (RM 83.8) - 9 miles, **Appendix A.2**
Subreach 3. Tuolumne River (RM 83.8) to RM 99.5 - 15.7 miles, **Appendix A.3**
Subreach 4. RM 99.5 to the Merced River (RM 118) - 18.5 miles, **Appendix A.3**

The Stanislaus River study reach was subdivided into three subreaches on the basis of the degree of confinement of the river as follows (**Appendix A.4**):

Subreach S1. San Joaquin River to Head of Project Levees
Subreach S2. Head of Project Levees to Highway 120
Subreach S3. Highway 120 to Knight=s Ferry

The Tuolumne River study reach was subdivided into four subreaches on the basis of the degree of confinement of the river and the historical and present day man-made modifications to the system as follows (**Appendix A.4**):

Subreach T1. San Joaquin River to Shiloh Road
Subreach T2. Shiloh Road to J14 Road
Subreach T3. J14 Road to Robert=s Ferry
Subreach T4. Robert=s Ferry to La Grange

The study reach of the Merced River was subdivided on the basis of the degree of confinement and the historical and present day man-made modifications to the system as follows (**Appendix A.4**):

Subreach M1. San Joaquin River to River Road
Subreach M2. River Road to Shaffer Bridge
Subreach M3. Shaffer Bridge to Snelling Road Bridge
Subreach M4. Snelling Road Bridge to Merced Falls

1.5. Climate and General Hydrology

The annual precipitation in the San Joaquin River basin ranges from about 6 inches on the valley floor at Mendota to about 70 inches in the headwaters of the San Joaquin River in the Sierra Nevada. Precipitation in the valley occurs primarily in the November to April timeframe, and very little occurs during the summer months. The basins on the west side of the valley that drain the Coastal Ranges lie in a rain shadow and receive less precipitation than those on the east side of the valley that drain the Sierra Nevada. Snowpack accumulates on the east side of the basin above an elevation of about 5,000 feet, and the snowmelt generally begins to runoff by April (COE, 1993).

Two types of floods occur in the basin; those that result from intense rainfall during the late fall and winter and those that result from snowmelt during the spring and summer. The highest peak discharges occur from the rainfall-type floods, but the durations of flooding tend to be lower. Regional flood frequency curves (Pitlick, 1988) indicate that for rainfall-on-snow types of events in the central Sierra Nevada region, the magnitude of the 100-year event exceeds that of the mean annual flood by a factor of about 5. In contrast the 100-year snowmelt flood exceeds the mean annual flood by a factor of about 1.5. Prior to the 1997 flood, which had an estimated peak discharge of about 60,000 cfs downstream of Friant Dam, the largest rainfall flood recorded at the Friant gage (pre-dam) was 77,200 cfs in December 1937. The highest rainfall flood at the Newman gage was 36,900 cfs in March 1986, and at Vernalis, it was 79,000 cfs in December 1950 (**Table 1.1**) In contrast, the highest snowmelt flood at the same gages was 19,300 cfs in June 1968 and 37,300 cfs in May 1983, respectively (COE, 1993) (**Table 1.2**). Cain (1997), using simulated unimpaired flows at the Friant gage from 1908 to 1997 demonstrated that the largest floods (rain-on-snow) occurred in the upper reaches of the San Joaquin River basin between November and January. Before the development of the flood control and water storage projects in the basin, floodwaters were reported to stand in the lateral flood basins (tule basins) along the river for 3 to 5 months per year (Hall, 1887).

Table 1.1. Historic flooding from rain storms in San Joaquin River Basin (COE, 1993).					
San Joaquin River near Newman			San Joaquin River near Vernalis		
Date	Published Flow (cfs)	Exceedance Interval (years)	Date	Published Flow (cfs)	Exceedance Interval (years)
Dec 11, 1950	11,600	4	Dec 9, 1950	79,000[1]	160
Dec 29, 1955	16,800	8	Dec 25, 1955	50,900	60
Apr 6, 1958	21,600	13	Apr 5, 1958	41,400	41
Feb 26, 1969	34,700	50	Jan 27, 1969	52,600	65
Feb 25, 1980	23,500	18	Feb 27, 1980	33,900	9
Apr 17, 1982	20,300	12	Apr 18, 1982	29,800	8
Mar 4, 1983	30,300	40	Mar 7, 1983	45,100	45
Mar 19, 1986	36,900	60	Mar 18, 1986	23,100	5

[1]Estimated peak, including flow through levee breaks.

Table 1.2. Historic snowmelt flooding in San Joaquin River Basin (COE, 1993).					
San Joaquin River near Newman			San Joaquin River near Vernalis		
Date	Published Flow (cfs)	Exceedance Interval (years)	Date	Published Flow (cfs)	Exceedance Interval (years)
May 30,1952	13,200[1]	8	Jun 1, 1952	33,700	42
May 20,1958	11,600[1]	6	May 26,1958	29,100	18
Apr 27, 1967	15,400[1]	9	Apr 30, 1967	25,900	11
Jun 11, 1968	19,300[1]	18	Jun 1, 1968	35,000	50
Apr 29, 1978	15,300	9	May 3, 1978	26,200	17
May 4, 1983	18,400	16	May 6, 1983	37,300	60

[1] Does not include flows in Merced River Slough that bypass gage.

Reservoirs within the basin have significantly affected the flood hydrology in the basin. The peak of the 2-year event have been reduced by about 25 percent, and the 10-year flood peak has been reduced by about 41 percent (Bay Institute, 1997). Cain (1997), however argued that, although the water development projects have significantly affected the magnitude of the higher frequency floods, they have not affected the magnitudes of the less frequent events. In other words, the magnitude of the 200-year flood pre-and -post water development projects downstream of Friant Dam is similar (96,250 cfs). A more in-depth discussion of flood frequency and duration for the project reach and the individual major tributaries is provided in Chapter 4.

1.6. General Geology, Geomorphology and Soils

The San Joaquin River basin, an asymmetrical basin whose axis is offset to the west, lies between the crests of the Sierra Nevada and Coast Range, and extends from the northern boundary of the Tulare Lake basin (Kings River alluvial fan) to the southern boundary of the Sacramento-San Joaquin delta near Stockton. The basin is about 100 miles wide and about 120 miles in length. Elevations in the basin range from sea level at Stockton to about 13,000 feet in the Sierra Nevada. Within the project reach, floodplain elevations range from about 10 feet (msl) near Old River to 70 feet at Hills Ferry. The average slope of the San Joaquin River within the project reach varies from about 0.0001 to 0.00023 (0.5 to 1.2 ft/mile).

The San Joaquin River basin lies within parts of the Sierra Nevada, California Coast Range and the Great Central Valley geomorphic provinces. The Sierra Nevada is composed primarily of crystalline igneous rocks (granite, quartz monzonite, quartz diorite) with some metamorphic rocks (Western Metamorphic Belt) and volcanic and meta-volcanic rocks. The Coast range is composed of folded and faulted Jurassic and Cretaceous -age sedimentary rocks. The valley floor is underlain by relatively unconsolidated upper Tertiary- and Quaternary-age sediments that are water bearing, and are confined by the impermeable middle to late Pleistocene-age Corcoran clay (Norris and Webb, 1976).

The east side of the valley is composed of a series of coalesced alluvial fans that have formed at the base of the Sierras. The alluvial fans of the larger rivers, the Kings, San Joaquin, Merced, Tuolumne and Stanislaus Rivers have prograded out into the basin and have formed local baselevel controls and major geomorphic subunits along the valley. Each of the fans forms a local baselevel control. These fans have significantly affected the distribution of historic flood flows (Hall, 1887). The western margin of the valley along the project reach of the river is also composed of coalesced alluvial fans at the base of the Coastal Range. Major tributaries that are delivering coarser bed materials (gravels) to the project reach of the San Joaquin River include Del Puerto and Orestimba Creeks. From the foothills downstream to the San Joaquin River floodplain, the major eastside tributaries are deeply incised below confining Pleistocene-age terraces (Riverbank and Modesto) that are composed of paleo-alluvial fan sediments (Janda, 1965; Marchandt and Allwardt, 1978).

Soils in the valley bottom are poorly drained and fine textured and may be saline. Bordering, and just above, the basin bottoms are soils of the fans and floodplains, which are generally deep, well drained and fertile. Caliche layers are present within the soils of the distal fan margins. The soils of the terraces that border the outer edges of the valley are of poorer quality and have dense clay subsoils or hardpans at shallow depths (COE, 1993). Irrigation drainage (tailwater),especially in the reach upstream of the project reach, including Mud and Salt Sloughs, has been shown to contain high levels of salts, pesticides, and heavy metals. Since the cessation of discharge of tailwater to Kesterton National Wildlife Refuge, the discharge of agricultural tailwater to the San Joaquin River has doubled to the point where it now comprises about 12 percent of the flow in the river (Bay Institute, 1997). Salts and heavy metals loadings have increased significantly as a result (Saiki et al., 1993).

1.7. Riparian Vegetation

Riparian vegetation consists of the plant community that exists within a river channel and on the channel margins. Plant species that make up the riparian community tend to be adapted to the changing physical environment that characterizes a fluvial system. For example, Simon and Hupp (1987) demonstrated that specific geomorphic processes could be associated with riparian species in rapidly adjusting channels in Tennessee. The formation of fluvial landforms (bars, floodplains, and terraces) can be related to distinctive hydrogeomorphic processes (flow-duration and flood frequency) which appear to be largely independent of vegetation (Hupp and Osterkamp, 1985). Once established, however, vegetation is an integral part of the fluvial system. Riparian vegetation has the potential to affect sediment deposition, channel stability, and the channel dynamics (Williams and Wolman, 1984), but the persistence of riparian species depends on the stability of the substrate (Petts, 1979; Lisle, 1988; Hupp, 1988).

Many riparian species are able to tolerate burial by sediment (Hook and Brown, 1973; Harvey and Spitz, 1986; Harvey, Pitlick, and Laird, 1987; Simon and Hupp, 1987). However, this tolerance varies among species and appears to be dependent on the rate of sedimentation, the type of sediment deposited, and the age of the individual tree within a species (Harvey and Spitz, 1986). Because of increased hydraulic roughness, riparian species tend to induce sediment deposition in both channel and channel margin environments (Wilson, 1974; Harvey and Watson, 1987). High rates of overbank sedimentation tend to be associated with large floods (Sigafoos, 1964; Kesel et al., 1974; Watson et al., 1986). However, over longer periods of time, sedimentation rates in the floodplain tend to be low (i.e., 1-3 mm/yr.: Kesel et al., 1974). Rates are highest on the channel margin, and they decrease exponentially away from the channel (Allen, 1985; Bridge and Leeder, 1979). Significant reworking of overbank sediments can occur during a single flood or in subsequent floods (Sigafoos, 1964). The rate of sedimentation on a floodplain is governed by the elevation of the floodplain with respect to the water-surface elevation of floods. If an area is inundated frequently, the rate of deposition will be high. As the elevation increases, as a result of sedimentation, larger and less frequent floods are required to inundate the surface, and therefore, sedimentation rates will be lower (Wolman and Leopold, 1957). Ritter (1978) has argued that in meandering streams, the rate of sediment accumulation on the floodplain must be ultimately controlled by the rate of lateral migration of the channel.

The role of riparian vegetation in determining channel stability is less clearly understood. Zimmerman et al. (1967) concluded that vegetation had an effect on channel form in small streams, but it had only marginal effects on channel stability in larger streams, and he concluded that large trees that had been eroded from the top bank could induce further bank erosion, a point that was also made by Brice (1977). Towl (1935) and Brice (1974, 1977) attributed reduced sinuosity of the Missouri, White and Sacramento Rivers, respectively, to a reduction in riparian vegetation. Brice (1977) concluded from the morphology of meander cutoffs on the Sacramento River that the river was more sinuous and stable prior to removal of riparian vegetation, a point which is not supported by subsequent investigations (WET, 1988). Smith (1976) and Odgaard (1987) concluded that riparian vegetation increased bank material resistance to erosion, but Schifflet (1973) and Nanson and Hickin (1986) demonstrated that riparian vegetation had little effect on bank stability. Williams and Wolman (1984) suggested that, in some locations, encroachment of vegetation can lead to reduced channel capacity or conveyance of the channel. However, Harvey and Watson (1988) demonstrated that significant woody vegetation encroachment into a constructed flood control channel had little effect on conveyance of the design flows. This has also been corroborated by recent research (Masterman and Thorne, 1992, 1994; Darby and Thorne, 1996), showing that the effects of riparian vegetation growth on flow resistance may, in some cases, be smaller than previously perceived.

1.8. Land Use Along the San Joaquin River and Tributaries

The dominant land use category along the project reach of the San Joaquin River is agriculture. In the leveed reaches, row crops and orchards are present outside of the levees, whereas in the non-leveed reaches grazing is the dominant land use category. Along the tributaries. a similar pattern of land use is present, but confinement of the channel and floodplain is due primarily to Pleistocene-age terraces. Increasing urbanization is occurring along the Stanislaus and Tuolumne Rivers. Sand and gravel mining is occurring on the floodplain and on the terraces along upstream reaches of the Stanislaus, Tuolumne, and Merced Rivers (Subreaches; S3, T3, M3). Prior to construction of the dams on the mainstem San Joaquin River and the major tributaries, spring-run and fall-run chinook salmon were present in the San Joaquin River system. Chinook salmon production in the San Joaquin River Basin has declined by over 85 percent since the 1940s (COE, 1993). Currently, the spring-run has been extirpated, but fall-run chinook salmon still spawn in the Stanislaus, Tuolumne, and Merced Rivers (Subreaches; S3, T4, M4) downstream of the dams.

1.9. Dams and Reservoirs

Development of water resources in the San Joaquin River basin began over 130 years ago. Each of the main tributaries, as well as the San Joaquin River has a dam and reservoir that includes storage space for flood control. Pine Flat Dam on the Kings River was completed by the Corps of Engineers in 1954 and has a storage capacity of 1 million acre-feet, of which 475,000 acre-feet is reserved for flood storage. Except in unusual circumstances the reservoir has eliminated historic overflows into the San Joaquin River via the Kings River North and Fresno Slough.

Since 1911, nine reservoirs with a combined storage capacity of 1.14 million acre-feet, about 60 percent of the watershed yield, have been built upstream of the town of Friant on the San Joaquin River and its upper tributaries (Cain, 1997). Friant Dam and Millerton Lake, constructed by the U.S. Bureau of Reclamation (USBR) in 1941 has about 520,000 acre-feet of storage, of which about 170,000 acre-feet can be reserved for control of fall and winter rain floods and up to 390,000 acre-feet can be reserved for spring snowmelt floods (**Table 1.3**). In contrast to most dams which attenuate flood peaks but then release the stored water downstream, most of the storage in Millerton Lake is diverted for irrigation via the Madera canal (to the north) and Friant canal (to the south), that were completed in 1943 and 1948, respectively. Consequently, Friant Dam has radically changed the hydrology of the San Joaquin River.

Mendota Dam, located at the confluence of the San Joaquin River and Kings River North (Fresno Slough) was constructed in 1954 and is used to divert water for irrigation supply. The dam provides no flood control storage and has, in fact, filled with sediment (COE, 1993), thereby affecting upstream water-surface elevations during flood flows in the San Joaquin and Kings River North.

The eastside tributaries upstream of the Merced River are also dammed. Hidden Dam and Hensley Lake, located on the Fresno River, was completed by the COE in 1974. It has a capacity of 90,000 acre-feet, of which 65,000 acre-feet was reserved for flood storage. Buchanan Dam and H.V. Eastman Lake, is located on the Chowchilla River and it has a capacity of 150,000 acre-feet, of which 45,000 acre-feet are reserved for flood storage. Smaller structures with a combined flood storage capacity of about 33,300 acre-feet are located on Bear Creek (Burns Dam, Bear Dam), Owens Creek (Owens Dam), and Mariposa Creek (Mariposa Dam). Big Dry Creek Dam is located on Big Dry Creek northeast of Fresno.

Table 1.3. Summary of major reservoirs upstream from the project reach.						
Dam	Reservoir	River Basin	Drainage Area (mi^2)	Original Storage Capacity (ac-ft)	Maximum Flood Reservation (ac-ft)	Year Completed
Friant[1]	Millerton Lake	San Joaquin	1,638	520,500	390,000[1]	1942
New Exchequer	Lake McClure	Merced	1,037	1,025,000	350,000	1966
New Don Pedro	Don Pedro	Tuolumne	1,533	2,030,000	340,000	1971
New Melones[2]	New Melones	Stanislaus	904	2,420,000	450,000[2]	1978

[1]For Friant Dam, up to 170,000 acre-feet of storage is reserved for control of fall and winter rain floods, while up to 390,000 acre-feet of storage can be reserved for control of spring snowmelt floods.
[2]The New Melones project also includes Tulloch Dam and Lake which adds an additional total storage capacity of 67,000 acre-feet, which includes 10,000 acre-feet of flood storage.

New Exchequer Dam and Lake McClure are located about 25 miles northeast of Merced on the Merced River. About 1 million acre-feet of storage is available in McClure Lake, of which about 400,000 acre-feet is available for flood storage. The New Don Pedro Dam, located on the Tuolumne River about 35 miles east of Modesto, was completed in 1971 by a consortium consisting of the federal government, City and County of San Francisco, and the Turlock and Modesto Irrigation Districts. It has a gross storage capacity of about 2 million acre-feet, with 340,000 acre-feet of storage for rain flood control or snowmelt, and it provides flood control for the City of Modesto, several rural communities, and about 8,000 acres of agriculture along the lower Tuolumne River. The reservoir is also operated for irrigation and municipal water supply and power production. New Melones Dam and Lake is located on the Stanislaus River about 30 miles northeast of Modesto. It was constructed by the Corps of Engineers in 1978, and has a storage capacity of 2.4 million acre-feet, of which 450,000 acre-feet is reserved for flood storage. The lake also provides power generation, irrigation water supply, water quality control, and recreation benefits.

1.10. Flood Control Projects

Local levees and flood control projects along the San Joaquin River were commenced prior to 1914 by local landowners. Based on the information provided in the 1914 CDC survey of the river an estimate of the extent of the local levees is shown in **Table 1.4**. The data in this table indicate that significant lengths of Subreaches 1 and 2 had been leveed by 1914.

Table 1.4. Extent of levees along project reach of San Joaquin River in 1914.

Subreach	Reach Length (miles)	Left Bank (miles)	Right Bank (miles)	Average Levee Height (ft)
1	21.3	15.8	21	9
2	9.0	9.0	1.0	9
3	15.7	0	6.5	4
4	19.0	6.0	13.5	4

From about 1956 to 1972, the COE constructed the Lower San Joaquin River and Tributaries project from the Delta upstream to the Merced River, under the authorization of the 1944 Flood Control Act. The extent of the project levees and the design capacities are shown on **Figure 1.2** (and Appendix A1-A3). Additional modifications to the project were completed in the mid-1980s. The federally constructed portion of the project consists of about 100 miles of intermittent levees along the San Joaquin River, Paradise Cut, Old River, and the lower Stanislaus River. The levees vary in height from about 15 feet at the downstream end to an average of 6 to 8 feet over much of the project. The project levees, along with the upstream flow regulation were designed to contain floods varying from once in 60 years at the lower end of the project to about once in 100 years at the upper limits. Local levees are located along many reaches of the river in the gaps between the project levees.

The COE has established objective flows for the San Joaquin River and its tributaries for use in flood control operation of the reservoirs within the system. These flows are generally considered to be safe carrying capacities, but some damages do occur when the objective flows occur. The objective flows are shown in **Table 1.5**. Design capacity was authorized as the amount of water that can pass through a reach with a levee freeboard of 3 feet within the historical San Joaquin River, and 4 feet along the Bypasses, except along the west side of the Eastside Bypass which has 3 feet of design freeboard.

Under the same authorization, 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 (COE, 1985). The bypass system consists primarily of manmade channels (Chowchilla, Eastside and Mariposa Bypasses) which divert and carry flood flows from the San Joaquin River near Gravelly Ford, along with flows from the eastside tributaries, downstream to the mainstem San Joaquin River upstream of the Merced River confluence (Figure 1.2). Design flow capacities for various portions of the system are shown in Table 1.5. The system consists of about 193 miles of levees, several control structures (Chowchilla Canal Bypass Structure, San Joaquin River Control Structure, Sand Slough Control Structure, Eastside Bypass Control Structure, Mariposa Bypass

Figure 1.2. Map showing the locations of the various elements of the San Joaquin Flood Control Project, the design

flows and the Levee Districts
responsible for system maintenance.

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 (R. Hill, LSJLD, personal communication).

Table 1.5. Design channel capacities for the San Joaquin River Flood Control Project (COE, 1993).

Reach	Flow[1] (cfs)
San Joaquin River, Friant Dam to Chowchilla Bypass Structure	8,000
Chowchilla Bypass	5,500
Mariposa Bypass	8,500
Eastside Bypass	10,000-18,500
Kings River North	4,750
San Joaquin River - San Joaquin River Structure to Mendota[2]	2,500
Mendota Dam to Sand Slough	4,500
Sand Slough to Mariposa Bypass	1,500
Mariposa Bypass to Merced River	10,000-26,000
Merced River to Tuolumne River	45,000
Tuolumne River to Stanislaus River	46,000
Stanislaus River to Paradise Dam (at head of Paradise Cut)	52,000
Paradise Dam to Old River	37,000[3]
Old River to Stockton Deep Water Ship Channel	22,000

[1]Source: Report on Flood Control Operation and Maintenance, San Joaquin River, Friant Dam to Stockton, California.
[2]Chowchilla Bypass Structure and San Joaquin River Structure are adjacent facilities comprising the bifurcation works at the head of Chowchilla Bypass.
[3]Diversion capacity of Paradise Cut is 15,000 cfs.

The State of California has a designated floodway program that is administered by the Reclamation Board. The designated floodway provides a non-structural means of reducing potential flood damages by preventing encroachments into floodprone areas. Designated floodways within the San Joaquin River system are located along the Kings River North and between Friant Dam and Gravelly Ford (RM 267-229) and Salt Slough and the Merced River (RM 168 -118) and between the Merced River and Airport Way (RM 118-72.5). The FEMA 100-year floodplain for the project reach of the San Joaquin River from RM 56 to RM 118 is shown on **Figures 1.3a** and **1.3b.**

Figure 1.3a. Map showing the extent of the FEMA 100-year flood from RM 60 to RM 85 (COE, 1993).

Figure 1.3b. Map showing the extent of the FEMA 100-year floodplain from RM 85 to RM 118 (COE, 1993).

Following floods in 1969, 1983 and 1986 it appeared that the San Joaquin River in various reaches no longer had the ability to convey channel design flows (**Table 1.6**). Of primary concern were the reaches between RM 84 (Tuolumne River confluence) and the Merced River (RM 118) and between the Merced River and RM 205 (Mendota Dam). Loss of capacity was attributed to sedimentation and vegetation encroachment (COE, 1993). Sedimentation was attributed to erosion of the river banks and to erosion of agricultural fields. It has been suggested that encroachment of vegetation has occurred because of the formation of lower elevation bar surfaces along the channel derived from the products of bank and agricultural erosion coupled with the 1980s drought condition that prevented natural removal of the vegetation (COE, 1993). Institutional and statutory constraints (NEPA, CEQA) have limited the ability of the State of California and the Levee Districts to carry out operation and maintenance procedures including clearing and snagging and sediment removal (COE,1993). The extent of the levee problems in the 1997 flood are shown on **Figure 1.4** (FEAT, 1997).

Table 1.6. Channel capacities by reach along the San Joaquin River (COE, 1993).

River Miles	Project Design Capacity (including Bypass)	1992 Estimated Channel Capacity
229-267	8,000	8,000
205-229	8,000[1]	11,000[2]
118.5-205	18,000[3]	12,300[4]
84-118.5	45,000	45,000
75-84	52,000	46,000
58-75	37,000	56,000

[1] 2,500 San Joaquin + 8,500 Chowchilla Bypass.
[2] 2,500 San Joaquin + 8,500 Chowchilla Bypass.
[3] 1,500 San Joaquin + 16,500 Eastside Bypass.
[4] 4,500 San Joaquin + 7,800 Eastside Bypass.

1.11. Data Sources

Previous studies and information that were relied on in this investigation include: historical maps of the system prior to significant man-made interventions (Hall, 1887), a hydrographic survey of the San Joaquin River conducted by the California Debris Commission (Corps of Engineers) in 1914 and updated in 1930 by DWR, geological maps showing surface and subsurface geology of the valley (Marchandt and Allwardt, 1978; Bartow, 1985), and a repeat survey of some of the 1914 cross sections by the U.S. Geological Survey (Simpson and Blodgett, 1979). Following the floods of 1997, the Corps revised the flood frequency curves for the mainstem and tributaries, and the revised values were utilized in this investigation (COE, 1998). As part of the Comprehensive Study, a *Hydrologic Engineering Management Plan (HEMP)* was developed (COE, 1998). In order to develop numerical models of the system as described in the HEMP for use in the Comprehensive Study, topographic and hydrographic surveys of the San Joaquin River and the

Figure 1.4. Map showing the locations of the levee problems along the San Joaquin River during the January 1997 flood (FEAT, 1997).

lower reaches of the major tributaries were conducted. The surveys were used to develop cross sections to compare the existing morphology of the river with that established by the 1914 survey. Bridge plans and bridge inspection reports for the major tributaries were obtained from CALTRANS to evaluate the aggradational or degradational status of the tributaries. Cross sections surveyed by DWR in 1983 following a major flood were used to evaluate changes in thalweg elevations between the 1914 and 1998 surveys.

Existing conditions in the San Joaquin River Basin were summarized by the *Reconnaissance Report for the San Joaquin River Mainstem* (COE, 1993), and of particular value to this study were the detailed descriptions of the flood control project. The Bay Institute=s Report (1998) *From the Sierra to the Sea: Lessons from the Ecological History of the San Francisco Bay Delta Watershed,* summarized the ecological changes that have attended the physical transformation of the San Joaquin River since the early part of the 20th century. *The Governor=s Flood Emergency Action Team Report* (1997) following the January floods of 1997 provided useful information on the flood control system and existing deficiencies and damages within the system. *The San Joaquin River Management Plan* (The Resources Agency, 1995) identified a number of problems and potential solutions for the San Joaquin River from Friant Dam downstream to the Delta, including the major tributaries from their confluences with the San Joaquin River to the first major dam. *The Analysis of Physical Processes and Riparian Habitat Potential of the San Joaquin River Report* (Jones & Stokes Associates and Mussetter Engineering, Inc., 1998) provided a thorough understanding of the San Joaquin River upstream of the project reach (Merced River to Friant Dam)

Data and information on the major tributaries are somewhat limited, but useful information was available for the Tuolumne River, from the *Draft Tuolumne River Corridor Restoration Plan, Stanislaus County, CA.* Report (McBain and Trush, 1998) and from the *Gravel Mining Reach and Special Run Pools 9/10, Restoration and Mitigation Projects* report (U.S. Fish and Wildlife Service and Turlock Irrigation District Report, 1998). Useful information on sediment yields to the tributaries and the impacts of sand and gravel mining on the major tributaries is provided in Kondolf and Mathews (1993), *Management of Coarse Sediment on Regulated Rivers*.

Between November 16 and 23, 1998, an aerial and ground-based field reconnaissance of the project reach of the San Joaquin River and its major tributaries was conducted. The San Joaquin River and the lower reaches of the tributaries were boated, and the non-navigable portions of the tributaries were viewed from roads and bridges. Sediment samples for laboratory gradation analysis were recovered from the San Joaquin River and the lower tributaries (Appendix A). Photographs of the river and tributaries were used to record field observations and some of these are presented in **Appendix B.** Cross sections from the 1914 survey of the San Joaquin River and the 1998 survey of the river and lower reaches of the major tributaries were used to develop coarse HEC-RAS models to evaluate channel capacities and sediment transport capacities. The plotted cross sections are included in **Appendix C**.

2. GEOLOGY

2.1. Introduction

The San Joaquin River Basin is an asymmetrical basin lying between the Sierra Nevada and Coast Range. The basin has a complex structural history that may be influencing the form of the modern San Joaquin River (Section 2.2). The surficial geology of the basin represents the Pleistocene and Recent erosional and depositional history of the basin and this has an impact on the erodibility of the riverbank sediments, the extent of overbank flooding, and the degree of confinement of the San Joaquin River and the major tributaries (Section 2.3). Finally, the size of the bed materials within the mainstem San Joaquin River and the lower reaches of the major tributaries affects the sediment transport capacities of the various reaches and ultimately controls the vertical and lateral stability of the rivers (Section 2.4).

2.2. Structural Geology

The Great Valley is a northwest trending synclinal trough with its axis off-center to the west, and is interrupted by two major surface cross structures, the Stockton Fault in the Stockton Arch and the White Wolf Fault in the south near Bakersfield (Lettis and Unruh,1991). The geologic evidence indicates that the valley has been undergoing almost continuous deformation since the Mesozoic (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/yr (Janda, 1965; Ouchi, 1983; Page, 1986; Bartow, 1991). The geometry of the valley is expressed by structural contours on the 615,000-year old upper surface of the Corcoran clay. The line of maximum subsidence is about 20 to 30 km west of the present course of the San Joaquin River. Structural contour maps of the clay show several late Quaternary basins and arches superimposed on the major syncline.

Lettis and Unruh (1991) conclude that tectonic subsidence and growth of the syncline have continued into late Quaternary time. They base this conclusion on the following:

1. Late Quaternary deposits thicken toward the structural axis not the topographic axis of the valley.

2. Middle Pleistocene sediments occur up to several hundred meters below sea level in the synclinal axis.

3. Gradients of depositional and erosional surfaces increase with age, indicating progressive uplift and valley-ward tilting of the foothills and valley subsidence.

4. Fanheads shift progressively westward with decreasing age indicating westward tilting of the Sierra Nevada block.

Widely scattered earthquake epicenters in the valley (Hill et al., 1991) suggest active deformation north of the Tulare basin. Microseismicity has been detected near Madera (Marchand and Allwardt, 1978). However, Bartow (1991) concluded that subsidence history of the San Joaquin valley is not well known. For example, he suggested that the Stockton Arch is more the result of deposition on the delta than uplift (Bartow, 1991, p. 14). Nevertheless, Lettis (1985) suggested that many small northeast trending anticlines and synclines noted in the foothills A*may project into and slightly deform the San Joaquin Valley*.@

The key to an interpretation of structural variability in the San Joaquin Valley is the lacustrine Corcoran clay of Pleistocene age. There are multiple lenses or units of the clay and Croft (1972) mapped six, designating them as A through F, youngest to oldest. The E clay ranges in depth from 0 at the outcrop along the western edge of the valley to about 900 feet beneath the Tulare Lake bed. Page (1986) prepared a map showing the depth to the E clay and although it is not a structural contour map, it does show basins in the clay, and the trough that underlies the entire western part of the San Joaquin Valley.

Being flanked by the tectonically active Sierra Nevada and the Coast Range, it would be surprising if the San Joaquin Valley were not affected. In addition to the variable depths of the E clay, Marchand and Allwardt (1978) identified numerous lineaments and faults in the alluvial valley, and Bartow (1985) prepared a map showing structural contours on the post-Eocene unconformity at the base of the Valley Springs formation, which shows closed basins along the western margin of the valley.

The variety of evidence from surface to subsurface suggests that deformation of the floor of the San Joaquin Valley in the recent past and perhaps at present is probable. Active deformation is occurring in the Sacramento Valley and south of the San Joaquin River. Therefore, it may be affecting the San Joaquin River. It is possible, based on an analogy of the response of streams in the Mississippi Embayment to the neotectonically active Wiggins uplift (Burnett and Schumm, 1983), that the head of the delta where the San Joaquin River bifurcates into a number of distributary channels, which is just upstream of the Stockton Arch and the east-west trending Stockton Fault, is controlled by the ongoing deformation of the valley floor. Whether this is the result of sediment loading on the delta or tectonic uplift is unknown. A structural basin underlies the reach of river between the Tuolumne River and Orestimba Creek which coincides with one of the historical flood basins identified by Hall (1887).

2.2.1. Groundwater Withdrawal and Subsidence

Within the southern part of the San Joaquin Valley upstream of the project reach, groundwater-withdrawal and hydrocompaction of the soils by irrigation has led to accelerated subsidence since the 1920s (Poland et al., 1975; Bull, 1964). Maximum amounts of subsidence (about 30 feet) occurred in the Los Banos-Kettleman City area, but from 1 to 6 feet of subsidence occurred along portions of the San Joaquin River between Mendota and about Los Banos, a rate of about 35 to 43 mm/year (Ouchi, 1983). However, the man-made subsidence has not caused the expected changes in the river (Ouchi, 1983), probably because the development of the upstream water storage projects and attendant reduced flood peaks coincided with the period of groundwater overdrafting (JSA-MEI, 1998).

Groundwater overdrafting may be having a significant effect on salt and boron concentrations in the San Joaquin River within the project reach. Phillips et al.(1991) demonstrated that high pumping rates east of the river between Hills Ferry and Patterson induced groundwater flow from the west, where naturally occurring salinity is higher, to the east and increase the salt and boron concentrations in the river as a result. During drought conditions in 1988 and 1989, 76 percent of the discharge in the river was derived from groundwater inflow. Boron concentrations higher than about 2 ppm can have an adverse impact on plant growth and may be a cause of the lack of riparian regeneration along the San Joaquin River (JSA-MEI, 1998).

2.3. Surficial Geology

The surficial deposits that flank the San Joaquin River within the project reach are composed primarily of Holocene-age, relatively fine-grained fluvial sediments that are inset below Pleistocene-age, primarily fine-grained alluvial terrace deposits of the Modesto Formation (Marchand and Allwardt, 1978). Predominantly fine-grained and less erodible swamp, lacustrine and marsh deposits are interspersed with the somewhat coarser sand-dominated and more erodible fluvial sediments within the historical flood basins. Along the western side of the valley, the coalesced alluvial fans contain gravels derived from the Coast Range. Tributaries draining the Coast Range (Del Puerto and Orestimba Creeks) locally deliver gravel-size sediments to the San Joaquin River, but the channel sediments throughout the project reach are dominated by granitic sands derived from the Sierran drainages. The three major tributaries have alluvial floodplains of varying width that are inset below Pleistocene-age Riverbank and Modesto terraces (Marchand and Allwardt, 1978). The alluvial sediments in the three tributaries have a downstream-fining trend in size, with gravels and cobbles present in the upstream reaches and sands predominating in the downstream reaches (McBain and Trush, 1998).

2.3.1. Sedimentology

During the course of the field reconnaissance of the project reach of the San Joaquin River, bed material samples were collected for subsequent laboratory determination of their gradations. Additionally, the surface sediments on a coarse-grained mid-channel bar located downstream of the confluence with Del Puerto Creek (RM 87.8) were sampled with a pebble count (Wolman, 1954). A subsurface sample was also obtained from the mid-channel bar to determine the sediment gradation. A single bed material sample was also collected in the lower reach of the Stanislaus, Tuolumne, and Merced Rivers. **Table 2.1** presents the gradation parameters for the individual samples which include the median size (D_{50}), the size of which 84 percent is finer (D_{84}) and the size of which 16 percent is finer (D_{16}). Included in Table 2.1 is a bed material sample obtained at RM 133 (JSA-MEI, 1998). **Figures 2.1 and 2.2** present the gradation curves for the individual samples identified in Table 2.1.

The sediment samples were collected to determine whether there were significant differences between the subreaches. Samples LSJR-S1 and LSJR-S2 were collected downstream of the confluence with the Stanislaus River and have almost identical D_{50} values (0.57 mm). LSJR-S3 was collected upstream of the Stanislaus River confluence and it has the same D_{50} which suggests that even though the D_{50} of the Stanislaus River sample (Stanislaus-S3) was a little larger (0.62 mm), the Stanislaus River has little effect on the bed material gradation of the San Joaquin River. Samples LSJR-S4, LSJR-S5 and LSJR-S6 which were collected in the reach from downstream of the Tuolumne River to downstream of the Merced River are somewhat finer (D_{50}, 0.32-0.39 mm) even though both the Tuolumne and Merced Rivers are delivering somewhat coarser sediment (D_{50}, 0.5 mm).

The finer gradation could be the result of the river eroding and reworking the finer-grained historical flood basin sediments in this reach. The single bed material sample from the San Joaquin River upstream of the project reach has a D_{50} of 0.6 mm. The local effect of the Coast Range tributaries can be seen in sample LSJR-S7 and WC-1, where the D_{50} values are 7 and 22 mm, respectively. Unlike the flatter gradient east side tributaries where backwater effects limit sediment delivery from the tributaries, the steep slope of Del Puerto Creeks allows sediment delivery to the main river.

Figure 2.1. Gradation curves for sediment samples collected from the San Joaquin River. Sample locations are shown in Table 2.1 and in Appendix A1, A2, and A3.

Figure 2.2. Gradation curves for sediment samples collected from the Merced, Tuolumne and Stanislaus Rivers. Sample locations are shown in Table 2.1 and in Appendix A4.

Table 2.1. Bed material gradation parameters along project reach of San Joaquin River and the lower reaches of the Stanislaus, Tuolumne, and Merced Rivers.			
Sample Number (River Mile)	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)
LSJR-S1 (63.5)	1.5	0.57	0.22
LSJR-S2 (73.5)	0.83	0.56	0.29
LSJR-S3 (76.6)	0.81	0.57	0.31
LSJR-S4 (83.6)	0.60	0.32	0.20
LSJR-S6 (84.2)	0.70	0.39	0.20
LSJR-S5 (117.8)	0.62	0.32	0.19
WC-1 (87.8)	31.3	22.0	14.5
LSJR-S7 (87.8)	24.4	7.0	0.75
Merced-S1	0.74	0.51	0.26
Tuolumne-S2	0.80	0.52	0.25
Stanislaus-S3	1.23	0.62	0.35
SJR (133)	1.5	0.6	0.25

3. GEOMORPHOLOGY

3.1. Historical Conditions, San Joaquin River

The San Joaquin River within the project reach from the head of the delta at Old River (RM 54) to the confluence with the Merced River (RM 118) was a relatively low gradient (0.5 to 1.2 ft/mile) meandering river, characterized by the presence of numerous cutoff channel segments (oxbows), meander scroll (ridge and swale) topography, and adjacent flood basins (Hall, 1887) that were confined between coalesced alluvial fans along the western margin of the valley and Pleistocene-age terraces along the eastern margin. The average sinuosity of the river (ratio of channel length to valley length) was about 1.7 in 1914. The major tributaries, Stanislaus and Tuolumne Rivers do not appear to have provided as much local base level control for the respective upstream segments of the San Joaquin River as the Merced River did for the reach upstream of Hills Ferry since the river maintained a single channel planform within the project reach. Within the project reach the San Joaquin River was capable of adjusting to the tributary influences (flow and sediment) by locally increasing or decreasing slope (sinuosity) (Schumm, 1977). In contrast, upstream of the Merced River, the San Joaquin River had developed a multi-channeled anastomosed or anabranched planform (Nanson and Knighton 1993). Anabranched rivers tend to form when there is a very limited ability of the river to increase channel slope (Nanson and Huang, 1999). The multi-channeled anabranching planform concentrates hydraulic energy where flows would otherwise be dispersed into the overbank areas and thus maintains the ability of the river system to convey water and sediment downstream.

Quantitative information on the characteristics of the San Joaquin River prior to man-made modifications to both the watershed hydrology and the floodplain is not available. The first survey of the river and floodplain was conducted by the CDC in 1914, but by that time there had been some reservoir construction in the basin, levees had been constructed along the river (Table 1.3) and dredge mining for gold had commenced in the Merced, Tuolumne, and Stanislaus Rivers. The river was, however, considered to be navigable up to Hills Ferry annually, and as far as Firebaugh, occasionally. Steamboats were probably responsible for removal of much of the original riparian forest for fuel. Riparian forests were much less extensive along the San Joaquin River than they were on the Sacramento River because of the absence of wide natural levees (Katibah, 1984).

Channel and valley-floor cross sections surveyed in 1914 provide a reasonable indication of the pre-development conditions along the San Joaquin River. **Figure 3.1** includes cross section 117 located at RM 69.2 in Subreach 1. The valley floor is confined between the coalesced alluvial fans on the west and a Pleistocene-age terrace on the east. Man-made and natural levees border the channel of the San Joaquin River, and the flood-basin is evident between the river and Red Bridge Slough, a cutoff channel remnant. Cross section 112, located at RM 78.2 is representative of conditions in Subreach 2 (**Figure 3.2**). The flood-basin is bounded to the west by the channel of the San Joaquin River and the western alluvial fans, and to the east by the Finnegans Cutoff channel. Numerous former channels and sloughs can be seen across the valley floor. The influence of the Del Puerto Creek alluvial fan on the west side of the valley and the Pleistocene-age terrace on the east side are very clear in **Figure 3.3** (cross section 103) located at RM 93.8 in Subreach 3. **Figure 3.4** shows cross section 92 at RM 109.9 in Subreach 4. The Orestimba Creek alluvial fan confines the valley floor on the west. A 4- to 5-foot high man-made levee can be seen on the east side of the San

Joaquin River. Former channels and sloughs are evident on the floodplain. Confinement of the San Joaquin River between the coalesced alluvial fans on the

Figure 3.1. Valley floor cross section (117) at RM 69.2 in Subreach 1 (CDC 1914 Survey).

Figure 3.2. Valley floor cross section (112) at RM 78.2 in Subreach 2 (CDC 1914 Survey).

Figure 3.3. Valley floor cross section (103) at RM 93.8 in Subreach 3 (CDC 1914 Survey).

Figure 3.4. Valley floor cross section (92) at RM109.9 in Subreach 4 (CDC 1914 Survey).

west and the Merced River fan on the east is clearly seen on cross section 88 at RM 116.7 (**Figure 3.5**). A distributary channel on the Merced River fan (Merced Slough) can be seen on the east side of the cross section.

Figure 3.6 shows the 1914 thalweg, water surface and top-of-bank profiles for the project reach of the San Joaquin River. Also shown on the figure are the cross sections that were used to develop the profiles. Reach-averaged morphometric data for the 4 subreaches derived from the 1914 survey and indicated cross sections are shown in **Table 3.1**. The bank height data were obtained from a coarse HEC-RAS model that was developed for the project reach to determine channel hydraulics and sediment transport capacities (see Chapter 5). Cross sections used in the HEC-RAS model are located in **Appendix C1**. The bank height was defined as the difference in elevation between the low flow, 95 percent exceedance flow water surface and the top of the bank. The 95 percent exceedance flow water surface was selected for this analysis to represent a common reference plane that is near the channel bed, but eliminates the influence of deepened thalweg in the channel bends.

Table 3.1. Summary of reach-averaged morphometric data for subreaches of the San Joaquin River based on the 1914 CDC survey.

Subreach	Sinuosity	Slope (ft/ft)	Bankfull Depth (ft)	Bankfull Width (ft)	Width-Depth Ratio	Bank Height (ft)
1	1.9	0.00014	18.6	410	22	14.1
2	1.5	0.00023	18.1	406	22	14.2
3	1.5	0.00017	18.7	360	19	16.3
4	1.7	0.00015	18.7	389	21	14.1

Subreach 1 (RM 54-75) had the highest sinuosity and the flattest average slope. The steepest average slope was located in Subreach 2 between the Stanislaus and Tuolumne Rivers (RM 75-84). The sinuosities of Subreaches 2 and 3 (RM 84-99.5) were similar (1.5) even though the slope in Subreach 3 was flatter. The sinuosity (1.7) increased in Subreach 4 (RM 99.5-118) and the slope flattened. The 1914 survey indicated that about 10 miles of river had been, or were in the process of cutting off (Finnegans Cutoff, Lairds Slough Cutoff) at the time of the survey in Subreach 3, which may explain the relatively low sinuosity and relatively steep slope in the subreach.

The average bankfull width of the channel was highest in the lower subreaches (1, 2) and it was lower in the upstream direction in Subreaches 3 and 4 which is expected since the volume of flow increases in the downstream direction with the addition of flows from the Tuolumne and Stanislaus Rivers. However, the smallest average channel width was located in Subreach 3 where the most extensive flood basin was located (Hall, 1887). Average channel depths (difference in elevation between the thalweg and top-of-bank) (18-19 ft) and width-depth ratios (19-22) are very similar for all of the subreaches. With the exception of Subreach 3 (16.3 ft), the bank heights were very similar for the subreaches (14 ft).

Estimates of the channel capacities at bankfull stage were made for each of the cross sections in the HEC-RAS model and subreach-averaged values were computed (**Table 3.2**). Estimates of the

Figure 3.5. Valley floor cross section (88) at RM 116.7 in Subreach 4 (CDC 1914 Survey).

Figure 3.6. Thalweg, water surface and top-of-bank profiles of the project reach of the San Joaquin River derived from the 1914 CDC survey.

recurrence interval of the bankfull discharge were made with pre-1966 flood frequency curves since pre-development hydrology is not available (see Chapter 4). Based on the 1913 to 1941 flow-duration curve at the appropriate gages estimates were also made for the duration of the bankfull event in each of the subreaches.

Table 3.2. Reach-averaged channel capacities and flow-durations for the subreaches of the San Joaquin River based on the 1914 CDC survey .

Subreach	Bankfull Discharge (cfs)	Duration (%)	Duration (Days)	Estimated Recurrence Interval (years)
1	11,800	16.6	61	2
2	11,400	14.5	53	2
3	9,300	7.0	26	2
4	8,400	8.3	30	2

The data in Table 3.2 show that the magnitude of the bankfull discharge increases in the downstream direction as would be expected given the tributary inflows, and that the estimated recurrence interval for the bankfull discharge in all of the subreaches is about 2 years which is also reasonable on a large alluvial river (Leopold et al., 1964: Williams, 1978). In the lower subreaches (1,2) the duration of the bankfull event is about twice as long as in the upstream reaches (3 and 4) which probably reflects the snowmelt dominated hydrology of the lower basin.

3.2. Historical Conditions, Major Tributaries

Little quantitative information is available on the historical condition of the Merced, Tuolumne and Stanislaus Rivers prior to the onset of major watershed -scale perturbations. Perturbations to the watersheds and channels included: placer mining (1848-1880), dredge mining (1880-1960s), flow regulation (1890s to the present), sand and gravel mining (1940s to present), urbanization (1850s to the present) and grazing and farming (1850s to the present) (McBain and Trush, 1998). The tributaries do, however, have common general geomorphic characteristics that can be described in terms of the degree of confinement of the rivers and the downstream-fining trends in the bed material. Near the upstream ends of all three rivers, the bed material is composed of gravel and cobble-size materials. At the downstream ends of the rivers, the bed material is all sand. Whether this pattern existed historically is unknown because flood flow regulation and interruption of the watershed sediment supply have significantly altered the sediment dynamics of the tributaries. Dredge mining in the tributaries has the effect of retaining all of the coarser size fractions of the alluvial valley fill in the mining area while flushing downstream the finer fractions.

The east-west flowing rivers exit the Sierra Nevada into the Great Valley where the channels change from being bedrock -bound to being confined by terraces composed of Pleistocene-age alluvial fan sediments (Marchand and Allwardt, 1978). The height and number of confining terraces declines to the west. The highest and oldest terraces are located near the upstream ends of the project reaches of the tributaries where Turlock Lake and Riverbank-age terraces confine the rivers. Farther west, the channels are confined by younger Modesto-age terraces. The width of confinement is variable along the individual rivers. The widest valley floor occurs in Subreaches M3 and M4 along the Merced River (Appendix A4), where the dredge tailings are about 1.5 miles wide. In the upper subreaches of the Tuolumne River (T3 and T4), the valley width is about 0.5 miles, and in Subreach S3 on the Stanislaus River, it is about 0.5 miles as well (Appendix A4). The valley widths between the terraces generally narrow in the downstream direction until the channels become unconfined, and on all three rivers they vary from about 0.5 to 0.25 miles. The three rivers become unconfined by the terraces at the heads of Subreaches M1, T1 and S1, respectively (Appendix A). **Figure 3.7** (McBain and Trush, 1998) provides an example of the variable valley width for the Tuolumne River. On average the valley width in T4 is about 0.6 miles, in T3 it is about 0.3 miles and in T2 it is about 0.2 miles. The valley width expands rapidly in T1 downstream of the confining terraces.

Although the Tuolumne River has been heavily modified since the 1850s the original form of the channel and the valley can be seen on cross sections of the modern river that were assembled by McBain and Trush (1998). **Figure 3.8** that shows the cross section at the New La Grange Bridge (Subreach T4) clearly shows that the channel and its floodplain were confined between variable height terraces, and the effective valley width was about 500 feet. The cross section near Basso Bridge (Highway 132) (Subreach T4) shows that the channel and floodplain are wider, but they are still confined by terraces, but the effective valley width is on the order of 1000 feet (**Figure 3.9**). The cross section located about 4 miles upstream of the J14 Bridge (Subreach T3) shows about half the valley floor (**Figure 3.10).** The valley width at this location is on the order of 5,000 feet (Figure 3.7). McBain and Trush (1998) estimated that the bankfull discharge was on the order of 10,000 to 11,000 cfs which had a historical (pre-water development projects) recurrence interval at the La Grange gage of about 1.6 years. At the J7 Bridge (Subreach T2), the river and the historical floodplain are confined by terraces (**Figure 3.11**). The historical floodplain was inundated by a 3-year recurrence interval flood prior to the New Don Pedro project (McBain and Trush, 1998). **Figure 3.12** shows the cross section about 0.5 miles upstream of the San Joaquin River confluence (Subreach T1). The channel is bordered by an unconfined floodplain, but the frequency of overbank flooding was dependent on the backwater caused by high stage on the San Joaquin River. Backwater effects from the San Joaquin River extend about 14 miles up the lower Tuolumne River (COE, 1993). Similar relationships can be expected for the Stanislaus and Merced Rivers prior to their extensive modification. In the lower subreaches (1 and 2) the slope of the Tuolumne River was on the order of 0.0003, whereas the average slope in Subreaches 3 and 4 was on the order of 0.0015. The changes in average slope correspond with changes in the character of the bed materials along the channel from sand to gravels.

3.3. Existing Conditions, San Joaquin River

This section on the existing conditions along the project reach of the San Joaquin River is based on observations made during the field reconnaissance, the 1998 hydrographic survey of the river and a coarse HEC-RAS model of the project reach that was developed from topography generated by the 1998 survey. Photographs (**Appendix B**) taken during the field reconnaissance are referenced in this section. Subreach boundaries and RM markers are included on the maps in Appendix A1, A2, and A3. Thalweg elevations from a hydrographic survey conducted by DWR in 1983 are also used in this section. During the field reconnaissance the locations of the upstream and downstream ends of the eroding banks were noted, and these were used to compute lengths of bank erosion in the individual subreaches (Appendix A1, A2, and A3).

3.3.1. Subreach 1 (RM 54- RM 74.8)

Subreach 1 is an actively meandering reach of the San Joaquin River with ample evidence of old and more recent cutoffs, that extends from Old River to the confluence with the Stanislaus River

Figure 3.7. Estimates of valley width along the Tuolumne River based on the extent of the pre-1900 riparian corridor (McBain and Trush, 1998).

Figure 3.8. Cross section of the Tuolumne River at the New La Grange Bridge(McBain and Trush, 1998).

Figure 3.9. Cross section of Tuolumne River at Basso Bridge (Highway 132) (McBain and Trush, 1998).

Figure 3.10. Cross section of Tuolumne River located about 4 miles upstream of J14 Bridge (McBain and Trush, 1998).

Figure 3.11. Cross section of the Tuolumne River at the J7 Bridge (McBain and Trush, 1998).

Figure 3.12. Cross section of the Tuolumne River located about 0.5 miles upstream of the confluence with the San Joaquin River (McBain and Trush, 1998).

at RM 74.8 (Appendix A1). Project levees extend for the entire reach along the right (east) bank of the river, and from RM 54 to RM 70 on the left (west) bank (**Plate 1**) (plates are located in Appendix B). Non-project levees are located along the left bank between RM 70 and RM 72.5 which is the downstream end of the designated floodway. Paradise Cut flood relief structure with a diversion capacity of 15,000 cfs (Table 1.5) is located at RM 60L. Local levees are present within the project levees between RM 68L and RM 70L. There are no levees (local or project) located along the left bank between RM 72.5 and RM 73.5. Project levees extend upstream into Subreach 2 from about RM 73.5L. Where the levees are close to the river bank, revetments have been emplaced to prevent erosion of the levees, but where the levees are set back, the river is free to erode its banks. Where the banks are composed of fine-grained flood basin deposits (**Plate 2**), the rates of erosion are low and the radius of curvature to width ratio (R/W) of the bends tends to be low (<2). In contrast, where the bank sediments are sandy and noncohesive (**Plates 3 and 4**) the erosion rates tend to be high , and the R/W values tend to be high (>3). Bank erosion within the subreach and upstream is producing a significant amount of sand-sized sediment (**Plate 5**) that tends to be deposited in the overbank areas during flood flows (**Plate 6**) and in within-channel, bank-attached and mid-channel bars (**Plate 7**). Bank erosion within the reach leads to destruction of the remaining mature riparian forest and generates snag fields that tend to nucleate sand bars (**Plate 8**). Based on the field reconnaissance there are about 20,000 lineal feet of eroding bank, which represents 19 percent of the total length of eroding bank in the project reach from Old River to the Merced River and about 14 percent of the total bank length in Subreach 1 (**Figure 3.13**).

Evidence for the dynamic nature of the subreach can be seen on **Figure 3.14,** which is a recent aerial photograph (1998) of the reach between RM 73.5 and RM 75.5, and includes the confluence with the Stanislaus River. An active chute cutoff can be seen at RM 73.5R, and the remains of the 1914 channel can be seen in the left overbank area at RM 73.5L.. The project levees on both sides of the river and on the north side of the Stanislaus River can be easily distinguished on Figure 3.13, as can the non-leveed portion of the designated floodway downstream of RM 73.5L.

3.3.2. Subreach 2 (RM 74.8 - RM 83.8)

Subreach 2 is an actively meandering reach of the San Joaquin River with ample evidence of old and more recent cutoffs, that extends from the Stanislaus River to the confluence with the Tuolumne River at RM 83.8 (Appendix A2). Project levees extend from the Stanislaus River to RM 81 on the right bank and as far as RM 77.3 on the left bank. Local levees extend from RM 77.3L to RM 78.0L where they join a short reach of project levee that extends upstream to about RM 79.2L. No levees are present along the left bank between RM 79.2L to about RM 82.0L. Local levees extend upstream on both banks to the confluence with the Tuolumne River at RM 83.8. The extent of the project and local levees near the confluence can be seen on **Figure 3.15**, as can the damage to a local levee resulting from the 1997 flood. This is one of the subreaches of the river where concern has been expressed that the conveyance capacity does not meet the design capacity (Table 1.6).

Where the banks are not protected, active bank erosion is occurring within the reach (**Plate 9**). About 29,000 lineal feet of eroding bank is present in the subreach based on the field reconnaissance, and this represents about 20 percent of the total amount of eroding bank between Old River and the Merced River confluence, and about 31 percent of the total bank length in Subreach 2 (Figure 3.13). The 1997 flood caused significant damage to local levees in the reach (**Plate 10**) and significant bank erosion where the bank materials were weak (**Plate 11**). The active meandering nature of the river, which involves point bar deposition, cutbank retreat, and meander cutoffs, can be seen on **Plate 12.**

Figure 3.13. Field identified bank erosion in subreaches of the San Joaquin River.

Figure 3.14. 1998 aerial photograph of the confluence of the San Joaquin and Stanislaus Rivers at the upstream end of Subreach 1.

Figure 3.15. 1998 aerial photograph of the confluence of the San Joaquin and Tuolumne Rivers at the upstream end of Subreach 2.

3.3.3. Subreach 3 (RM 83.8 - RM 99.5)

Subreach 3 is an actively meandering reach of the San Joaquin River with ample evidence of old and more recent cutoffs, that extends from the Tuolumne River to RM 99.5 where the sinuosity of the river increases significantly (Appendix A3). Project levees extend along the left bank from RM 84.5L to RM 86.2L, and along the right bank from RM 85R to RM 88.5R. The project levee also extends from RM 92.5R to RM 112.5R in Subreach 4. Local levees are located along both banks of the river between RM 91 and RM 93, and along the left bank between RM 94L and RM 97L.

The lower portion of the subreach between RM 84 and RM 87 is more sinuous than the channelized Laird=s Slough reach which extends from RM 87 to RM 89. Within the more sinuous reach there is active channel meandering and the potential for at least one bend cutoff in the near future (**Plate 13;** Figure 3.15). The Laird=s slough reach represents the new channel of the San Joaquin River following final abandonment of a 4.5 mile long section of channel that was shown to be cutting off in the 1914 CDC survey (**Figure 3.16**). Extensive concrete rubble revetment has been placed along the banks in this section of the river where the river is narrower than average (**Plate 14**). At RM 87.8 a coarse-grained mid-channel bar is located in the Laird=s slough cutoff reach (**Plate 15**). The source of the gravels is most probably Del Puerto Creek (**Plate 16**) that drains the Coast Range and has its confluence with the San Joaquin River at RM 92.8L.

Approximately 47,000 lineal feet of eroding bank were identified during the field reconnaissance in Subreach 3 which represents about 32 percent of the total length of eroding bank in the reach between Old River and the Merced River. About 29 percent of the total length of the banks in Subreach 3 are eroding (Figure 3.13).

3.3.4. Subreach 4 (RM 99.5 - RM 118)

Subreach 4 is an actively meandering reach of the San Joaquin River with ample evidence of old and more recent cutoffs, that extends from RM 99.5 to the confluence with the Merced River at RM 118 (Appendix A3). Project levees extend along the right bank from RM 99.5R to RM 112.5R and from about RM 100L to RM 104.5L (**Plate 17**). Short reaches of local levees are located between RM 106.5L and RM 107.5L, between RM 111L and RM 113.5L and between RM 115.5R and RM 117R, but this subreach is the least leveed of the four subreaches. A recent bend cutoff has occurred at RM 100.5 and older ones are evident on the floodplain (**Figure 3.17**). A bend cutoff leads to rapid erosion of the cutoff channel as it develops into the main river channel, and this leads to very high local in-channel sedimentation rates downstream (**Plate 18**). Reworking of the floodplain leads to the formation of lower elevation surfaces that are inundated more frequently, and appear to support regeneration of riparian forest (**Plate 19**).

Although there are fewer levees along Subreach 4 this does not mean that the flood flows are unconfined. Along the western (left) margin of the active meanderbelt of the river, the coalesced alluvial fans from the Coast Range tributaries prevent overbank flows (**Figure 3.18**). The Orestimba Creek confluence with the San Joaquin River is located at RM 109L, and the tributary does introduce gravels to the river, and may also be responsible for the chute cutoff that is taking place at RM 108.5L (**Plate 20**). A chute cutoff is also occurring at RM 111.5R (**Plate 21**). The meanderbelt width at the upstream end of Subreach 4 is relatively narrow because the channel is confined between the Merced River alluvial fan and the coalesced fans along the western margin of the valley (**Plate 22**). Approximately 43,000 lineal feet of eroding bank were identified during the field reconnaissance in Subreach 4 which represents about 29 percent of the total length of eroding

Figure 3.16. 1998 aerial photograph of the Lairds Slough reach of the San Joaquin River within Subreach 3.

Figure 3.17. 1998 aerial photograph of the San Joaquin River meanderbelt centered on RM 101 in Subreach 4.

Figure 3.18. 1998 aerial photograph of the San Joaquin River meanderbelt centered on RM 105.5 in Subreach 4.

bank in the reach between Old River and the Merced River. About 22 percent of the total length of the banks in Subreach 4 are eroding (Figure 3.13).

3.3.5. Existing Conditions Channel Morphometry

Figure 3.19 shows the 1998 thalweg, the 1983 thalweg and the 1914 thalweg as well as the top-of-bank profiles for the project reach of the San Joaquin River. It is apparent from the comparative profiles plotted on Figure 3.19 that there has been a general trend of degradation between 1914 and 1998, which appears to be in conflict with the assessment that the channel has aggraded since the flood control project was implemented (COE, 1993). The significance of the comparative profiles is further discussed in Chapter 6. Also shown on Figure 3.19 are the cross sections that were used to develop the profiles. Reach-averaged morphometric data for the 4 subreaches derived from the 1998 survey and indicated cross sections are shown in **Table 3.3**. The bank height data were obtained from a coarse HEC-RAS model that was developed for the project reach to determine channel hydraulics and sediment transport capacities (see Chapter 5). Plots of the cross sections used in the HEC-RAS model are presented in **Appendix C2**. Similar to the elevation of the 1914 data, the bank height was defined as the difference in elevation between the 95 percent exceedance flow water surface and the top of the bank.

Table 3.3. Summary of reach-averaged morphometric data for subreaches of the San Joaquin River based on the 1998 COE survey.

Subreach	Sinuosity	Slope (ft/ft)	Bankfull Depth (ft)	Bankfull Width (ft)	Width-Depth Ratio	Bank Height (ft)
1	1.8	0.00014	20.0	418	21	15.1
2	1.6	0.00023	20.7	384	19	14.3
3	1.5	0.00017	21.5	228	11	15.6
4	1.7	0.00015	19.0	231	12	15.3

Comparisons between the 1914 and 1998 morphometric data are discussed more fully in Chapter 6, but it is apparent that the average channel depth has increased as a result of degradation, and there has been some channel narrowing in Subreaches 3 and 4.

Estimates of the channel capacities at bankfull stage were made for each of the cross sections in the HEC-RAS model and subreach-averaged values were computed (**Table 3.4**). Estimates of the recurrence interval of the bankfull discharge were made with post-1966 flood frequency curves (see Chapter 4). Based on the post-1966 flow-duration curve at the appropriate gages estimates were also made for the duration of the bankfull event in each of the subreaches.

Comparisons between the 1914 and 1998 hydraulic data are discussed more fully in Chapter 6, but it is apparent that the average channel capacity has increased in all of the subreaches, and that the recurrence interval of the bankfull discharge has approximately doubled.

Figure 3.19. 1998, 1983 and 1914 thalweg profiles of the San Joaquin River between Old River and the Merced River confluence.

Table 3.4. Reach-averaged channel capacities and flow-durations for the subreaches of the San Joaquin River, based on the 1998 COE survey.				
Subreach	Bankfull Discharge (cfs)	Duration (%)	Duration (Days)	Estimated Recurrence Interval (years)
1	20,016	7.1	26	4
2	14,835	9.1	33	4
3	10,203	7.8	29	3.6
4	9,463	8.7	32	3.3

3.4. Existing Conditions, Major Tributaries

This section on the existing conditions along the major tributaries to the project reach of the San Joaquin River is based on the observations made during the field reconnaissance, the 1998 hydrographic survey of the lower portions of the rivers and estimated hydraulic conditions based on normal depth calculations at two cross sections in the downstream reach of each of the rivers that were developed from topography generated by the 1998 COE survey. Photographs (Plates in Appendix B) taken during the field reconnaissance are referenced in this section. Subreach boundaries are included on the map in Appendix A 4 . Bridge cross-section data were obtained from CALTRANS for a number of bridges on each of the tributaries to evaluate aggradation and degradation trends.

3.4.1. Merced River

The upstream reach (Subreach M4) of the Merced River between Merced Falls and Snelling Road Bridge was totally reworked by dredge mining (**Plate 23**), and the present day river traverses the very coarse grained dredge tailings (**Plate 24**). The bulk of the finer sediments were washed downstream and may have been responsible for the very thick and droughty sand deposits along the lower Merced River (Plate 22) and in Subreaches 4 and 3 of the San Joaquin River. Bedrock outcrop is exposed in the bed of the river in the subreach which indicates that there is very little potential for further channel incision in response to the elimination of the upstream watershed sediment supply (**Plate 25**). Prior to construction of Lake McLure, the annual watershed sediment yield was estimated to be 299,000 yd^3. In the lower part of Subreach M4 and the upper part of Subreach M3, the bed material is predominantly cobble-sized (up to 180 mm) (**Plate 26**).

Within Subreach M3, which extends from Snelling Road to Shaffer Bridge, there has been, and continues to be a significant sand and gravel mining impact on the channel (**Plate 27**). Abandoned in-channel and channel margin gravel pits that have been captured by the river are present up-and downstream of the J59 Bridge (**Plate 28**). It has been estimated that between 7 and 14 million tons of material were excavated from the Merced River between 1940 and 1993 (Bay Institute, 1998) At the upstream end of Subreach M2 that extends from Shaffer Bridge to the River Road Bridge the channel and a narrow floodplain are confined between Modesto-age terraces (**Plate 29**). The bed material is composed primarily of gravel-sized sediments but clasts up to 128 mm are present on the bed (**Plate 30**). Within Subreach M2, the channel is confined between the Modesto-age terraces and is flanked by a relatively narrow floodplain that supports the riparian forest (**Plate 31**). At about the Highway 99 Bridge, the bed material transitions from gravel to sand, and the bed material in the lower subreach (M1) appears to be exclusively sand-sized (**Plate 32**). The river is not confined by the Modesto-age terraces in Subreach M1 that extends downstream to the confluence with the San Joaquin River (Plate 22).

The HEC-RAS program was used to perform normal depth calculations at two cross section in the lower reach of the Merced River based on the 1998 COE topography (Appendix C3) was developed to determine the channel capacity. The bankfull discharge is about 6,000 cfs, the average width of the channel is 190 feet, the average depth is 16 feet, the width-depth ratio is 12 and the slope is about 0.00022. The bankfull discharge has a post-Lake McLure duration of about 4 days per year, which may explain why there has been little replenishment of the riparian forest in the lower reaches of the river.

Comparative cross-section profiles at the J16 (Merced Falls Road) Bridge, Highway 99 Bridge and the Hills Ferry/River Road Bridge were obtained from CALTRANS to evaluate aggradation or degradation trends along the river. The J16 Bridge (located in Subreach M4) profiles indicate that there was about 6 feet of aggradation between 1967 and 1992 (**Figure 3.20**). However, the effects of the 1997 flood (about 8,000 cfs) are unknown at the present. Between 1992 and 1997 there appears to have been about 3 feet of degradation at the Highway 99 Bridge in Subreach M2 (**Figure 3.21**). **Figure 3.22** indicates that there may have been some aggradation at the Hills Ferry/River Road Bridge at the upstream end of Subreach M1 between 1978 and 1992.

3.4.2. Tuolumne River

The upstream reach (Subreach T4) of the Tuolumne River between La Grange and Roberts Ferry was totally reworked by dredge mining (**Plate 33**), and the present day river traverses the very coarse grained dredge tailings in a relatively unconfined valley (Figure 3.7). The bulk of the finer sediments that comprised the historical alluvial valley fill were washed downstream. The maximum size of the bed material in the reach is about 180 mm (**Plate 34**). Subreach T3 extends from Roberts Ferry to the J14 Bridge, and the river and a relatively narrow floodplain are confined between Pleistocene-age terraces (**Plate 35**). The bed material is somewhat finer than in the upstream reach, with the largest sizes being about 128 mm. Sand and gravel mining has occurred extensively through the subreach. McBain and Trush (1998) report that 40-foot deep and 400-foot wide pits in the bed of the river were not uncommon.

The channel and floodplain in Subreach T2, that extends from the J14 Bridge to the Shiloh Road Bridge, are confined by the Pleistocene-age terraces. A considerable length of the river in this subreach is bordered by urban development. Peak flow discharges are kept below 9,000 cfs in the floodway to prevent flooding. Between the Shiloh Road Bridge, which is the downstream extent of the confining terraces (**Plate 36**), and the confluence with the San Joaquin River, the river in Subreach T1 is unconfined. From about the J14 bridge downstream, the bed material of the river is sand (**Plate 37**).

HEC-RAS generated normal depth calculations at two cross sections for the lower reach of the

Tuolumne River based on the 1998 COE topography (Appendix C3) were used to estimate the channel capacity. The bankfull discharge is about 5,200 cfs, the average width of the channel is 189 feet, the average depth is 13 feet, the width-depth ratio is 15 and the slope is about 0.00023. The bankfull discharge has a post-New Don Pedro Reservoir duration of about 14 days per year.

Figure 3.20. Comparative 1967 and 1992 cross sections at the J16 Bridge across the Merced River (data from CALTRANS).

Figure 3.21. Comparative 1992 and 1997 cross sections at the Highway 99 Bridge across the Merced River (data from CALTRANS).

Figure 3.22. Comparative 1978 and 1992 cross sections at the Hills Ferry/River Road Bridge across the Merced River (data from CALTRANS).

Comparative cross sections were obtained for the Old La Grange Bridge (McBain and Trush, 1998), the J7 Bridge, the Highway 99 Bridge and the Shiloh Road Bridge (CALTRANS) to evaluate the aggradational or degradational status of the subreaches. **Figure 3.23** shows that there was about 5 feet of degradation during the 1997 flood event (about 56,000 cfs) at the Old La Grange Bridge. Degradation was probably due to the elimination of the upstream watershed sediment supply (about 520,000 yd^3/yr; Kondolf and Mathews, 1993) by New Don Pedro Reservoir. At the J7 Bridge, it appears that there may have been about 2-3 feet of degradation between 1947 and 1972, but the cross section aggraded between 1972 and 1996 (**Figure 3.24**). Between 1972 and 1997, it appears that the channel degraded by about 4 to 6 feet at the Highway 99 Bridge (**Figure 3.25**). At the Shiloh Road Bridge, the channel aggraded by 3 to 4 feet between 1964 and 1993, but the effects of the 1997 flood are unknown (**Figure 3.26**).

3.4.3. Stanislaus River

The upstream reach (Subreach S3) of the Stanislaus River between Hills Ferry Bridge and Highway 120 was placer and dredge mined, but not to the same extent as the Merced and Tuolumne Rivers. Upstream sediment sources to the reach have been cutoff by the upstream reservoirs, and the river traverses a bedrock-bounded canyon before it enters Subreach S3 (**Plate 38**). At Knights Ferry Bridge, the river is confined between the valley walls and Pleistocene-age terraces. The controlled flows from upstream have allowed development of a well defined channel with relatively dense riparian vegetation (**Plate 39**). The bed material in the reach is gravel-sized (**Plate 40**). Siltation of the spawning gravels in Subreach S3 has been reported by Kondolf and Mathews (1993). At about the mid-point of the subreach at Orange Blossom Road, the river is confined by Pleistocene-age terraces and is bounded by dense riparian vegetation (**Plate 41**). Within Subreach S2, that extends from the Highway 120 Bridge to the head of the project levees, the floodplain is inset below the terraces and the river is actively meandering (**Plate 42**). Mature riparian forest occupies the floodplain between the confining terraces (**Plate 43**). Within Subreach S1, which is confined between the project levees, the river is highly sinuous and recent cutoffs are present on the floodplain (**Plate 44**). Within Caswell State Park, a densely vegetated floodplain borders the channel (**Figure 3.27**). Cobble revetments have been emplaced along the river to protect the project levees (**Plate 45**).

HEC-RAS generated normal depth calculations at two cross sections for the lower reach of the Stanislaus River based on the 1998 COE topography (Appendix C3) were used to estimate the channel capacity. The bankfull discharge is about 5,450 cfs, the average width of the channel is 140 feet, the average depth is 13 feet, the width-depth ratio is 11 and the slope is about 0.00033. The bankfull discharge has a post-New Melones Reservoir duration of about 5 days per year.

Comparative cross sections were obtained from CALTRANS for the Knights Ferry Bridge, the Orange Blossom Road Bridge, the J9 (Highway 120) Bridge, the J6 Bridge and the Highway 99 Bridge to evaluate the aggradational or degradational status of the subreaches. Between 1986 and 1993, there was about 6 feet of degradation at the Knights Ferry Bridge, but the effects of the 1997 flood (7,300 cfs) cannot be determined (**Figure 3.28**). At the Orange Blossom Road Bridge the 1965, 1980 and 1993 cross sections indicate that there has been some aggradation of the channel (**Figure 3.29**). At the J9 (Highway 120) Bridge, it also appears that the channel aggraded somewhat between 1969 and 1993 (**Figure 3.30**). At the J6 Bridge, it appears that the floodplain aggraded by about 5 feet between 1958 and 1972, but the channel degraded by about 5 feet between 1958 and 1997 (**Figure 3.31**). Between 1968 and 1993, it appears that the floodplain elevation at the Highway 99 Bridge was lowered by as much as 10 feet. In the same period the thalweg aggraded by about 5 feet, but there was very little change between 1993 and 1997 (**Figure 3.32**).

Figure 3.23. Comparative 1996 and 1997 cross sections at the Old La Grange Bridge across the Tuolumne River (McBain and Trush, 1998).

Figure 3.24. Comparative 1947, 1972 and 1996 cross sections at the J7 Bridge across the Tuolumne River (data from CALTRANS).

Figure 3.25. Comparative 1960, 1972 and 1997 cross sections at the Highway 99 Bridge across the Tuolumne River (data fro CALTRANS).

Figure 3.26. Comparative 1964 and 1993 cross sections at the Shiloh Road Bridge across the Tuolumne River (data from CALTRANS).

Figure 3.27. 1998 aerial photograph of the Caswell State Park reach of the Stanislaus River within Subreach S1.

Figure 3.28. Comparative 1986 and 1993 cross sections at Knights Ferry Bridge across the Stanislaus River (data from CALTRANS).

Figure 3.29. Comparative 1965, 1980 and 1993 cross sections at the Orange Blossom Road Bridge across the Stanislaus River (data from CALTRANS).

Figure 3.30. Comparative 1969 and 1993 cross sections at the J9 (Highway 120) Bridge across the Stanislaus River (data from CALTRANS).

Figure 3.31. Comparative 1958, 1972, 1993 and 1997 cross sections at the J6 Bridge across the Stanislaus River (data from CALTRANS).

Figure 3.32. Comparative 1968, 1993 and 1997 cross sections at the Highway 99 Bridge across the Stanislaus River (data from CALTRANS).

4. HYDROLOGY

4.1. General

As discussed in Chapter 1, the flow characteristics of the San Joaquin River and its major tributaries are significantly affected by water resources development that has occurred over the past approximately 130 years, including large multi-purpose reservoirs, levee and channel improvements, bypasses, and local diversions (COE, 1993). Major dams are present on the mainstem San Joaquin River and each of the three main tributaries upstream from the study reach. The most upstream of those dams include Friant Dam on the San Joaquin River, approximately 140 river miles upstream from the Merced River confluence; New Exchequer Dam on the Merced River approximately 60 river miles upstream from the mouth; New Don Pedro Dam on the Tuolumne River, approximately 50 river miles upstream the mouth; and New Melones Dam on the Stanislaus River, approximately 58 river miles upstream from the mouth (Figure 1.1, Table 1.3). (The New Melones project includes both New Melones Dam and the smaller Tulloch Dam and Reservoir approximately 8 miles downstream.) Approximately 85 percent of the combined watershed area of the three main tributaries is above the dams. Since most of the runoff originates from the upper portions of the watershed, these dams have a significant effect on the runoff characteristics of both the tributaries and the mainstem.

To facilitate analysis of the present and historic hydrology, and the qualitative evaluation of hydraulic and sediment transport conditions in the study reach, the available recorded mean daily discharges of various gaging stations on the San Joaquin River and the tributaries were obtained and analyzed. The recorded annual maximum instantaneous peak flows (or annual maximum mean daily flows) were also obtained for use in the analysis. As will be discussed below, because of the effects of reservoir operations during flood conditions on the peak discharges, and the different times at which the upstream reservoirs were constructed, a standard flood frequency analysis of the peak flow data does not provide a realistic representation of the long-term flood frequency curve at each of the gages. For this reason, the flood frequency curves that were recently developed by the COE as part of the Post Flood Assessment for the Sacramento-San Joaquin Comprehensive Study (COE, 1999) were adopted for use in this study.

4.2. Mean Daily Flow-Duration Curves

Mean daily flow-duration curves provide a representation of the average percentage of time that flows equaled or exceeded a given value during the period of record used to develop the curves. To aid in evaluating differences in the magnitude and duration of flows along the study reach for similar time-periods, and in evaluating changes in the flows among different time-periods, mean daily flow-duration curves were developed for three gages along the mainstem San Joaquin River within the study reach and for two gages on each of the major tributaries. A summary of the gages that were used in the mean daily flow-duration analysis is presented in **Table 4.1**. The three mainstem gages encompass the study reach, with the Newman gage at RM 118.2 near the upstream end, the Vernalis gage at RM 72.5, which is about 2.5 miles downstream from the Stanislaus River confluence, and the Maze Bridge gage at RM 77.5 representing flows in the mainstem between the Stanislaus and Tuolumne Rivers (**Figure 4.1**). The two gages on each tributary represent flows near the up- and downstream ends of the study reaches, respectively.

Table 4.1

Figure 4.1

At least two curves were developed for each of the gages that were analyzed to represent flow conditions prior to construction of the major downstream dams and flow conditions since completion of those dams. Because several upstream water control projects were already in place when most the gages began operating, the flow-duration curves for the early period should not be interpreted as unregulated flows.

4.2.1. Annual Flow-Duration Curves

4.2.1.1. San Joaquin River flow-duration based on measured data at USGS gages

An initial analysis of the flow-duration at the Newman and Vernalis gages was made based only on the measured flows at those two gages. This analysis provides an accurate representation of the actual flow regime that occurred during the periods of record at the two gages. As will be discussed below, however, limitations in the record length at the Vernalis gage during the pre-Friant Dam period limit the usefulness of these results for evaluating differences in long-term flow regime to which the river would tend to adjust between the two periods.

The Newman gage (USGS Gage #1127400) is located on the San Joaquin River at RM 118.2, approximately 600 feet downstream from the Hills Ferry Bridge and the Merced River confluence at the upstream end of the study reach (Figure 4.1). The gage has a period of record extending from 1913 to the present (Table 4.1). Three annual flow-duration curves were developed for this gage for the periods from 1913 through 1940, 1949 through 1966 and 1967 through 1998, respectively (**Figure 4.2**). The period from 1941 through 1948 was not used in the analysis because water was not diverted into the Madera and Friant Canals until 1943 and 1948, respectively; thus, the recorded flows during the period are not a good representation of post-dam conditions (Cain, 1997, p37). The resulting curves represent flows in the river prior to construction of Friant Dam in 1941, between completion of the Friant project and New Exchequer Dam on the Merced River in 1966, and after construction of New Exchequer Dam, respectively. The median flow for the three periods varied from about 640 cfs during the 1913 to 1941 period to 380 cfs between 1949 and 1966 to 720 cfs during the post-dam period from 1967 through 1998. Annual runoff volumes during the three periods were approximately 1.75 million acre-feet, 860,000 acre-feet, and 1.61 million acre-feet, respectively. The recorded average annual runoff volume during the pre-Friant Dam period was about 9 percent larger than during the modern period after completion of New Exchequer Dam, and was about 50 percent less during the time period between completion of Friant Dam and New Exchequer Dam. The reason for this significant difference is unknown, but is likely related to a combination of dry years and upstream water diversions. The flow-duration curves indicate that the operation of the upstream water projects have tended to increase the duration of low flows. Comparison of the pre-Friant and post-New Exchequer flow-duration curves further indicates that the duration of intermediate flows between about 800 and 8,000 cfs has decreased, and that the duration of flows greater than 8,000 cfs has slightly increased.

The Vernalis gage (USGS Gage #11303500) is located on the San Joaquin River at the Durham Ferry highway bridge (also known as Airport Way), 2.6 miles downstream from the Stanislaus River at RM 72.5 (Figure 4.1). The gage has a period of record extending from 1924 through the present (Table 4.1). Four annual flow-duration curves were developed for this gage for the periods from 1924 through 1940, 1949 through 1966, 1967 through 1978, and from 1979 through 1998, respectively (**Figure 4.3**). The 1967 through 1998 period that was used at the Newman gage was further subdivided into two periods (1969-1978 and 1979-1998) to represent the flow conditions prior to and after construction of New Melones Dam on the Stanislaus River in 1978. The median

Figure 4.2 Mean daily flow-duration curves for the San Joaquin River near Newman (USGS Gage # 11274000) for water years 1913 through 1940, 1949 through 1966, and 1967 through 1998.

Figure 4.3 Mean daily flow-duration curves for the San Joaquin River near Vernalis (USGS Gage # 11303500) for water years 1924 through 1940, 1949 through 1966, 1967 through 1978, and 1979 through 1998.

flow for the four periods were about 1,820, 1,680, 2,300, and 2,320 cfs, respectively. Annual runoff volumes during the four periods were approximately 3.38, 2.58, 3.12, and 3.98 million acre-feet, respectively. Comparison of the flow-duration curves indicates that the period between 1941 and 1978 had relatively low runoff compared to the earlier and later periods. Additionally, the pre- Friant Dam period, which is based on recorded flows in 1924 and 1930 to 1940, had average annual runoff that was about 15 percent less than during the post-New Melones period. This is in contrast to the to the higher recorded runoff at the Newman gage during the pre-Friant Dam period. The general trend indicated by the Newman gage data is likely to be more representative of long term conditions because the Newman record extends over a longer time period, and the relatively short record at the Vernalis gage occurs during the drought years in the 1930s.

4.2.1.2. San Joaquin River flow-duration based on extended records

Due to the limitations in the record lengths that are apparent from the above analysis of the recorded flows, and to obtain flow-duration curves for portions of the mainstem reach for which recorded flows are not available, it was necessary to extend and fill-in portions of the available records and to estimate flows at other locations by combining existing records. The procedures used to accomplish this are described in this section.

To obtain a better long-term representation of the pre-Friant Dam flows in the downstream portion of the study reach, the Vernalis gage record was extended back to Water Year 1913, and the missing years between 1924 and 1930 were filled-in, using the Maintenance of Variance Extension (MOVE.1) technique (Hirsch et al., 1992; Hirsch, 1982), and the recorded flows at the Newman gage for the 1913 through 1940 period. The MOVE.1 technique is carried out by developing a relationship between the gaged flows for the overlapping period of record at the two stations, and then estimating the missing flows at the short station from that relationship. In evaluating the results that are obtained from this procedure, it is important to understand that the objective of the flow extension is to correctly predict the overall statistical distribution of the flow record, rather than predicting each individual flow. The MOVE.1 relationship differs from standard least-squares regression in that it preserves both the mean and variance of the distribution at the short station, whereas least-squares regression tends to under-estimate the variance. MOVE.1 is, therefore, the preferred technique for such extensions. A plot of recorded flows during the overlapping period of record between 1930 and 1940 at the two gages, and the MOVE.1 extension relationship is presented in **Figure 4.4**. Considering the good correlation between the corresponding flows during the overlapping record ($R^2 = 0.9$), the extension is believed to provide a reasonable representation of the longer-term record at the Vernalis gage.

To obtain a better representation of the flow distribution along the mainstem study reach, flow-duration curves were also developed for the Maze Bridge gage that is operated by the California Department of Water Resources, and for Subreach 3, which extends from the Tuolumne River confluence (RM 83.5) upstream to RM 99.5. Flows at the Maze Bridge gage represent conditions in Subreach 2 (between the Stanislaus and Tuolumne River confluences). In combination with the Newman and extended Vernalis records, these intermediate flow-duration curves provide information for each of the four subreaches along the mainstem. Two sets of curves were developed for each of the reaches to represent conditions prior to construction of Friant Dam in 1941 and after completion of the last major dam on the tributaries in 1978 (**Figures 4.5** and **4.6**). Because records were not available for Water Year 1998 for all of the gages, the analysis only considered data collected through 1997.

Figure 4.4 Recorded mean daily flows at the San Joaquin River near Newman gage (USGS Gage # 11274000) Water Years 1930 through 1940 plotted against the corresponding recorded flows at the San Joaquin River near Vernalis gage (USGS

Gage # 11303500). Also shown is the MOVE.1 relationship used to estimate the Vernalis flows from 1913 through 1923, and from 1925 through 1929.

Figure 4.5 Estimated annual flow-duration curves for Subreaches 1 through 4 on the mainstem San Joaquin River for the period 1913 through 1940.

Figure 4.6 Estimated annual flow-duration curves for Subreaches 1 through 4 on the mainstem San Joaquin River for the period 1979 through 1997

As noted in Table 4.1, the Maze Bridge gage has been in operation since 1966; however, records are not available for 14 of the 32 years from 1966 through 1997. For the 1978 to 1997 period, mean daily discharges for the missing years were filled-in by subtracting the recorded flows at the Stanislaus River at Ripon from the corresponding recorded flows at the Vernalis gage. A comparison of the recorded flows at the Maze Bridge gage and the difference between the recorded Vernalis and Stanislaus River flows for the overlapping period of record indicates that this approach to filling-in the missing flows is reasonable (**Figure 4.7**). The flow-duration curve for Subreach 3 was estimated by subtracting the recorded flows at the Tuolumne River at Modesto gage (USGS Gage #11290000) from the filled-in record at the Maze Bridge gage. Because flow records are not available for Subreaches 2 and 3 for the pre-Friant Dam period, flow-duration curves were estimated by interpolating between the Vernalis and Newman curves based on the ratios of flows indicated by the 1978 through 1997 curves.

4.2.1.3. Merced, Tuolumne and Stanislaus River flow-durations

Mean daily flow-duration curves were developed for the recorded flows at the Merced River below Merced Falls Dam gage (USGS Gage #11270900) (**Figure 4.8**) and at the Stevinson gage (USGS Gage #11272500) (**Figure 4.9**) for the period before and after construction of New Exchequer Dam in 1966. The available period of record at the Merced Falls gage extends from 1902 to 1913, and from 1917 through 1997, and from 1941 to 1995 at the Stevinson gage.

Similar curves were developed for the Tuolumne River near La Grange Dam (**Figure 4.10**) and at Modesto (USGS Gage #11290000) (**Figure 4.11**) for the periods before and after construction of New Don Pedro Dam in 1971. The pre-dam curves for the upstream gage were based on the Aabove La Grange Dam@ gage (USGS Gage #1128800) which operated from 1896 through 1970, and the post-dam curves were based on the Abelow La Grange Dam@ gage (USGS Gage #11289650), which has operated from 1971 to the present.

Mean daily flow-duration curves were also developed for the Stanislaus River below Goodwin Dam (USGS Gage #11302000) (**Figure 4.12**) and at the Ripon gage (USGS Gage #11303000) (**Figure 4.13**) for the periods before and after construction of New Melones Dam in 1978. The available period of record at the below Goodwin Dam gage extends from 1958 through 1997 and from 1941 through 1998 at the Ripon gage.

4.2.2. April-May Flow-Duration Curves

To facilitate the evaluation of existing conditions riparian ecology that was performed for this study by JSA, mean daily flow-duration curves were developed for the April and May time period for each of the mainstem subreaches and each of the tributary gages. The procedure used to develop these curves was identical to that described above for the annual flow-duration curves, but used only the April-May discharges rather than discharges for the entire year. The pre-Friant Dam and post-tributary dam curves for each of the four mainstem San Joaquin River subreaches are presented in **Figures 4.14** and **4.15**, respectively. Similar curves for each of the tributary gages are presented in **Figures 4.16** through **4.21**.

4.2.3. Comparison of Historical Changes in Mean Daily Flow-duration

Based on the flow-duration curves described in the previous sections (Figures 4.5 and 4.6), the average annual runoff volume during the pre-Friant Dam period (1913-1940) in the mainstem San Joaquin River study reach varied from about 1.8 million acre-feet in the upstream portion of the

Figure 4.7 Recorded mean daily flows at the San Joaquin River at Maze Road gage for Water Years 1979, 1980, 1983, 1986, 1995 and 1997 plotted against the difference between the corresponding recorded flows at the San Joaquin River near Vernalis gage (USGS Gage # 11303500) and the Stanislaus River at Ripon gage (USGS Gage # 11303000)

Figure 4.8 Annual mean daily flow-duration curves for the Merced River below Merced Falls Dam near Snelling (USGS Gage # 11270900) for the periods prior to (1902-1913, 1917-1966) and after completion of (1967-1997) New Exchequer Dam.

Figure 4.9 Annual mean daily flow-duration curves for the Merced River near Stevinson (USGS Gage # 11272500) for the periods prior to (1941-1966) and after completion of (1967-1995) of New Exchequer Dam.

Figure 4.10 Annual mean daily flow-duration curves for the Tuolumne River above La Grange Dam near La Grange (USGS Gage # 11288000) for the period 1896 to 1970, prior to construction of New Don Pedro Dam in 1971, and for the Tuolumne River below La Grange Dam (USGS Gage # 11289650) for the period 1971 through 1997.

Figure 4.11 Annual mean daily flow-duration curves for the Tuolumne River at Modesto (USGS Gage # 11290000) for the periods prior to (1896, 1941-1971) and after completion of (1972-1997) of New Don Pedro Dam.

Figure 4.12 Annual mean daily flow-duration curves for the Stanislaus River below Goodwin Dam near Knights Ferry (USGS Gage # 113002000) for the periods prior to (1958 to 1978) and after (1979-1997) completion of New Melones Dam.

Figure 4.13 Annual mean daily flow-duration curves for the Stanislaus River at Ripon (USGS Gage # 11303000) for the period prior to (1941-1978) and after completion of (1979-1997) of New Melones Dam.

Figure 4.14 Estimated April-May flow-duration curves for Subreaches 1 through 4 on the mainstem San Joaquin River for the period 1913 through 1940.

Figure 4.15 Estimated April-May flow-duration curves for Subreaches 1 through 4 on the mainstem San Joaquin River for the period 1979 through 1997

Figure 4.16 April-May mean daily flow-duration curves for the Merced River below Merced Falls Dam near Snelling (USGS Gage # 11270900) for the periods prior to (1902-1913, 1917-1966) and after completion of (1967-1997) New Exchequer Dam.

Figure 4.17 April-May mean daily flow-duration curves for the Merced River near Stevinson (USGS Gage # 11272500) for the periods prior to (1941-1966) and after completion of (1967-1995) of New Exchequer Dam.

Figure 4.18 April-May mean daily flow-duration curves for the Tuolumne River above La Grange Dam near La Grange (USGS Gage #11288000) for the period 1896 to 1970, prior to construction of New Don Pedro Dam in 1971, and for the Tuolumne River below La Grange Dam (USGS Gage # 11289650) for the period 1971 through 1997.

Figure 4.19 April-May mean daily flow-duration curves for the Tuolumne River at Modesto (USGS Gage # 11290000) for the periods prior to (1896, 1941-1971) and after completion of (1972-1997) of New Don Pedro Dam.

Figure 4.20 April-May mean daily flow-duration curves for the Stanislaus River below Goodwin Dam near Knights Ferry (USGS Gage # 113002000) for the periods prior to (1958 to 1978) and after (1979-1997) completion of New Melones Dam.

Figure 4.21 April-May mean daily flow-duration curves for the Stanislaus River at Ripon (USGS Gage # 11303000) for the period prior to (1941-1978) and after completion of (1979-1997) of New Melones Dam.

reach (Subreach 4) to about 3.7 million acre-feet in the portion of the reach downstream from the Stanislaus River (Subreach 1) (**Figure 4.22**). The average annual runoff volume during the post-New Melones Dam period (1979-1997) was essentially the same as the earlier period, varying from about 1.8 million acre-feet in Subreach 4 to 4.0 million acre-feet in Subreach 1. The increase between the early and modern periods varied from less than 2 percent in the upstream reach to about 6 percent in the downstream reach.

Comparison of the flow-duration curves, however, demonstrates that, while the annual runoff volumes were similar, the flow patterns were quite different. The median discharge (discharge that is equaled or exceeded 50 percent of the time), for example, increased from about 640 to 740 cfs between the two time periods in the upstream portion of the reach, a difference of about 16 percent (**Figure 4.23**). In the most downstream reach, the median discharge increased from about 2,160 to about 2,320 cfs, a difference of about 8 percent. The upstream water projects tend to increase the duration of lower flows (less than about 3,000 cfs at Vernalis), and decrease the duration of intermediate flows (3,000 to 16,000 cfs at Vernalis). The duration of flows greater than 16,000 cfs was also greater during the modern period, which may be more related to several extreme flood years in this portion of the record than to the operational characteristics of the upstream water projects.

The average annual hydrograph, which represents the average discharge on each day of the year, was computed for the Newman gage and the extended flow record at the Vernalis gage for each of the two time periods discussed above to illustrate the effect of the upstream projects on the timing of flows in the reach (**Figures 4.24** and **4.25**, respectively). These hydrographs clearly show that, prior to completion of Friant Dam in 1941, flows were relatively high during the winter months of February and March, but that the highest flows tended to occur during the spring runoff in May and June. The upstream water projects store water during the snowmelt runoff period, releasing that water over a longer period of time during the late summer through early winter period. This can also be seen by comparing the average runoff volume and median discharges during the April-May period (**Figures 4.26** and **4.27**, respectively). Although the average annual runoff increased slightly from the early to later period, the runoff volume during April and May decreased significantly. For example, in Subreach 4, at the upstream end of the study reach, the April-May runoff volume decreased from 550,000 acre-feet during the pre-Friant Dam period to about 460,000 acre-feet during the post-dam period, a difference of about 16 percent (Figure 4.26). The median discharges decreased even more dramatically, from about 3,700 cfs during the earlier period to about 970 cfs during the recent period, a difference of nearly 75 percent (Figure 4.27). Similar changes occurred in the other subreaches of the mainstem, as well.

A summary of the runoff volumes and median discharges for the pre- and post-dam periods on each of the three major tributaries is presented in **Table 4.2**. On the Merced River at the below Merced Falls Dam gage, the annual runoff volume increased by about 9 percent from 930,000 acre-feet for the period prior to construction of New Exchequer Dam in 1967 to about 1.01 million acre-feet during the post-dam period, and the median discharge increased by about 34 percent from 860 cfs to about 1,150 cfs. The duration of flows less than about 2,500 cfs increased, and the duration of larger flows decreased between the pre- and post-dam periods at this gage (Figure 4.8).

At the Stevinson gage, which is located near the downstream end of the Merced River, the annual runoff decreased by about 1 percent between the pre- and post-dam periods, but, similar to the upstream gage, the median discharge increased by about 32 percent from 200 to 270 cfs. At this gage, the duration of flows less than about 150 cfs decreased during the post-dam period, the

Figure 4.22 Average annual runoff in the San Joaquin River, by subreach, for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods.

Figure 4.23 Annual median discharge in the San Joaquin River, by subreach, for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods.

Figure 4.24 Average annual hydrographs for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods in the San Joaquin River near Newman (Subreach 4).

Figure 4.25 Average annual hydrographs for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods in the San Joaquin River near Vernalis (Subreach 1).

Figure 4.26 Average April-May runoff in the San Joaquin River, by subreach, for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods.

Figure 4.27 April-May median discharge in the San Joaquin River, by subreach, for the pre-Friant Dam (1913-1940) and post-New Don Pedro Dam (1979-1997) periods.

Table 4.2

duration of flows between 150 cfs and about 750 cfs increased and the duration of flows greater than 750 cfs was about the same (Figure 4.9).

On the Tuolumne River, the annual runoff at both the upstream La Grange Dam and downstream Modesto gages decreased significantly during the period after construction of New Don Pedro Dam in 1971 compared to the pre-dam period (Table 4.2), with the runoff at the upstream gage decreasing by over 55 percent (1.67 million acre-feet versus 734,000 acre-feet) and the downstream by over 30 percent (1.05 million acre-feet versus 730,000 acre-feet). Some of the recorded decrease may also have been due to a change in the gage location in 1971.

On the Stanislaus River, the average annual runoff at the upstream below Goodwin Dam gage was higher during the post-New Melones Dam period (1979-1997) than it was prior to construction of the dam (1958-1978), increasing by about 10 percent from 525,000 acre-feet to 579,00 acre-feet (Table 4.2). In contrast, at the downstream near Ripon gage, the runoff for the post-dam period was about 4 percent less than during the pre-dam period from 1941 to 1978 (728,000 acre-feet versus 700,000 acre-feet). The different trends at the two gages are probably mostly related to different hydrologic conditions during the respective periods of analysis since the 1958 to 1978 period was relatively dry. The average annual runoff at the Ripon gage was about 9 percent higher during the 1958 to 1978 period than during the post-dam period. The median discharge increased substantially at both gages from the pre-dam to post-dam periods. Comparison of the flow-duration curves (Figures 4.12 and 4.13) shows that the duration of flow less than about 1,000 cfs at the below Goodwin Dam gage and less than about 1,200 cfs at the Ripon gage increased and the duration of larger flows decreased from the pre-dam to post-dam periods.

Table 4.2 contains similar information for the April-May period at each of the tributary gages. Similar to the mainstem San Joaquin River, both the average runoff and the median discharge during the period decreased substantially at both gages on the Merced and Tuolumne Rivers. On the Stanislaus River, the average runoff during the period also decreased from the pre-dam to post-dam periods at both gages. The median discharge however increased substantially at the upstream below Goodwin Dam gage, while it decreased at the downstream Ripon gage.

4.3. Peak Flood Frequency Curves

4.3.1. Curve Development

The Sacramento District COE recently completed a Regulated Flood Flow Frequency Analysis for the Sacramento/San Joaquin River Basins and Delta Tributaries as part of the Sacramento-San Joaquin Comprehensive Study Post Flood Assessment (COE, 1999). In that study, the COE developed regulated peak flood flow frequency curves for several selected locations within the San Joaquin River Basin by re-evaluating and updating earlier curves to account for recent flood years in 1983, 1986, 1995 and 1997. The curves for the tributaries also include an estimated unregulated peak flood frequency relationship. A summary of the curves that are within the area of concern for this study, along with the COE estimated exceedance interval of the 1983, 1986, 1995 and 1997 flood events is presented in **Table 4.3**, and copies of the curves are presented in **Figures 4.28** through **4.36**. According to COE (1999, p1):

> A*The regulated hypothetical events were developed using balanced inflow hydrographs based on unregulated flow frequency curves fitted to a distribution and derived from long-term historical records. The unregulated flow frequency curves used to develop the hypothetical events were based on computed probability.*@

Table 4.3. Estimated exceedance interval of historical flood events in the

San Joaquin River Basin (COE, 1999).					
		Historical Flood Events (Exceedance Interval, range in years)			
Location	Figure No.	Feb-Mar 83	Feb 86	Mar 95	Dec 96-Jan97
Merced River at New Exchequer Dam and at Cressey[1]	4.31, 4.32	10-20	20-40	10-20	50-60
San Joaquin River at Newman	4.28	25-50	10-20	5-10	90-110
Tuolumne River at Don Pedro Dam and at Modesto[1]	4.33, 4.34	15-25	30-40	5-15	80-110
San Joaquin River at Maze Road Bridge	4.29	15-25	10-20	5-10	80-110
Stanislaus River at New Melones Dam and at Orange Blossom Bridge[1]	4.35, 4.36	5-10	30-50	10-15	50-70
San Joaquin River at Vernalis	4.30	30-50	15-25	5-10	80-110

[1]Exceedance interval of flood event estimated from unregulated volume-duration flood flow frequency relationships.

Figure 4.28. One-day rain flood flow frequency curve, regulated condition, San Joaquin River near Newman, CA (COE, 1999).

Figure 4.29. One-day rain flood flow frequency curve, regulated condition, San Joaquin River near Maze Road Bridge (COE, 1999).

Figure 4.30. One-day rain flood flow frequency curve, regulated condition, San Joaquin River near Vernalis (COE, 1999).

Figure 4.31. Peak rain flood frequency curve, regulated condition, Merced River at New Exchequer Dam (COE, 1999).

Figure 4.32. Peak rain flood frequency curve, regulated condition, Merced River at Cressey (COE, 1999).

Figure 4.33. Peak rain flood frequency curve, regulated condition, Tuolumne River at Don Pedro Dam (COE, 1999).

Figure 4.34. Peak rain flood frequency curve, regulated condition, Tuolumne River at Modesto (COE, 1999).

Figure 4.35. Peak rain flood frequency curve, regulated condition, Stanislaus River at New Melones Dam (COE, 1999).

Figure 4.36. Peak rain flood frequency curve, regulated condition, Stanislaus River at Orange Blossom Bridge (COE, 1999).

The estimated exceedance intervals shown in Table 4.3 for the tributaries are based on unregulated flood frequency-volume-duration estimates for each flood event. The estimated exceedance intervals for the mainstem San Joaquin River are, however, based on regulated peak flood flow frequency estimates because the effects of low-lying basins, weirs, bypasses, and co-mingling of tributary flows make it difficult to estimate unregulated flows and volumes (COE, 1999).

An explanation of each of the curves in Figures 4.28 through 4.36 was provided in COE (1999) and is repeated here for the convenience of the reader:

1. San Joaquin River at Newman (Figure 4.28). *Flow at this site is regulated by additional reservoirs on the Merced River, Los Banos Creek, and Merced Streams. The channel design flow at this location is 45,000 cfs, however, levees begin to fail or are overtopped when flows exceed 40,000 cfs near Newman. The maximum 1-day flow frequency curve of simulated and recorded flows reflects in-channel flows and flow out-of-bank along the latitude of the channel.*

2. San Joaquin River at Maze Road Bridge (Figure 4.29). *Flow at this site is regulated by additional reservoirs on the Tuolumne River. The channel design flow at this location is 46,000 cfs; however, levees begin to fail or are overtopped when flows exceed 40,000 cfs from Newman to Maze Road Bridge, with the exception of one stretch. The San Joaquin River has limited channel capacity near the town of Grayson just upstream of the Tuolumne River. For periods of high flow at that location, Laird Slough carries most of the San Joaquin flow. The combined carrying capacity of San Joaquin River and Laird Slough is 26,000 cfs. The maximum 1-day flow frequency curve of simulated and recorded flows reflects in-channel flows and flow out-of-bank along the latitude of the channel. Out-of-channel flows may have occurred in 1938 (41,6000 cfs), and did occur in 1969 (41,800 cfs), 1983 (38,400 cfs), and 1997 (59,300 cfs).*

3. San Joaquin River at Vernalis (Figure 4.30). *Flow at this site is regulated by additional reservoirs on the Stanislaus River. The channel design flow at this location is 52,000 cfs; however, levees begin to fail or are overtopped when flows exceed 40,000 cfs near Vernalis. The maximum 1-day flow frequency curve of simulated and recorded flows reflects in-channel flows and flow out-of-bank along the latitude of the channel. Out-of-channel flows occurred in 1938 (45,600 cfs), 1969 (34,800 cfs), 1983 (44,700 cfs), and 1997 (48,800 cfs).*

4. Merced River at New Exchequer Dam (Figure 4.31) and at Cressey (Figure 4.32). *The historical record (1968-1997) is the period after completion of New Exchequer Dam. The maximum objective flood control release from New Exchequer Dam is 6,000 cfs. Flow in Dry Creek enters the Merced River above Cressey and must be accounted for in the operation of New Exchequer Dam.*

5. Tuolumne River at Don Pedro Dam (Figure 4.33) and at Modesto (Figure 4.34). *The historical record (1971-1997) is the period after completion of the New Don Pedro Dam. The maximum objective flood control release from Don Pedro Dam is 9,000 cfs. Flow in Dry Creek enters the Tuolumne River at Modesto and must be accounted for in the operation of Don Pedro Dam*

   The plotted hypothetical events were given more weight when fitting the graphical regulated flow-frequency curve to the more rare events. This is because the regulated by hypothetical events are developed using balanced inflow hydrographs based on frequency curves fitted to a distribution and derived from long-term historical records. Accordingly, the plotted regulated hypothetical events are considered more statistically reliable than the plotted regulated historical events.

6. Stanislaus River at New Melones Dam (Figure 4.35) and at Orange Blossom Bridge (Figure 4.36). *The historical record (1978-1997) is the period after completion of New Melones Dam and includes regulation by Tulloch Dam. Tulloch Dam impounds a portion of the runoff from the foothill drainage area below New Melones Dam. The maximum objective flood control release from New Melones and Tulloch is 8,000 cfs.*

4.3.2. Evaluation of Regulated Versus Unregulated Curves

The shape of the regulated peak rain flood frequency curves for the tributaries and the mainstem generally reflect the effects of the operating rules during controlled releases, and the effects of flood peak attenuation in the reservoirs during higher, uncontrolled releases. For the Merced River, for example, the maximum objective release from New Exchequer Dam is 6,000 cfs. The Merced River at New Exchequer Dam curve flattens, in the range of events between about the 10- and 50-year, reflecting the ability of the reservoir to contain the flood volumes associated with these events. For events greater than the 50-year, the curve steepens significantly, indicating that uncontrolled releases occur because the reservoir has insufficient volume to fully control the inflowing flood hydrograph. The regulated peak rain flood frequency curves for the other tributaries are similar. The maximum objective release for the New Don Pedro Dam on the Tuolumne River is 9,000 cfs and the frequency curve is relatively flat between the 10- and 30-year events. On the Stanislaus River, New Melones Dam has a maximum objective release of 8,000 cfs, and a flat frequency curve between about the

5- and 150-year events.

In each case, the unregulated peak flood frequency curves indicate substantially higher discharges for the entire range of frequencies. For the Merced River at Cressey, for example, the 2-year frequency flood for unregulated conditions was about 7,300 cfs compared to about 1,800 cfs for regulated conditions, and the 100-year flood peak was about 78,000 cfs compared to 26,000 cfs, respectively (Figure 4.32). Similarly, the Tuolumne River at Modesto curves show 2-year unregulated and regulated peaks of approximately 19,000 and 4,000 cfs, and 100-year peaks of 200,000 and 70,000 cfs, respectively (Figure 4.34). On the Stanislaus River at Orange Blossom Bridge, the estimated 2-year unregulated and regulated flood peaks are 10,000 and 2,900 cfs, and the 100-year peaks are 140,000 and 8,000 cfs, respectively (Figure 4.36).

5. HYDRAULIC AND SEDIMENT TRANSPORT ANALYSIS

5.1. Historical Conditions Hydraulics

Historic hydraulic conditions in the study reach of the San Joaquin River between the Old River (RM 54) and the Merced River confluence (RM 118.8) were estimated using a coarse HEC-RAS model with 18 channel cross sections that were surveyed by the California Debris Commission in 1914. The locations of the cross sections are shown on the maps in Appendix A.1, A.2 and A.3, and plots of the cross sections with the estimated water surfaces are presented in Appendix C.1. As shown on the cross-sections plots, main channel Manning=s *n* roughness coefficients of 0.035 and 0.07 were used for the main channel and overbanks, respectively. While the results obtained from this evaluation should be treated as very approximate, they are believed to provide a reasonable indication of the in-bank capacity of the river along the reach, and the range of velocities and depths that would have occurred for the range of in-bank flows.

The HEC-RAS model was run for a series of discharges ranging from low flows to in-excess of the estimated bankfull discharge in each reach. Because of the coarse nature of the model, no attempt was made to accurately model high, out-of-bank flows. To provide a realistic flow distribution, the discharge profile along the study reach for each flow level was established so that the same frequency of flow from the mean daily flow-duration curves was run in each of the four subreaches. As an example, the median (50 percent exceedance) flow for the pre-Friant Dam flow-duration curve varied from about 640 cfs in Subreach 4 at the upstream end of the study reach to about 2,100 cfs in Subreach 1 at the downstream end (Figure 4.5). These flows, and the corresponding median flows for Subreaches 2 and 3, were thus used to compute the water-surface profile and associated hydraulic conditions for one of the analyzed conditions, and a similar procedure was used for the other water-surface profiles that were analyzed. Reach-averaged hydraulics for each of the subreaches were then computed from the results obtained at the individual cross sections. A summary of the reach-averaged hydraulic results is presented in **Table 5.1**.

The HEC-RAS results were also used to estimate the average bankfull discharge for each of the subreaches. The approximate mean daily flow-duration and flood peak exceedance frequencies associated with the reach-averaged bankfull discharge were then estimated from the pre-Friant Dam flow-duration and flood frequency curves that are applicable to each subreach. The results of these computations, along with reach-averaged morphometric data including the bankfull topwidth, flow depth, and bank height were presented in Tables 3.1 and 3.2.

5.2. Historic Conditions Sediment Transport

The hydraulic results were also used to estimate the bed material transport capacity of each of the subreaches for the range of discharges used in the HEC-RAS analysis. Integration of the resulting bed material rating curves over the appropriate pre-Friant Dam flow-duration curve (Figure 4.5) provided an approximation of the annual bed material sediment loads along the study reach. The sediment transport computations were performed using the Yang Unit Stream Power Equation (Yang, 1972), as formulated in the COE SAM program (COE Waterways Experiment Station, 1992). The average gradation of the sediment samples that were taken along the mainstem San Joaquin River (Samples S1 through S6, Figure 2.1) was used in the computations. This gradation had median

(D_{50}), D_{84} ,and D_{16} sizes of 0.45 mm, 0.78 mm and 0.22 mm, respectively. The gravel/cobble samples taken from the mid-channel bar near RM 87.8 (LSJR WC and LSJR S6, Figure 2.1) were not used in the analysis because these samples are believed to represent a
Table 5.1

localized, coarse-grained segment of the reach associated with local tributary input and strongly influenced by man-made activities including channelization and bank protection. The estimated average annual bed material transport capacity for each subreach are presented in **Table 5.2**. The annual capacities generally increase in the downstream direction, varying from about 63,000 tons per year in Subreach 4 to about 102,000 tons per year in Subreach 1, and increase of about 62 percent. The amount of sediment contributed by the tributaries under historic conditions cannot be estimated from the available information because pre-dam channel geometry and, in most cases, historic hydrology are not available. Based on the drainage areas at the most downstream gage on each tributary, the major tributaries constitute about 13 percent, 25 percent, and 31 percent of the total drainage area at the Newman, Maze Road Bridge and Vernalis gages, respectively. Based on the pre-dam hydrology, the Merced River contributed about 28 percent of the annual runoff at the Newman gage, the Merced and Tuolumne Rivers contributed slightly less than half the total runoff at the Maze Road Bridge gage, and the Merced, Tuolumne and Stanislaus Rivers contributed slightly more than 60 percent of the annual runoff at the Vernalis gage. These tributaries would, thus, have contributed a significant amount of sediment to the mainstem. Backwater conditions in the downstream portions of the tributaries caused by high stages in the mainstem, however, would have had a tendency to reduce the amount of sediment actually reaching the mainstem.

Table 5.2. Summary of average annual bed material transport capacities for each subreach of the mainstem San Joaquin River.

	Bed Material Transport Capacity	
Reach	tons/year	yd^3/year
4	62,700	50,000
3	87,700	69,800
2	88,600	70,600
1	102,200	81,400

5.3. Existing Conditions Hydraulics

5.3.1. Mainstem San Joaquin River

Hydraulic conditions for the existing channel geometry and flow regime in the mainstem San Joaquin River were estimated using a coarse HEC-RAS model with 19 channel cross sections that were developed from topographic mapping that was provided by the Corps of Engineers based on aerial photography and hydrographic surveys performed in 1998. Eighteen of the cross sections used for the existing conditions hydraulic analysis were at approximately the same location as those used for the 1914 analysis (Appendix A.1, A.2 and A.3). Plots of the cross sections with the estimated water-surface for a range of discharges up to the reach-averaged bankfull discharge are presented in Appendix C.2. Main channel Manning=s *n* roughness values of 0.035 and 0.07 were used for the portions of main channel and overbanks, respectively. Similar to the hydraulic analysis using the 1914 cross sections, the results obtained from this evaluation should be treated as very approximate due to the coarse nature of the HEC-RAS model.

The existing conditions HEC-RAS model was run for a series of discharges ranging from low flows to in excess of the estimated bankfull discharge in each reach. Because of the coarse nature of the model, no attempt was made to accurately model high, out-of-bank flows. As described above in relation to the 1914 conditions analysis, to provide a realistic flow distribution, the discharge profile along the study reach for each flow level was established so that the same frequency of flow from the mean daily flow-duration curves was run in each of the four subreaches. Reach-averaged hydraulics for each of the subreaches were then computed from the results obtained at the individual cross sections. A summary of the reach-averaged hydraulic results is presented in **Table 5.3**. The HEC-RAS results were also used to estimate the average bankfull discharge for each of the subreaches. The approximate mean daily flow-duration and flood peak exceedance frequencies associated with the reach-averaged bankfull discharge were then estimated from the post-New Melones Dam flow duration and flood frequency curves that are applicable to each subreach. The results of these computations, along with reach-averaged morphometric data, including the bankfull topwidth, flow depth, and bank height that were obtained from the HEC-RAS analysis were presented in Tables 3.3 and 3.4.

5.3.2.   Tributaries

Hydraulic conditions for the existing channel geometry and flow regime was estimated for each of the three major tributaries based on normal depth calculations performed using the HEC-RAS program, with two typical cross sections developed from the 1998 topographic mapping in the lower reach of each tributary. The location of the cross sections is shown on the maps in Appendix A1, A2, and A3, and plots of the cross sections showing the estimated water surface are presented in Appendix C3. The energy gradient used in the normal depth computations was taken as the average water surface over the reach encompassing the two cross sections in each tributary. As with the mainstem, Manning=s *n* roughness coefficients of 0.035 and 0.07 were used for the main channel and overbanks, respectively.

Hydraulic computations were performed for a series of discharges ranging from low flows to in-excess of the estimated bankfull discharge in each tributary. Results for the two cross sections were then averaged to obtain the representative hydraulic conditions for each of the tributaries. A summary of the reach-averaged hydraulic results is presented in **Table 5.4**. These results were also used to estimate the average bankfull discharge for each of the subreaches. The approximate mean daily flow duration and flood peak exceedance frequencies associated with the reach-averaged bankfull discharge was then estimated from the post-dam flow-duration and flood frequency curves. The results of these computations, along with reach-averaged morphometric data including the bankfull topwidth, flow depth, and bank height were presented in Section 3.4. It should be noted the hydraulic calculation performed for the tributaries do not take into account backwater that exists during high stages in the mainstem. Because the timing of the runoff hydrographs were similar on the tributaries and the mainstem, the estimated bankfull capacities may, therefore, significantly overestimate the capacities of the downstream portion of the tributaries.

5.4.   Existing Conditions Sediment Transport

The bed material transport capacity and annual sediment yield for each of the subreaches for the range of discharges used in the HEC-RAS analysis were estimated using the same procedure as described above for the historic conditions analysis. The estimated average annual bed material transport capacity for each subreach, and for each of the three major tributaries is presented in

Table 5.3

Table 5.4

Table 5.5. The annual capacities generally increase in the downstream direction, varying from about 140,000 tons per year in Subreach 4 to about 291,000 tons per year in Subreach 1, and increase of about 110 percent. The annual transport capacity of the Tuolumne and Stanislaus Rivers, which are based on the normal depth hydraulic computations, total about 104,000 tons, which is about 14 percent less than the difference in transport capacity between Subreaches 1 and 4 on the main stem San Joaquin River. As discussed above in relation to the historic sediment loads, backwater conditions in the downstream portions of the tributaries caused by high stages in the mainstem would reduce the amount of sediment actually reaching the mainstem; thus, the tributary sediment yield estimates are likely higher than actually occurs. Considering this factor, and the uncertainty in the hydraulic and sediment computations, the tributary sediment supply under existing conditions is likely to be slightly less than the difference in transport capacity between the up- and downstream subreaches of the mainstem, which may further indicate that the mainstem is somewhat degradational.

Comparison of the historic and present annual bed material transport capacities (Tables 5.2 and 5.5, respectively) indicates that the transport capacities have increased by about 60 percent in Subreach 3 to about 185 percent in Subreach 1 between 1914 and 1998. The indicated increase is caused primarily by increased hydraulic energy associated with deepening and general narrowing of the channel between 1914 and the present. As discussed in Chapter 3, the channel degraded by a few to over 6 feet during this time period (Figure 3.19). The available information indicates that the channel is continuing to degrade, at least in the reaches upstream from the Tuolumne River.

Table 5.5. Summary of existing annual bed material transport capacities.

Reach	Bed Material Transport Capacity	
	tons/year	yd^3/year
4	139,600	111,200
3	136,500	108,700
2	228,300	181,900
1	291,100	231,900
Merced	41,300	32,900
Tuolumne	63,222	50,355
Stanislaus	40,701	32,416

6. EXISTING CONDITIONS RIPARIAN ECOLOGY

6.1. Introduction

This section provides a general description and qualitative evaluation of the existing conditions of riparian vegetation along the project reach of the San Joaquin River and its major tributaries. Vegetation descriptions are based on observations made during the field reconnaissance, and a review of aerial photographs, topographic maps, and surveyed cross sections. This study does not include vegetation type mapping or quantitative analysis of changes in cover types, although it draws upon information and trends described and analyzed from two recent studies of historic and current conditions on the San Joaquin River between Friant Dam and the Merced River (JSA 1998; JSA and MEI 1998) which employed detailed, computer-generated mapping and GIS spatial data about vegetation and other cover types between the late 1800s and 1997. Photographs (Appendix B) taken during the field reconnaissance are referenced in this section. Subreach boundaries and RM markers are included on the maps in Appendices A1, A2, and A3.

6.1.1. Information Sources

A one-day aerial, low-altitude survey occurred on November 17 1998, followed by a ground level survey from November 17 to 22. Most field reconnaissance of the San Joaquin River and lower tributaries was conducted from a river boat, and remaining areas were surveyed by vehicle and on foot. Primary sources of aerial photography used included the San Joaquin River Aerial Atlas - Stockton to Merced, April 1984 (USACE 1984; photographs taken April 27 and June 6, 1976; scale 1 inch = 500 feet), San Joaquin River Atlas - Old River to Merced River (USBR 1995; color photographs taken May 23 through June 10,1993; scale 1inch = 500 feet), and recent aerial photography of the San Joaquin River and its major tributaries and floodplains by USACE (unpublished) taken July 30, 1998, at a scale of 1:10,000.

Interpretations of historic conditions were based in part on a review of topographic and hydrographic maps and cross sections prepared in 1914 (CDC 1914; scale 1inch = 400 feet) which also provide delineations of cover types that appear to include distinctions between tule marsh, riparian forest, willow scrub (ABrush@), valley oak woodland (AOaks,@ AOak and Brush@), and oak/grassland savannah (AScattered Oak@), as well as open water and unvegetated sand and gravel bars. Additional information about historic conditions is found on the earliest detailed USGS topographic maps of the region and W.H. Hall=s map of the San Joaquin Valley in 1886, but mapped cover types are limited to open water and large marshlands.

Interpretations of the vertical distribution of vegetation types and the relationship to flow stage frequency and channel migration is based on the analysis of physical data presented in other sections of this report, including a comparison of paired survey cross sections between 1914 and 1998. This part of the study does not include a detailed botanical survey of the river, but focuses on the pattern and distribution of dominant species and plant associations, and apparent trends or limiting factors in dominant cover types.

Information about soils is based on published soil surveys and field reconnaissance, and more historical soils information comes from a 1938 series published by the USDA in 1948 describing western Stanislaus County, including the San Joaquin River and its floodplain. In addition, several soil samples were collected in the field and then analyzed at a professional laboratory for characteristics that may affect plant growth along the river (**Table 6.1**). The primary purpose of the soil sampling was to determine if surface salinity, pH, or boron concentrations in sampled locations along the river could be a limiting factor on the establishment of native riparian trees and shrubs.

Therefore, soil samples were collected on moist bars and low floodplains where seedlings could be expected to germinate, or where vegetation cover was sparse or dominated by herbaceous species with a known tolerance of saline soils (e.g., saltgrass, Sueda, Cotula).

Table 6.1. Soil Sample Lab Analysis Results for Texture, pH, Boron, and Soluble Salts.

Soil Sample	River Mile and Bank	Feet Above Water Level	Soil Texture	pH	Boron (parts per million)	Soluble Salts (mmhos/cm)
SS1	63.6 R	+4	sand	6.62	0.4	0.38
SS2	Stanislaus River - R	+4	very fine sandy loam	5.73		0.60
SS3	76.6 L	+4.5	fine sandy clay loam	5.99		0.69
SS4	76.6 R	+5	silty clay loam	6.47	1.4	47.7
SS6	100.5 L	+4	silt loam	5.13	0.8	1.43
SS7	100.5 L	+12	loamy fine sand	5.23		1.44
SS8	108.6 L	+3	loamy fine sand	6.15		0.47
SS9	117.8 R	+6	silt loam	6.15	0.7	1.48

6.1.2. Public Ownership of Riparian Habitat

A few large tracts of forested and range land along the San Joaquin River are state parks (Durham Ferry State Recreation Area (SRA) and George Hatfield SRA), county parks (Laird Park and South County Regional Park) and national wildlife refuge conservation areas (Mapes Ranch). A large tract of public land combines the Fremont Ford SRA and Great Valley Grasslands State Park just upstream of the Merced River confluence. Public boat ramps (e.g., Mossdale Park and river access) and marinas are typically small and widely spaced along the river, and river recreational use is light compared to the Sacramento River or Delta waterways. Several state and county regional parks, small and large, occupy nodes of the riparian corridor on the major tributaries (Including Caswell Memorial SRA on the lower Stanislaus River, George Hatfield SRA, McConnell SRA , and Henderson Park on the Merced River, and other smaller local riverside parks).

6.2. Historical Conditions

6.2.1. San Joaquin River

Historical vegetation distribution along the mainstem SJR between Old River and Merced River prior to widespread water development and conversion to agricultural uses is poorly documented other than in a collection of anecdotal narratives and old photographs of agricultural reclamation activities in the basin. Generalized maps of the valley prepared by W. H. Hall in 1886 show the broad outlines of the large tule basins clustered along the river and intersected by secondary channels and sloughs. The most detailed and reliable spatial representation of riparian and tule vegetation along the river are the detailed CDC maps of the river and its floodplain prepared in 1914 and referred to in other sections of this report. Much of the river terrace, floodplain, and basin was already reclaimed for cropland between 1850 and 1914. However, extensive natural topography and vegetation boundaries were mapped which indicate most of the active floodplain of the river was occupied by a wide swath of dense riparian forest or valley oak woodland. Low-lying basins and depressions straddling the river supported large expanses of tule marsh or open water depending on the water depth, and meanderbelts with actively migrating channels appeared to support a predominance of willow scrub type vegetation (labeled ABrush@ in 1914). The higher floodplain surfaces and river terraces appear to have been occupied by oak/grassland savannah or valley oak woodland. Unlike the river today, the active channel had many large unvegetated sand bars. Numerous secondary channels and sloughs split off the mainstem river and then coalesced farther downstream (Walthall Slough, Red Bridge Slough, Riley Slough, Laird Slough, and many unnamed channels and oxbow complexes).

6.2.2. Major Tributaries

Even less is known about historical vegetation distribution along the tributaries, although the 1914 CDC maps include the lower 1 to 2 miles above the confluence with the San Joaquin River. The pattern of the overbank areas mapped on the lower 1 to 2 miles was similar to the mainstem floodplain. One or more major secondary channels appeared to connect high flows from the lower tributaries to points farther downstream on the mainstem river, flowing northwest on the east side of the valley floodplain or basin. Examples still present in disconnected segments include Red Bridge Slough at the lower Stanislaus River and Riley Slough at the lower Tuolumne River.

6.3. Existing Conditions, San Joaquin River

[Note: Photographs referenced in this section were taken during the November 1998 field reconnaissance, and are included in (Appendix B). Subreach boundaries and River Mile (RM) markers are included on the maps in Appendices A1, A2, and A3.]

Since 1913, the channel thalweg in Subreach 1 has been lowered, and bankfull capacity has increased significantly along most of the river. Regulated flows have reduced the frequency of overbank flows to an average of twice as many years, and bankfull discharge duration has decreased roughly to half as many days per year, occurring primarily in mid winter. Median spring flows have decreased significantly, with the greatest reduction occurring in subreaches 3 and 4 where the median flows are 1/3 to 1/4 of the pre-1940 conditions respectively (**Table 6.2**). At the same time, the regulated base flow in spring has approximately doubled in all subreaches. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of

Table 6.2. Changes in April and May exceedance flows (cfs) for the four subreaches of the San Joaquin River, 1913 to 1940 and 1979 to 1998.

1913-1940 Subreach	10% Exceedance	50% Exceedance	90% Exceedance	99% Exceedance
1	21,000	9,800	550	350
2	18,000	7,900	430	190
3	10,000	5,000	350	120
4	10,000	3,600	300	105
1979-1998 Subreach	10 % exceedance	50 % exceedance	90 % exceedance	99 % exceedance
1	21,000	3,100	1,200	650
2	21,000	2,100	700	300
3	11,000	1,400	530	250
4	11,000	900	420	200

the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- (alder, box elder, ash) and spring-released (cottonwood, willow species) seed of riparian trees and shrubs. While the frequency and magnitude of overbank, spring flows have been reduced, peak annual flows have increased causing a net degradation of 1.2 feet from 1914 to 1998. Thus, in-channel scour and meander growth have actually increased compared to pre-project conditions. The moist, low channel surfaces are currently occupied by dense herbaceous cover and thatch or rhizomatous shrubs (narrow-leaved willow, wild rose), reducing the possibility that riparian tree seed can germinate in a favorable, high-sunlight environment without competition from fast-growing annual and perennial herbaceous grasses and weeds, or dense shrubs, that reproduce by vegetative cloning.

The formerly extensive tule basins which bordered the river and sloughs are currently found as small, isolated remnants in shallow portions of protected oxbow ponds and saturated channel fill deposits (Plate 2).

Terraces and higher floodplain surfaces are generally dominated by agricultural cover types, principally row crops, except in Subreach 4 where grassland and oak woodland are used to graze livestock primarily. The predominant natural cover types on higher and intermediate floodplain surfaces are annual grassland (wild oats, brome, peppergrass, yellow star thistle, wild mustard, owls clover), and valley oak savannah and woodland (primarily valley oak, with some mature cottonwood, box elder, elderberry, wild rose, and mugwort). Less common but significant in local patches are cottonwood forest (mature cottonwood with valley oak, black walnut, black willow, box elder, and elderberry with an understory of annual or rhizomatous perennial grassland), and native perennial grassland (beardless wildrye, saltgrass, sedge meadow, and mugwort with herbaceous weeds such as peppergrass and star thistle).

Lower floodplain surfaces and point bar deposits are typically either unvegetated sand bars or dominated by willow scrub (narrow-leaved willow, arroyo willow, red willow, black willow, and occasionally young cottonwood), mixed riparian forest (black willow, red willow, cottonwood, black walnut, ash, box elder), or cottonwood forest (cottonwood-dominant with willows). Forest types on lower floodplain surfaces and tree-less moist bars have a ground cover of watergrass, sprangletop, smartweed, beggar ticks, peppergrass, and saltgrass. Shallow, protected oxbow ponds and saturated channel fill deposits are dominated by tule, cattail, smartweed, and watergrass, with water hyacinth and yellow water primrose locally common. Non-native trees and shrubs are present but uncommon, whereas the herbaceous ground cover is dominated by non-native grasses and annual and perennial weeds, including wild mustard, telegraph plant, wild oats, yellow star thistle, and Bermuda grass.

6.3.1. Subreach 1 (RM 54- RM 74.8)

Subreach 1 covers 20.8 river miles between Old River and the confluence of the Stanislaus River. Although this subreach is the most confined by levees, bridge abutments (Plate 1), and bank revetment (**Plate 47**), it includes significant riparian habitat patches, oxbows, and active meanders. Actively eroding banks observed in the subreaches in November 1998 encompassed 11 percent of total bank length in Subreach 1.

Since 1913, the channel thalweg in Subreach 1 has lowered an average of 1.3 feet and bankfull capacity has increased 170 percent. This subreach is also distinctive because it has a very straight channel and would appear to have high-flow degradational conditions. Regulated flows have reduced the frequency of overbank flows from an interval of 2 years to 4 years, and bankfull discharge duration has decreased from 61 days to 26 days per year, occurring primarily in mid winter. Median spring flows have decreased from 9800 cfs to 3100 cfs (Table 6.2), while regulated base flows have doubled. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs.

There are three somewhat distinct segments in terms of vegetation pattern within Subreach 1 which are described below. Subreach 1A (RM 54-57) is bounded by levees close to the channel margins on both sides, with a high proportion of revetted banks and armoring at the six bridge abutments. Narrow remnant berm width with steep banks inside the levees has greatly reduced the extent of original forest and limits availability of new regeneration sites. There are large gaps in the continuity of riparian vegetation (Plates 3 and 46).

Subreach 1B (RM 57-69) has highly variable berm width within the leveed floodway, with large floodway expansions where oxbow lakes and old slough confluences are contained within the levees (e.g., Weatherbee Lake, Walthall Slough). This subreach is also distinctive because it has a very straight channel and would appear to have high flow degradational conditions. Although much of the floodplain is cultivated for row crops, there is less revetted bank and greater continuity of riparian vegetation along the channel margins and surrounding oxbows in large habitat nodes (**Plate 47** and Plate 4). Although vegetation on the higher, uncultivated surfaces is primarily patchy, remnant old growth riparian forest, some recruitment of cottonwood has occurred recently, whereas most willow seedlings and saplings are found on low, moist bars within the channel (**Plates 48 and 49**) Small marina developments, abandoned mine pits, and urban homes and trailer parks occupy portions of the floodplain within the levees near oxbows and sloughs.

Subreach 1C (RM 69-74.8) is upstream of where Red Bridge Slough formerly reentered the main channel. The channel is more dynamic and unconfined in this segment of Subreach 1 with bank erosion and meander cutoff chutes (Plates 7 and 8), although internal levees in several bendways restrict the meander pattern. More active channel dynamics has led to a higher proportion of early seral willow scrub and mixed riparian and willow forest on point bars, mid-channel islands, and in channel fill deposits of cutoff oxbows. Portions of the old growth valley oak woodland are gradually being eroded, contributing large woody debris to the river aquatic zone. Urban encroachment into the riparian floodplain and off-road vehicle use has occurred at San Joaquin City and Durham Ferry.

6.3.2. Subreach 2 (RM 74.8 - RM 83.8)

Actively eroding banks observed in November 1998 encompassed 37 percent of total bank length in Subreach 2, the highest in the study area.

Since 1913, the channel thalweg in Subreach 2 has lowered an average of 6.5 feet and bankfull capacity has increased 130 percent. Regulated flows have reduced the frequency of overbank flows from an interval of 2 to 4 years, and bankfull discharge duration has decreased from 53 to 33 days per year, occurring primarily in mid winter. Median spring flows have decreased from 7,900 to 2,100 cfs (Table 6.2) , while regulated base flows have increased 150 percent. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs.

There are two somewhat distinct segments in terms of vegetation pattern within Subreach 2 which are described below. Subreach 2A (RM 74.8-78) is somewhat confined by levees, which are close to the channel margin on the west flank of the river. The east side berm has an average width of 500-1,000 feet and is mostly cultivated. Shoreline riparian vegetation is generally continuous but narrow, with larger nodes at old oxbows and on larger point bar deposits. Portions of the higher floodplain supporting oak woodland or grassland are eroding in places (Plate 9). A soil sample at RM 76.6R in the face of the eroding bank had extremely high levels of boron and salinity (Table 6.1) sufficient to discourage riparian plant growth (**Plate 50**).

Subreach 2B (RM 78-83.8) stretches from the lower end of Finnegan=s Cut to the confluence of the Tuolumne River (Plate 12). This segment of Subreach 2 encompasses a floodway and floodplain up to a mile wide, including a 3,500-acre basin and plain of natural meander scroll topography between the San Joaquin River at Finnegan=s Cutoff and the old river channel to the west. The pre-cutoff topography in 1913 is depicted in Cross Section 112 (Figure 3.2) and has not changed significantly over the floodplain and basin between the current and former channel. Natural vegetation types range along a vertical gradient from grassland and valley oak woodland on the higher floodplain surfaces (**Plate 51**), to mixed riparian forest and willow scrub on lower floodplain surfaces, and seasonal wetland and emergent marsh fringing oxbows and floodplain depressions. The largest stand of cottonwood saplings observed during the field reconnaissance was found at RM 83.3R

(**Plate 52**) where overbank flow from the Tuolumne River converges with high water in the San Joaquin River on a high floodplain 15 feet above the low flow channel (Plate 11).

6.3.3. Subreach 3 (RM 83.8 - RM 99.5)

Actively eroding banks observed in November 1998 encompassed 25 percent of total bank length in Subreach 3.

Since 1913, the channel thalweg in Subreach 3 has lowered an average of 5.6 feet and bankfull capacity has increased 110 percent. Regulated flows have reduced the frequency of overbank flows from an interval of 4 to 3.6 years, while bankfull discharge duration has changed little from 26 to 29 days per year, occurring primarily in mid winter. Median spring flows have decreased from 5,000 to 1,400 cfs (Table 6.2), while regulated base flows have increased 150 to 200 percent. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs.

There are three somewhat distinct segments in terms of vegetation pattern within Subreach 3 which are described below. Subreach 3A (RM 83.8-89) below Grayson is greatly confined by local levees and revetted banks within the meanderbelt, and has the most extensive development of agricultural fields on intermediate height floodplain surfaces (Plate 13). Up to 400 acres of fields at numerous locations experienced levee breaches and large sand splays in the fields during the 1997 flood (Plate 13). Small cottonwood and willow saplings were observed in dry depressions and eroded swales on the cultivated floodplains fringing the breach openings. Width of riparian vegetation bordering the channel varies from none to 200 feet, with few larger nodes at old oxbows.
Subreach 3B (RM 89-95.5) stretches from upstream of Grayson Road bridge to the City of Modesto sewage lagoons. The width of floodplain varies from 1,200 to 3,000 feet and includes large tracts of uncultivated land with meander scroll topography dominated by valley oak woodland and savannah on higher floodplain surfaces and mixed riparian and willow forest on lower floodplains and within old channel fill deposits (**Plate 53**). Channel meanders are mostly unconfined and dynamic on the east side of the river, and partially confined by natural terraces or local levees protecting cropland on the west. Channel dynamics has allowed large habitat nodes to develop. Of particular importance and size is the 4.5 mile long abandoned channel and floodplain of the old San Joaquin River between Laird Park (RM 89.5) and the former Laird Slough intersect (RM 87). This area floods during high water events and conveys the larger proportion of channel flow in large floods. Portions are cultivated, but most of the historic 1,500- to 2,400-foot wide floodway supports a diverse mosaic of natural vegetation types, including open water sloughs and ponds, emergent marsh, willow scrub, and mixed riparian and oak forest. Graded features (farm road crossings and earthen plugs) appear to prevent average high flows from entering the old channel oxbows.

Subreach 3C (RM 95.5-99.5 at Patterson) has similar features and floodplain width as 3B, but the floodplain vegetation generally appears less lush and with lower tree density and overall canopy cover. Numerous sand splays have recently been deposited on lower floodplain surfaces and on adjoining fields where local levees were breached in 1997 or before (Plate 17), further contributing to the droughty conditions of the floodplain surface. The channel in both 3B and 3C is very sinuous with numerous connected and isolated oxbow channels surrounded by riparian scrub and forest within the active floodplain.

6.3.4. Subreach 4 (RM 99.5 - RM 118)

Actively eroding banks observed in November 1998 encompassed 25 percent of total bank length in Subreach 4.

Since 1913, the channel thalweg in Subreach 4 has lowered an average of 3.2 feet and bankfull capacity has increased 113 percent. Regulated flows have reduced the frequency of overbank flows from an interval of 2 to 3.3 years, and bankfull discharge duration has changed little from 30 days to 32 days per year, occurring primarily in mid winter. Median spring flows have decreased from 3,600 to 900 cfs (Table 6.2), while regulated base flows have increased 150 to 200 percent. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs.

There are three somewhat distinct segments in terms of vegetation pattern within Subreach 4 which are described below. Subreach 4A (RM 99.5-107) stretches from Patterson to Crows Landing. A broad floodplain (locally up to 3,400 feet wide) between outer terraces and discontinuous local levees contains a sinuous channel and numerous oxbows and dry swales. Numerous sand splays have recently been deposited on aggrading point bars, on lower floodplain surfaces, and on adjoining fields where local levees were breached in 1997 or before (Plate 18), further contributing to the droughty conditions of the floodplain surface. Most of the higher and intermediate floodplain surfaces appear on aerial photographs to be more arid than Subreaches 1, 2, or 3A and 3B, with the predominant cover types annual grassland and valley oak savannah which are grazed (Plate 18). Mixed riparian and black willow forest occurs primarily on channel fill deposits within oxbow fragments. However, erosion and bank migration from recent major flood flows (1983, 1986, 1995, and 1997) have created new lower floodplain surfaces on point bars and high-water cutoff chutes that are being colonized by willow scrub and herbaceous riparian meadow species (**Plates 54 and 55,**and Plate 19). Saline surface soils from shallow, naturally saline groundwater may be a factor suppressing riparian regeneration of moist surfaces at some sites where saltgrass predominates and is often associated with surface efflorescence and soil crusting. The reduced frequency of inundation from overbank flows that scour the surfaces and leach surface concentration of salts in this subreach would tend to exacerbate saline growing conditions.

Subreach 4B (RM 107-112) has a sinuous channel but fewer oxbows and a more confined meanderbelt (approximately one half the meander ban width, or 500 to 2,000 feet) contained by flanking terraces and agricultural levees (Plate 20). The more arid floodplain vegetation pattern described in 4A applies here as well, although sporadic recruitment of willows can be found on moist, low sandy deposits (**Plate 56**). An exception to the general pattern is a grove of mixed riparian forest and scrub at the small fan formed at the mouth of Orestimba Creek. Outside bends adjoining agricultural levees are typically revetted and devoid of woody vegetation.

Subreach 4C (RM 112-118) extends to the confluence of the Merced River (Plate 22) and is the widest continuous floodway with the largest expanse of natural meander scroll topography within the study area. The higher and intermediate floodplain surfaces have a similar vegetation pattern to 4A and 4B, dominated by grassland and oak savannah, but recently created moist, low bars are being colonized by willows and some cottonwood seedlings and saplings (**Plate 57 and 58**). On stable channel segments, the channel margins typically support mature black willow and ash (**Plate 58**) and weedy herbaceous cover. Cropland is largely confined to the better soils on the distant terraces and alluvial fan margins on the west side of the valley.

6.3.5. General Observations of All Subreaches

The primary mechanism of recruitment and regeneration of riparian habitat on the San Joaquin River between Old and Merced Rivers is by occupation of moist low floodplains on accreting point bars of active meanders, or on channel fill deposits of cutoff oxbow channels. The rate and extent of meander migration and sediment transport and deposition appear to be important factors in the renewal and spread of natural vegetation in the study area. The floodway of the river is generally wide enough on major channel segments in portions of all subreaches to allow for channel migration to occur, although some local berms protecting low agricultural fields within bendways failed as a result of bank erosion during the 1997 flood flows. Revetted banks are less common than natural banks, except in the lower portion of Subreach 1 near Old River, on Finnegan=s Cut, and in the vicinity of Grayson within Subreach 3, and along portions of other subreaches. Functionally, major segments of the river floodway represent a dynamic meanderbelt system, with exceptions at bridge crossings and other leveed constrictions, which supports natural riparian succession on the new, lower created floodplain surfaces. However, hydrologic changes from increased storage and diversion in the watershed have reduced the duration and rate of occurrence of channel-forming flows, thereby reducing the rate and extent of forest regeneration through meander processes.

The historic floodplain of the river within the terraces and outer levees supports a less dynamic vegetation type and succession. Large areas of the floodplain and ABottom Land@ were mapped in 1914 as relatively dense riparian forest (typically labeled ABrush and Timber@ or AOak and Brush@) occupying most of the meander scroll topography. Cropland has since 1914 encroached into portions of the formerly forested floodplain. Although the overall extent of farmed floodplain has remained approximately the same since 1976, field boundary expansion requires local levees to be constructed on bendways and older point bars within the floodway. Encroachment of local fields within the floodway in recent decades appears to have caused some additional loss of riparian and oak vegetation, and these sites seem to be where most local berms were breached or overtopped in 1997.

A significant change appears to be the gradual aging of the forest on higher floodplain surfaces, and to vegetation type conversion from mixed riparian and cottonwood forest to valley oak savannah and annual grassland with scattered oaks. Analysis of geomorphic and hydrologic data in this report has shown that channel capacity has increased over time while the duration of high flows have decreased in response to additional water storage projects on the tributaries. This has limited the replenishment rate and potential area of riparian regeneration to lower, narrower floodplain surfaces closer to the active channel.

Riparian vegetation types on the San Joaquin River within the study area are dominated by native species of trees and shrubs and non-native herbaceous plants, although native grasses (e.g., beardless wildrye and saltgrass) and forbs (e.g., mugwort) are also common. Large trees and shrubs of invasive, non-native species such as eucalyptus, tamarisk, and giant reed that intrude into other riparian environments are present but in very low numbers and small clusters. These species do not appear to be a threat to the riparian corridor, but should be monitored to detect changes in percent cover and range expansion.

The primary factors that appear to limit the extent and quality of riparian habitat on the river, in order of importance, are reduction of the duration of overbank flows (especially in the spring), reduction of channel forming flows that drive meander processes, and confinement by local levees and bank revetment that reduce the potential meanderbelt width or prevent inundation of floodplains within bendways. Other factors that appear to limit riparian vegetation along specific segments of the river include grazing, salinity of surface soil and groundwater, bridge constrictions, isolation of natural high water channels and oxbows from the river by construction of earthen plugs, and expansion of local agricultural fields into lower areas that supported, or could be colonized by, riparian vegetation. Relatively small local levees (berms) within meander bends exist primarily to allow farming of intermediate floodplain surfaces within the meanderbelt.

In spite of the limitations caused by reduced flows, and the changes to the floodplain and basins that have occurred since 1914, the floodway of the lower San Joaquin River represents a significant natural resource. A nearly continuous corridor of natural meander scroll topography and diverse vegetation cover types are found along the 54-mile study reach. Some floodway segments are one half to three quarters of a mile wide with little disturbance (i.e., no mass grading or forest clearing) to natural topography or vegetation other than grazing. Channel migration by bank erosion throughout the study reach provides a significant component of shaded riverine aquatic habitat by contributing instream woody materials and overhanging tree canopy.

6.4. Existing Conditions, Major Tributaries

This section on existing vegetation conditions along the major tributaries to the project reach of the San Joaquin River is based on observations made during the November 1998 field reconnaissance, and hydrologic data analyzed in this report. Photographs (Plates 58 to 73 in Appendix B) taken during the field reconnaissance are referenced in this section. Subreach boundaries are included on the map in Appendix A 4.

All three major tributaries share similar physical, botanical, and land use characteristics described in other sections of this report, so the vegetation patterns are quite similar throughout their lengths. Notable differences are that dredger mine fields and modern sand and gravel mining are less common and less extensive on the Stanislaus River, urbanization is more extensive on the Tuolumne River (primarily Modesto and suburban communities), the largest dredger tailings stradling the riparian corridor occur along the upper Merced River, and closed canopy forest is more common on the SR whereas unvegetated bars are more common though not extensive on the lower Tuolumne and Merced Rivers. In all three rivers, channel margin vegetation on the coarse grained upper subreaches (S3, T3, and M3) is dominated by alder and broad-leaved willow species, whereas channel margins on the lower subreaches are dominated by narrow-leaved willow, box elder, ash, and buttonbush. Cottonwood, sycamore, valley oak, and black willow tend to grow in forest stands behind dense shrubs or lower-statured trees flanking the low-flow channel margin. Vegetation structure, density, and diversity of botanical composition along the tributaries is greater than the average condition along the San Joaquin River corridor, but not as wide and there is more recent and historic development on the floodplains.

6.4.1. Stanislaus River

Since 1914, the channel thalweg in Subreach S2 has lowered an average of 6 feet at the Knights Ferry bridge. Regulated flows have reduced the frequency of overbank flows to just 5 days per year at a bankfull discharge of 5,450 cfs, occurring primarily in mid winter. The 2-year peak flow changed from 10,000 cfs before large dam regulation of flow to the present 2-year discharge of 2,900 cfs. Median spring flows at Ripon gage have decreased from 1,500 to 900 cfs. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs. Stable channel conditions with infrequent, reduced disturbance cycles and predictable base flow during the growing season have favored the establishment of shrubs and small, shallow-rooted trees along channel margins that have the ability to reproduce clonally (e.g.,narrow-leaved willow) or sucker sprout and tolerate saturated root zones (e.g., alder, buttonbush).

Plates 59 through 64 show typical views of vegetation on the Stanislaus River between the State Route J6 bridge and 1mile upstream of the confluence with the San Joaquin River near Red Bridge Slough (refer also to Plates 38 to 45). The channel and banks of the lower Stanislaus River appear to be the most stable for riparian vegetation. Bare sand and gravel bars are less evident on 1998 aerial photographs, and field reconnaissance found forest or scrub vegetation had colonized most of the channel bars and channel margins ((Plates 39, 41-43, 59, and 60). Botanical composition is generally diverse, with alder and sycamore more common in upstream subreaches and narrow-leaved willow, box elder, and ash more common in the lower subreach. Canopy overhanging the river shoreline was present at most locations observed (Plates 39, 41-43, 59, and 60). Predictable base flow in the river, higher than pre-regulated conditions during the growing season, has prevented vegetation encroachment beyond the channel margins. Mature, closed canopy riparian forest and valley oak/sycamore woodland is more common along the Stanislaus River than the other tributaries, with the best example in the study area at Caswell Memorial State Park (Plates60-62). Within the park is a classic new meander cutoff becoming an oxbow by deposition at the mouth of the cutoff neck that formed in 1997 or 1998 (Plate 44). Agricultural fields and local levees have encroached into the flanks of the riparian corridor and floodplain (Plate 67). Gravel mines and dredger tailings are not extensive on the Stanislaus River compared to the other tributaries.

6.4.2. Tuolumne River

Since 1913, the channel thalweg in Subreach T1 has lowered an average of 4 to 6 feet at the Highway 99 bridge. Regulated flows have reduced the frequency of overbank flows to just 14 days per year at a bankfull discharge of 5,200 cfs, occurring primarily in mid winter. The 2-year peak flow changed from 19,000 cfs before large dam regulation of flow to the present 2-year discharge of 4,000 cfs. Median spring flows at Modesto gage have decreased from 800 to 400 cfs. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs. Stable channel conditions with infrequent, reduced disturbance cycles and predictable base flow during the growing season have favored the establishment of shrubs and small, shallow-rooted trees along channel margins that have the ability to reproduce clonally (e.g., narrow-leaved willow) or sucker sprout and tolerate saturated root zones (e.g., alder, buttonbush).

Plates 65 through 67 show typical views of vegetation on the Tuolumne River between Modesto and 5 miles upstream of the confluence with the San Joaquin River near Service Road (refer also to Plates 33 to 37 that cover the river between La Grange and the confluence with San Joaquin River). The channel and banks of the lower Tuolumne River appear to be relatively stable for riparian vegetation, but less so compared to the Stanislaus River. Bare sand and gravel bars are evident on 1998 aerial photographs although not extensive. Field reconnaissance found forest or scrub vegetation had colonized most of the channel margins (Plates 33, 35, 65, and 66). Botanical composition is generally diverse, with alder and sycamore more common in upstream subreaches and narrow-leaved willow, box elder, and ash more common in the lower subreach (Plates 35, 65, 66). Canopy overhanging the river shoreline was present at most locations observed, but not as extensive as the Stanislaus River (Plates 33, 35, 65, and 66). Predictable base flow in the river, higher than pre-regulated conditions during the growing season, and scour of mid-channel bars from recent flood years has prevented vegetation encroachment beyond the channel margins. Agricultural fields, local levees, and low-density residential and recreational developments have encroached into the flanks of the riparian corridor and floodplain (Plates 36, 65 and 67). Gravel mines and dredger tailings are extensive on the Tuolumne River, and create gaps in the continuity of riparian vegetation from disturbance, channel capture of large wet pits, and removal of fine sediment near the channel margins and on low floodplains.

6.4.3. Merced River

Since 1913, the channel thalweg in Subreach M1 has lowered an average of 3 feet at the Highway 99 bridge. Regulated flows have reduced the frequency of overbank flows to just 4 days per year at a bankfull discharge of 6,000 cfs, occurring primarily in mid winter. The 2-year peak flow changed from 7,300 cfs before large dam regulation of flow to the present 2-year discharge of 1,800 cfs. Median spring flows at the Stevinson gage have decreased from 500 to 300 cfs. The combined effects of these changes in channel geometry and seasonal flow reduce the wetting of the floodplain, reduce deposition of fine sediment and organic matter on the higher floodplain surfaces, and greatly reduce dispersal and germination of both fall/winter- and spring-released seed of riparian trees and shrubs. Stable channel conditions with infrequent, reduced disturbance cycles and predictable base flow during the growing season have favored the establishment of shrubs and small, shallow-rooted trees along channel margins that have the ability to reproduce clonally (e.g., narrow-leaved willow) or sucker sprout and tolerate saturated root zones (e.g., alder, buttonbush).

Plates 68 through 73 show typical views of vegetation on the Merced River between Henderson Park and 0.5 mile upstream of the confluence with the San Joaquin River near River Road. Refer also to Plates 22 to 32. The channel and banks of the lower Merced River appear to be relatively stable for riparian vegetation, but less so compared to the Stanislaus River. Bare sand and gravel bars are evident on 1998 aerial photographs although not extensive. Field reconnaissance found forest or scrub vegetation had colonized most of the channel margins (Plates 25, 30, 31, 68, and 69). Botanical composition is generally diverse, with alder and sycamore more common in upstream subreaches and narrow-leaved willow, box elder, and ash more common in the lower subreach (Plates 68, 69, 31, and 72). Canopy overhanging the river shoreline was present at most locations observed, but not as extensive as the SR (Plates 25, 30, 68, 69, and 72). Predictable base flow in the river, higher than pre-regulated conditions during the growing season, and scour of mid-channel bars from recent flood years has prevented vegetation encroachment beyond the channel margins. Agricultural fields, local levees, and low-density residential and recreational developments have encroached into the flanks of the riparian corridor and floodplain (Plates 29, 31, 70, and 72). Gravel mines and dredger tailings are extensive on the Merced River, and create gaps in the continuity of riparian vegetation from disturbance, channel capture of large wet pits, and removal of fine sediment near the channel margins and on low floodplains (Plates 23, 24, 27 through 29). The lower mile of the Merced River experienced significant recent channel migration and bank erosion of sandy floodplain deposits that appears to have removed much of the riparian vegetation on the channel margins and higher floodplain surfaces (Plates 32 and 73). Low bars are expected to be recolonized by willow scrub.

7. GEOMORPHIC, CHANNEL STABILITY AND RIPARIAN ECOLOGICAL TRENDS

This section of the report discusses the geomorphic (Chapter 3) ,hydrologic (Chapter 4), sediment transport and channel stability (Chapter 5) and riparian ecological (Chapter 6) changes and trends for the project reach of the San Joaquin River from Old River to the Merced River confluence, and the major tributaries, the Merced, Tuolumne and Stanislaus Rivers.

7.1. San Joaquin River

7.1.1. Channel Morphometry and Hydraulic Capacity

Comparison of the 1914 and 1998 morphometric data in Tables 3.1 and 3.3, respectively, indicates that in general the sinuosity of the river in all of the subreaches has remained relatively constant, and this is supported by the reach-averaged slope data. This means that losses in the channel length from individual meander cutoffs and longer channel segment avulsive changes (Finnegans Cutoff (RM 85-90) and Lairds Slough Cutoff (RM 94.5-99)) have been balanced through time by increases in channel length as a result of bank erosion and meander bend growth. There are no data on the extent of bank erosion in 1914, but under existing conditions in Subreach 1, there are about 20,000 lineal feet of bank erosion, which represents about 14 percent of the total bank length in the subreach. In Subreach 2, about 31 percent of the total bank length is eroding (29,000 lineal feet), and in Subreach 3, there are 47,000 lineal feet of eroding bank which represents about 29 percent of the total bank length. About 22 percent of the total bank length is eroding in Subreach 4, which represents 43,000 lineal feet of erosion.

It is evident from the bank erosion data that bank erosion in Subreaches 3 and 4 is a major source of sediment to the lower reaches of the river. Because the non-project and project levees within the subreaches tend to be revetted where the river impinges against the levees, it is unlikely that the channel location will change very much in the future at these locations, unless there is a major channel avulsion. Since there has been less levee construction in Subreaches 3 and 4, it follows that there has been less bank protection in these subreaches, and therefore, the banks will continue to erode. Continued bank erosion will maintain the downstream sediment supply and reworking of the meanderbelt within the upstream subreaches.

The morphometric data in Tables 3.1 and 3.3 also show that on average the bankfull depth of the channel has increased in all of the subreaches between 1914 and 1998. In Subreaches 2 and 3, the increased depth (1.4 to 2.6 feet) is probably due to the construction of the levees along both banks of the river and confinement of the flows. Even though there were levees present in these subreaches in 1914 (Table 1.4), they were set farther back from the river and were not as continuous. The average bankfull depth of the river increased by about 2.8 feet in Subreach 3, primarily because of the extensive channel avulsions that occurred as a result of the Finnegans and Lairds Slough cutoffs. In 1914, the pre-cutoff channel segments were much wider and shallower than the modern channel in Subreach 3. The average bankfull channel depth did not increase very much in Subreach 4 (0.3 feet).

The 1983 hydrographic survey data (Figure 3.19) provide an intermediate view of conditions in the channel between 1914 and 1998, and also provide an indication of the trends in the channel between

1983 and 1998, a period in which there were a number of large flood events (Table 4.3). The Subreach 1 average thalweg elevation decreased by 1.3 feet between 1914 and 1983, but there was about 0.2 feet of channel aggradation between 1983 and 1998 when the average thalweg elevation was about 1.2 feet lower than in 1914. In Subreach 2, the average thalweg elevation decreased by about 6.5 feet between 1914 and 1983, but there was about 2.3 feet of aggradation between 1983 and 1998 when the average thalweg elevation was about 4.2 feet lower than in 1914. In Subreach 3, the average thalweg elevation decreased by about 5.6 feet between 1914 and 1983, but there was about 0.2 feet of further degradation between 1983 and 1998, when the average thalweg elevation was about 5.9 feet lower than in 1914. In Subreach 4, the average thalweg elevation decreased by about 3.2 feet between 1914 and 1983, but there was about 0.7 feet of further degradation between 1983 and 1998, when the average thalweg elevation was about 4 feet lower than in 1914.

The comparative thalweg elevation data suggest that the entire channel has degraded since 1914, but in Subreaches 1 and 2, there has been some channel aggradation since 1983, which may explain the concerns expressed by the COE (1993) and others that there has been a reduction in channel capacity since the flood control project was constructed. In Subreaches 3 and 4, it appears that the channel is continuing to degrade. This may be in response to the channel narrowing that has occurred in the subreaches, which may be due to channel recovery from the very large volumes of sand that were introduced to the river from the Merced River as a result of dredge mining. The 1914 CDC survey shows very large sand bars in the upper subreaches, and the fact that there were two abandoned reaches (Finnegans Cutoff and Lairds Slough Cutoff) that totaled about 9.5 miles in length suggests that the 1914 channel was responding to a major influx of sediment by increasing its slope (Schumm, 1977).

The average bankfull widths of the channel were similar in 1914 and 1998 in Subreaches 1 and 2. However, in Subreaches 3 and 4, the average bankfull widths in 1998 were between 37 and 40 percent narrower than in 1914. The reduction in channel width is consistent with the increases in channel depth, probably in response to recovery from the upstream influx of sand from the dredge mining on the Merced River. Width to depth ratios in Subreaches 1 and 2 are not significantly different in the 1914 and 1998 periods. However, the decreases in width and increases in channel depth in Subreaches 3 and 4 resulted in much lower width-depth ratios in 1998 (Tables 3.1 and 3.3). The lower width-depth ratio channel has the potential to transport more sediment (Nanson and Huang, 1999).

The average bankfull discharge in all of the subreaches increased between 1914 and 1998 (Tables 3.2 and 3.4). In Subreach 1, the bankfull capacity increased by about 59 percent between 1914 and 1998, primarily as a result of increased channel depth. In Subreach 2, the average bankfull capacity increased by about 33 percent between 1914 and 1998, and in Subreaches 3 and 4, the increases were 9 and 12 percent, respectively. In 1914, the bankfull discharge occurred for about 60 days per year in Subreach 1 and for 53 days in Subreach 2. The estimated frequency of the bankfull event was on the order of 2 years which is consistent with values reported for similar rivers (Williams, 1978). In contrast, the bankfull discharge occurred for about 26 days per year in Subreach 1, and for 33 days per year in Subreach 2 in 1998. The estimated frequency of the bankfull discharge is about 4 years. This indicates that the recurrence interval of the bankfull event has about doubled between 1914 and 1998 as a result of changes in channel capacity and the hydrology, which has implications for regeneration and maintenance of the riparian vegetation within the meanderbelts.

In Subreaches 3 and 4, the bankfull capacity of the channel increased by 9 and 12 percent, respectively between 1914 and 1998. However, the duration of the bankfull discharge remained constant at about 30 days per year. This further supports the idea that the upper reaches were not in equilibrium in 1914 because the increases in channel capacity and the modified hydrology should have resulted in a significant reduction in the duration. The absence of significant riparian regeneration within the meanderbelt within the upper reaches may indicate that the frequency (about 3.5 years) and duration of overbank flows are presently insufficient, and may have been insufficient in 1914 as well.

The size of the bed materials in the San Joaquin River subreaches and lower reaches of the major tributaries (Table 2.1) may also lend support to a disequilibrium state in Subreaches 3 and 4 in 1914. Upstream of the Merced River, the D_{50} of the bed material is 0.6 mm. Downstream of the Merced River, the D_{50} of the bed material is 0.3 mm in Subreach 4 and 0.4 mm in Subreach 3, even though the D_{50} of the bed material in the lower Merced River was 0.5 mm. The D_{50} in Subreach 2 is also 0.3 mm even though the Tuolumne River bed material has a D_{50} of 0.5mm. Downstream of the Stanislaus River (D_{50} 0.6 mm) confluence, the D_{50} of the bed material increases to 0.6 mm. Since the primary source of sediment in Subreaches 4, 3, and 2 is bank erosion and reworking of the floodplain, it is possible that the composition of the bed material sediments is influenced by the tailings from the extensive dredge mining in the Merced River, and that the floodplain sediments are, therefore, finer than would normally be expected.

7.1.2. Hydrology

The flow characteristics of the San Joaquin River, including peak flow magnitude and frequencies and flow durations have been significantly affected by water resource developments in the basin, levee and channel improvements, bypasses and local diversions during the last 130 years. Approximately 85 percent of the combined watershed area of the three main tributaries to the project reach is upstream of the dams, and since most of the runoff originates from the upper portions of the watershed, the dams have a significant effect on the flow characteristics of both the tributaries and the San Joaquin River mainstem.

The average annual runoff volume during the pre-Friant Dam period (1913-1940) in the mainstem San Joaquin River study reach varied from about 1.8 million acre-feet in the upstream portion of the reach (Subreach 4) to about 3.7 million acre-feet in the portion of the reach downstream from the Stanislaus River (Subreach 1) (Figure 4.22). The average annual runoff volume during the post-New Melones Dam period (1979-1997) was essentially the same as the earlier period, varying from about 1.8 million acre-feet in Subreach 4 to 4.0 million acre-feet in Subreach 1. The increase between the early and modern periods varied from less than 2 percent in the upstream reach to about 6 percent in the downstream reach.

Comparison of the flow-duration curves, however, demonstrates that, while the annual runoff volumes were similar, the flow patterns were quite different. The median discharge increased from about 640 to 740 cfs between the two time periods in Subreach 4, a difference of about 16 percent (Figure 4.23). In Subreach 1, the median discharge increased from about 2,160 to about 2,320 cfs, a difference of about 8 percent. The upstream water projects tend to increase the duration of lower flows (less than about 3,000 cfs at Vernalis), and decrease the duration of intermediate flows (3,000 to 16,000 cfs at Vernalis). The duration of flows greater than 16,000 cfs was also greater during the modern period, which may be more related to several extreme flood years in this portion of the record than to the operational characteristics of the upstream water projects.

The average annual hydrographs for the Newman and Vernalis gages (Figures 4.24, 4.25) clearly show that, prior to completion of Friant Dam in 1941, flows were relatively high during the winter months of February and March, but that the highest flows tended to occur during the spring runoff in May and June. The upstream water projects store water during the snowmelt runoff period, releasing that water over a longer period of time during the late summer through early winter period. This can also be seen by comparing the average runoff volume and median discharges during the April-May period (Figures 4.26 and 4.27, respectively). Although the average annual runoff increased slightly from the early to the later period, the runoff volume during April and May decreased significantly. For example, in Subreach 4, the April-May runoff volume decreased from 550,000 acre-feet during the pre-Friant Dam period to about 460,000 acre-feet during the post-dam period, a difference of about 16 percent (Figure 4.26). The median discharges decreased even more dramatically, from about 3,700 cfs during the earlier period to about 970 cfs during the recent period, a difference of nearly 75 percent (Figure 4.27).

Between 1983 and 1997, there have been four significant flood events (1983, 1986, 1995, 1997) on the San Joaquin River (Table 4.3). Estimates of the exceedance intervals of these events range from 5 to 10 years for the 1995 event to 80 to 110 years for the 1997 flood. The extensive bank erosion along the subreaches is probably related to the occurrence of these morphogenetically-significant flood events. The magnitude and duration of the 1997 flood appears to have been significant with respect to regeneration of riparian vegetation in all of the subreaches.

7.1.3. Sediment Transport and Channel Stability

For the 1914 conditions, the estimated annual bed material transport capacity generally increased in the downstream direction, varying from about 63,000 tons per year in Subreach 4 to about 102,000 tons per year in Subreach 1, an increase of about 62 percent. The amount of sediment contributed by the tributaries under historic conditions cannot be estimated from the available information because pre-dam channel geometry and, in most cases, historic hydrology are not available. Based on their hydrology, the major tributaries would have contributed a significant amount of sediment to the mainstem. Backwater conditions in the downstream portions of the tributaries caused by high stages in the mainstem, however, would have had a tendency to reduce the amount of sediment actually reaching the mainstem. Comparison of the historic and present estimated annual transport capacities (Tables 5.2 and 5.5), indicates that the transport capacities have increased by about 60 percent in Subreach 3 to about 185 percent in Subreach 1 between 1914 and 1998. The indicated increase is caused primarily by increased hydraulic energy associated with deepening and general narrowing of the channel between 1914 and the present. The available information suggests that the channel may be aggrading in Subreach 2, where concern has been expressed over the channel capacity, and is continuing to degrade in Subreaches 3 and 4.

7.1.4. Riparian Vegetation

Some general ecological trends apply to all subreaches of the San Joaquin River. Since the late 1800s, a gradual and persistent trend was the draining, regrading, and reclamation of the flood basins, oxbow lakes, and tule marshes flanking the river, primarily on the east side of the valley. Remnant flood basins, marshland, and open water/slough complexes clearly shown on the 1914 CDC maps within the river floodway, and some even outside the levees, have since disappeared or been disconnected from the river by cross levees (Figures 3.1 through 3.5). Examples of sloughs still present outside the levee system include Walthall, Red Bridge, Riley, and Pear Sloughs, and the old San Joaquin River channel that brushes against the historic town of Grayson. These slackwater habitats were formerly associated with riverine, riparian, and valley oak woodland, and all were interwoven in a complex matrix throughout the meanderbelt of the river. The modern river floodway retains within the levees and terraces most of the large groves of riparian forest and oak woodland, but little of the more aquatic and semi-aquatic habitats other than the riverine open water element and a fraction of the oxbow lakes.

Another overarching trend appears to be the general maturation of riparian vegetation types. Mature mixed riparian forest trends toward oak woodland and oak savannah, and a large fraction of what appears to be mapped as early seral riparian scrub (labeled ABrush,@ or Athicket@on 1914 maps) in particularly unstable reaches is now predominantly mature riparian forest types and valley oak woodland. Also, large areas shown in 1914 as dense forest are now scattered oaks or predominantly upland annual grassland. These trends in vegetation succession are assumed to be caused by the reduction of overbank flows and channel forming flows because water storage, and therefore, flow peak attenuation increased in the major tributaries since the 1920s. The reduction of flow energy has caused a corresponding reduction of disturbance cycles that drive forest regeneration. Lower flows in the spring have reduced the opportunity for seed dispersal and germination on the floodplain, which may contribute to the apparent reduction in early seral willow scrub cover types.

An interesting and unexpected development contrary to the hydrology-driven trend described above was observed during the field surveys. Four- to six-foot tall cottonwood saplings appear in small, isolated clusters throughout the study reach on the rim of sandy floodplain surfaces 10 to 15 feet above the low-flow water surface. They appear to have been established following the prolonged high water events of 1995 or 1997, and all clusters appear to be even-aged. Further compounding this anomaly is the surrounding landscape which is typically dominated by old growth valley oak woodland or savannah with upland annual grassland understory, or by weedy ruderal herbaceous cover. Immature cottonwood or mixed riparian forest or scrub were not present at the elevation of the young saplings. These small trees appeared healthy in the fall of 1998, although some had died or experienced tip dieback.

Agricultural conversion of Abottom lands@ and clearing of riparian vegetation within the floodway since 1914 represents a few hundred acres at most, as most cropland reclamation of the floodplain and basin lands preceded that date. However, there appears to be a cyclical pattern of gradual conversion of bendway floodplains to row crop fields, followed by partial retreat or field abandonment following damage to fields and local levees during large flood events. Examples of this cycle can be found in both directions when comparing bendway fields on the 1976 river atlas photographs to the 1993 atlas and 1998 aerial photography. Large infrequent flood events continue to have significant damage potential on cropland within the floodway, but the reduction of frequency and magnitude of lesser order flood events may have caused a tendency by landowners to experiment with crops on lower floodplains protected by perimeter berms from overbank high flows.

7.1.4.1. Old River to Stanislaus River (Subreach 1)

Since 1976, little change has occurred to vegetation patterns in most of Subreach 1. Channel confinement within narrowly spaced levees, and partially revetted banks, result in a somewhat static condition. During the field surveys, there was evidence in places of fire damage to mature trees on narrow berms near the levees. Oxbow lakes at RM 58 and 62.4 experienced moderate increases in riparian scrub in response to gradual channel fill of the cutoff channels. Channel migration from lateral bank erosion (RM 70-71, RM 73.3 and RM 74.5), and a channel chute cutoff at RM 70, caused a loss of riparian cover types, but a gain to instream habitat structure from the capture and transport of large woody debris. New areas of immature willow scrub have occupied new bars and islands in this active migration area. Some of the increase in riparian cover from channel fill and point bar recruitment was offset by small expansions of agricultural fields at RM 59, RM 65.8, and RM 67.

7.1.4.2. Stanislaus River to Tuolumne River (Subreach 2)

Agricultural encroachment of the riparian zone does not appear to be a factor in this subreach. Two moderate sized sand splays occurred in agricultural fields near the river where local levees failed in January 1997. One isolated, low field at RM 79.5L is idle and is expected to revert to riparian and moist meadow vegetation if it remains abandoned. The site had a cover of watergrass and smartweed at the time of the November 1998 field surveys. Cottonwood sapling clusters were observed on the rim of older, higher floodplains at RM 78.2, 79.5, and 83.4, and probably occur in other similar unsurveyed locations. A large stand of saplings occupies former grassland on the overbank floodplain of the Tuolumne River where it converged with the right overbank of the San Joaquin River in 1997 (RM 83.4). If they survive subsequent dry years, there will be a small increase in cottonwood forest on the higher floodplains. Moderate channel migration has occurred in the Finnegan=s Cut segment, RM79-83, with some loss of mature trees on high banks and new riparian scrub colonizing the aggrading point bars.

A potential for significant riparian succession and expansion is evident on a 3,500-acre tract of unleveed, idle land bordered on three sides by the river between RM 79 and RM 82.8. This area of meander scroll topography was mapped in 1914 as basin land with large lakes, tule marsh, and sinuous oxbows from the former channel of the main river. The 1997 floods inundated this area and deposited fine sediments, with persistent ponding, soil saturation, and comparatively lush undergrowth evident in the July 1998 aerial photography. Because this area is lower than most of the surrounding floodplain, and therefore, closer to the water table and subject to more frequent overbank flows, it is expected to have a higher rate of floodplain colonization by riparian and seasonal wetland vegetation.

7.1.4.3. Tuolumne River to Patterson (RM 99.5) (Subreach 3)

In Subreach 3, numerous large sand splays cover agricultural fields near the river where several non-project levee failures occurred in January 1997. An especially notable case occurs throughout a five mile segment between RM 83 and RM 88 over 300-400 acres of floodplain upstream of the Tuolumne River confluence. This portion of the river has experienced the most conversion of lower land within the floodway to cropland with perimeter berms constructed near the active channel. All, or portions of, severely damaged fields may become abandoned, and the remaining idled floodplain will likely revert to a mosaic of bare sand bar, riparian scrub and forest clusters, and grassland. This pattern of post-flood idled field succession is observed on earlier aerial photographs as well, particularly where fields were originally established on lower floodplain surfaces and within low-radius bendways, such as RM 84-85. Other large sand splays from breaches in low field berms occurred at RM 89.5, 91.5, 92, 93.5, and 95.

Areas of higher, sandy floodplain surfaces support grassland and mature valley oak savannah (e.g., west of Laird Park, RM 90-91), which is not expected to change substantially in the absence of channel migration in this subreach. Cottonwood sapling clusters were observed on the rim of higher floodplains at RM 89.7 and 93, and may occur in other similar unsurveyed locations.

Local revetment in the river segment downstream of Grayson Bridge, and narrow levees, will tend to maintain a static vegetation condition. The historic channel of the main river passing by the town of Grayson supports a wide floodway (from 500 to 2000 feet wide) with a complex mosaic of oxbows, willow scrub, mixed riparian, and oak woodland. Depending on the local management of water levels from agricultural tailwater that drains into this area, age succession may trend towards mature cottonwood forest. However, higher than normal static water levels may keep the bottom land in marsh, open water, and willow scrub-dominant cover types.

7.1.4.4. Patterson to Merced River (Subreach 4)

Agricultural encroachment of the riparian zone and floodway has been a moderate factor in the lower half of this subreach. Small to moderate sized sand splays occurred in agricultural fields near the river and within bendways where local levees failed in January 1997 (RM 95.5, 97.4, 99.5, and 103). Small portions of these fields now appear to be abandoned (e.g., RM 103) and may revert to scrub, grassland, and bare sand bar cover types. Because this subreach is upstream of the two largest tributary inflows, overbank flows and channel migration occur less often, or affect less land area. However, the 1995 and 1997 floods caused extensive deposition of sand on low bars and floodplain surfaces, and at least three new chute cutoffs of low radius bends. Resulting channel fill deposits and low depositional bars are expected to regenerate to willow scrub in small groves in this subreach. Little change is expected on the higher floodplain surfaces that predominate in the upper half of this subreach, other than senescence and aging of existing woody vegetation. The predominant cover types within the floodway are grassland, and valley oak woodland and savannah which are grazed extensively. The presence of grazing livestock will not affect mature woody vegetation, but will suppress the colonization and establishment of riparian vegetation along channel margins and oak seedlings on the floodplain. Livestock readily browse these species, especially after annual grass forage has dried for the summer.

7.2. Major Tributaries

7.2.1. Channel Morphometry and Hydraulic Capacity

Little quantitative information is available on the historical condition of the Merced, Tuolumne and Stanislaus Rivers prior to the onset of major watershed -scale perturbations. Perturbations to the watersheds and channels included: placer mining (1848-1880), dredge mining (1880-1960s), flow regulation (1890s to the present), sand and gravel mining (1940s to present), urbanization (1850s to the present) and grazing and farming (1850s to the present) (McBain and Trush, 1998). The tributaries do, however, have common general geomorphic characteristics that can be described in terms of the degree of confinement of the rivers and the downstream-fining trends in the bed material. Near the upstream ends of all three rivers, the bed material is composed of gravel and cobble-size materials. At the downstream ends of the rivers, the bed material is all sand. Whether this pattern existed historically is unknown because flood flow regulation and interruption of the watershed sediment supply have significantly altered the sediment dynamics of the tributaries. Dredge mining in the tributaries has the effect of retaining all of the coarser size fractions of the alluvial valley fill in the mining area while flushing downstream the finer fractions.

Quantitative data on tributary channel morphology are only available for the Tuolumne River (McBain and Trush, 1999). McBain and Trush (1998) estimated that the bankfull discharge of the historic channel was on the order of 10,000 to 11,000 cfs which had a historical (pre-water development projects) recurrence interval at the La Grange gage of about 1.6 years. The historical floodplain was inundated by a 3-year recurrence interval flood prior to the New Don Pedro project (McBain and Trush, 1998). In the lower reaches the channel is bordered by an unconfined floodplain, but the frequency of overbank flooding was dependent on the backwater caused by high stage on the San Joaquin River. Backwater effects from the San Joaquin River extend about 14 miles up the lower Tuolumne River (COE, 1993). Similar relationships can be expected for the Stanislaus and Merced Rivers prior to their extensive modification. In the lower subreaches (T1 and T2) the slope of the Tuolumne River was on the order of 0.0003, whereas the average slope in Subreaches T3 and T4 was on the order of 0.0015. The changes in average slope correspond with changes in the character of the bed materials along the channel from sand to gravels.

The bankfull discharge, based on normal-depth calculations, in the lower Merced River is about 6,000 cfs. The bankfull discharge has a post-Lake McLure duration of about 4 days per year, which may explain why there has been little replenishment of the riparian forest in the lower reaches of the river. The bankfull discharge in the lower Tuolumne River is about 5,200 cfs, and it has a post-New Don Pedro Reservoir duration of about 14 days per year. The bankfull discharge in the lower Stanislaus River is about 5,450 cfs and it has a post-New Melones Reservoir duration of about 5 days per year. The flow duration estimates do not take into account the effects of backwater from the San Joaquin River.

7.2.2. Hydrology

A summary of the runoff volumes and median discharges for the pre- and post-dam periods on each of the three major tributaries is presented in Table 4.2. On the Merced River at the below Merced Falls Dam gage, the annual runoff volume increased by about 9 percent from 930,000 acre-feet for the period prior to construction of New Exchequer Dam in 1967 to about 1.01 million acre-feet during the post-dam period, and the median discharge increased by about 34 percent from 860 cfs to about 1,150 cfs. The duration of flows less than about 2,500 cfs increased, and the duration of larger flows decreased between the pre- and post-dam periods at this gage (Figure 4.8).

On the Tuolumne River, the annual runoff at both the upstream La Grange Dam and downstream Modesto gages decreased significantly during the period after construction of New Don Pedro Dam in 1971 compared to the pre-dam period (Table 4.2), with the runoff at the upstream gage decreasing by over 55 percent (1.67 million acre-feet versus 734,000 acre-feet) and the downstream by over 30 percent (1.05 million acre-feet versus 730,000 acre-feet).

On the Stanislaus River, the average annual runoff at the upstream below Goodwin Dam gage was higher during the post-New Melones Dam period (1979-1997) than it was prior to construction of the dam (1958-1978), increasing by about 10 percent from 525,000 acre-feet to 579,00 acre-feet (Table 4.2). The median discharge increased substantially from the pre-dam to post-dam periods. Comparison of the flow-duration curves (Figures 4.12 and 4.13) shows that the duration of flow less than about 1,000 cfs at the below Goodwin Dam gage and less than about 1,200 cfs at the Ripon gage increased and the duration of larger flows decreased from the pre- to post-dam periods.

Table 4.2 contains similar information for the April-May period at each of the tributary gages. Both the average runoff and the median discharge during the period decreased substantially at both gages on the Merced River. At the upstream gage, the median value was reduced from about 2,000 to 1,600 cfs, and at the downstream gage it was reduced from about 500 to 300 cfs. On the Tuolumne River, the median discharge was reduced from about 3,500 to 200 cfs at the upstream gage, and at the downstream gage it was reduced from about 860 to 400 cfs. On the Stanislaus River, the average runoff during the period also decreased from the pre-dam to post-dam periods at both gages. The median discharge, however, increased substantially at the upstream gage from about 140 to 740 cfs, while it decreased from about 1,500 to 930 cfs at the downstream gage.

7.2.3. Sediment Transport and Channel Stability

Because of the absence of historic information, it was not possible to estimate the sediment transport characteristics for the lower reaches of the tributaries. However, the normal depth calculations for existing conditions in each of the tributaries were used to compute average annual bed material transport capacities (Table 5.5). The estimated transport capacity for the Merced River is about 41,000 t/yr, and those for the Tuolumne and Stanislaus Rivers are 63,000 and 41,000 t/yr., respectively. Because of backwater conditions in the lower reaches of the tributaries it is unlikely that the estimated volumes are delivered to the San Joaquin River.

Comparative cross sections at a number of bridges that span the tributaries provide an indication of trends, and especially the effects of the 1997 flood. At the Highway 99 Bridge across the Merced River (Figure 3.21) that had a peak discharge with a 50 to 60 year exceedance interval in 1997 (Table 4.3), the river appears to have degraded by about 3 feet. On the Tuolumne River, where the 1997 event had an exceedance interval of 80 to 110 years (Table 4.3) the bed of the river degraded by about 5 feet at the Old La Grange Bridge (Figure 3.23), and degraded by about 5 feet at the Highway 99 Bridge (Figure 3.25). On the Stanislaus River , where the 1997 event had an exceedance interval of 50 to 70 years (Table 4.3), the comparative bridge cross sections did not indicate significant channel change.

7.2.4. Riparian Vegetation

All three major tributaries of the San Joaquin River in the study area share some common characteristics and similar ecological trends. As stated earlier in this report, regulated flows in the tributaries with relatively constant base flows during the growing season and reduced bankfull discharge have created more stable channels. Greater channel stability has promoted highly stable vegetation on the margins of the channels throughout most of their length below the reservoirs. Occupation of banks, bars, and mid-channel islands is so complete that bare mineral substrate is not even visible on aerial photographs in parts of the lower reaches of the tributaries. Under the existing hydrologic regime, vegetation succession has trended towards a shrub-scrub dominated margin with closed-canopy, mature riparian forest or dense valley oak woodland in the adjacent floodplains confined within the levees. Vegetation has not encroached into the channel because of the combined effects of shade from the mature overstory, and wide shallow flow persisting throughout the growing season. Lower reaches of the tributaries depicted on the 1914 CDC maps indicate a different vegetation structure with large exposed point bar deposits and unvegetated channel banks.

The riparian corridors of the lower tributaries also share a common botanical composition as well as similar structure, which is in stark contrast to the more open conditions along the mainstem river as one travels in a small boat from the San Joaquin River into the mouth of each tributary. Large cottonwood and alder trees are more common. The channel margins are dominated by narrow-leaved willow with box elder, ash, shrubby alder, button bush, and wild grape. On the tributaries, vegetation has generally developed a more dense structure with greater botanical diversity than that found on the mainstem river, but it occupies a narrower flood way corridor confined by terraces upstream and levees downstream.

For reasons difficult to explain, riparian forest groves in the lower reaches of the tributaries are being colonized more by invasive non-native trees and shrubs compared to the San Joaquin River where few are present. Eucalyptus, locust, giant reed, edible fig, and mulberry are common in the understory of mature riparian forest stands and on recent bar deposits or disturbed areas. One factor may be greater proximity to the channel from adjacent urban, rural residential, and agricultural staging areas, and at more numerous bridge crossings where these species are often first introduced.

7.2.4.1. Stanislaus River

Conditions and trends on the lower subreach of the Stanislaus River are the same as those described above for all tributaries. Urban and agricultural encroachment of the riparian corridor within the levees does not appear to be likely downstream of Hwy. 99 at Ripon. Much of the best examples of mature riparian forest and oak woodland, and the widest forested floodplain on the river, are protected within the boundaries of Caswell Memorial State Park. A long term trend will likely be the gradual increase of valley oak and walnut canopy, and a gradual decline of cottonwood and sycamore. Sycamore, cottonwood, and tree willow species have a shorter expected life span than oak and walnut, but are not able to regenerate effectively within the dense shaded overstory and understory of the stable floodplain.

Some encroachment of the riparian zone by low density urban and recreational development and orchard expansion is occurring in subreach 2 between Ripon and Oakdale. Sand and gravel mines are small and uncommon on the Stanislaus compared to the other tributaries, so mining is not expected to influence future vegetation trends.

7.2.4.2. Tuolumne River

Conditions and trends on the lower subreach of the Tuolumne River are similar to those described above for all tributaries. However, the extreme high flow during the January 1997 flood (exceeded 60,000 cfs) caused considerably more scour and sand deposition within the lower riparian corridor than on the other tributaries. Willow scrub is expected to reoccupy low, moist sand bars and channel margins in future years, supported by regulated base flows and lateral seepage from irrigation of adjacent orchards during the growing season. Distance between levees is on average more narrow on the lower Tuolumne than the other tributaries, but large nodes of floodplain are found in segments. Existing and recolonizing willow scrub in these areas is more likely to transition into mixed riparian and cottonwood forest similar to other established forest nodes along the lower river. However, some widened nodes may be converted to orchards and vineyards within the flood way, depending on the calculation of future flood damage risk by agricultural landowners.

Urban and agricultural encroachment of the riparian corridor within and adjacent to the levees is considerable compared to the Merced and Stanislaus. Extensive encroachment of the riparian zone by urbanization within the expanding boundaries of the city of Modesto and satellite communities is occurring in subreach 2 between Carpenter Road and Empire, and low density rural residential and recreational development and orchard expansion has increased east of Modesto to Waterford. Active and abandoned sand and gravel mines are extensive on the Tuolumne compared to the other tributaries. The long-term effects of mining are expected to influence future vegetation trends in several ways. Coarse-grained deposits above the active floodplain will remain barren or weedy. Shallow pits subject to gradual channel fill will then revert to alder or willow scrub or mixed riparian forest types. Channel and wet pit margins will revert to alder/narrow-leaved willow/box elder-dominated thickets.

As with the Stanislaus River, a long-term trend will likely be the gradual increase of valley oak and walnut canopy, and a gradual decline of cottonwood and sycamore.

7.2.4.3. Merced River

Conditions and trends on the lower subreach of the Merced River are similar to those described above for all tributaries, and have more in common with land use influences and vegetation pattern on the Tuolumne River. The extreme high flows during the January 1997 flood also caused scour and sand deposition within the lower riparian corridor. Willow scrub is expected to reoccupy the low, moist sand bars and channel margins in future years, supported by regulated base flows and lateral seepage from irrigation of adjacent fields and orchards during the growing season. Distance between levees is on average more narrow on the lower Merced than the Stanislaus, but large nodes of vegetated floodplain are found in segments.

Urban encroachment of the riparian corridor within and adjacent to the levees is less extensive compared to the Tuolumne and Stanislaus Rivers. However, cropland and other agricultural encroachment of the riparian zone does occur within the levees, and may expand in the future with increasing orchard development in the region. Active and abandoned sand and gravel mines are also extensive on the Merced River, and future vegetation in mined areas will depend on reclamation plans and natural recolonization. However, captured deep wet pits are unlikely to be refilled by alluvial sediment, because flow magnitude and sediment supply have been greatly reduced by upstream reservoirs.

As with the Stanislaus and Tuolumne Rivers, a long-term trend will likely be the gradual increase of valley oak and walnut canopy, and a gradual decline of cottonwood and sycamore.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

This reconnaissance-level geomorphic, sediment transport and riparian ecology study of the San Joaquin River and the major tributaries, the Stanislaus, Tuolumne, and Merced Rivers was conducted as part of the Sacramento and San Joaquin River Basins Comprehensive Study, California. To date, little information on the geomorphology, sediment dynamics or riparian ecosystem is available for the project reach or the tributaries. The purpose of the current investigation was to remedy the lack of information for the project reach of the San Joaquin River and its major tributaries. The project reach extends from the Old River at RM 53 to the confluence with the Merced River at RM 118, a distance of 65 river miles. On the Merced River, the study reach extends from its confluence with the San Joaquin River to McSwain Lake, a distance of 35 river miles. The study reach of the Tuolumne River extends from the confluence with the San Joaquin River to Turlock Lake, a distance of 46 river miles. The project reach on the Stanislaus River extends from the confluence with the San Joaquin River to Knights Ferry, a distance of 55 river miles.

The primary objectives of this investigation of the lower San Joaquin River and its major tributaries that was conducted for the Sacramento District of the Corps of Engineers by Mussetter Engineering, Inc. and Jones & Stokes Associates, Inc. were to:

1. Determine, based on existing information and field reconnaissance, geologic, geomorphic, qualitative sediment transport and channel stability conditions through the study reach,

2. Qualitatively describe current sedimentation and channel stability trends through the study reach, and

3. Describe and explain the role of the existing riparian vegetation on channel stability and sedimentation patterns through the study reach, and qualitatively evaluate the potential for enhancement of riparian habitat.

Based on the information developed from this investigation, the following are the major conclusions of the study:

1. Bank erosion occurring along between 14 and 31 percent of the project reach of the San Joaquin River is a major source of sediment within the reach. Continued erosion of the banks, especially within Subreaches 3 and 4 will maintain the sediment supply to the downstream reaches, and will also permit reworking of the meanderbelt that will allow some vegetational succession to occur.

2. The bankfull depth of the San Joaquin River channel has increased in all of the subreaches between 1914 and 1998. Depending on the subreach, increases varied from 0.3 feet (Subreach 4) to 2.8 feet (Subreach 3).

3. Comparative thalweg elevation data (1914, 1983, 1998) for the San Joaquin River suggest that the entire channel has degraded since 1914, but in Subreaches 1 and 2, there has been

some channel aggradation since 1983. In Subreaches 3 and 4, it appears that the channel is continuing to degrade.

4. The average bankfull widths of the channel of the San Joaquin River were similar in 1914 and 1998 in Subreaches 1 and 2. However, in Subreaches 3 and 4, the average bankfull widths in 1998 were between 37 and 40 percent narrower than in 1914 because of channel degradation..

5. The average bankfull discharge in all of the subreaches of the San Joaquin River increased between 1914 and 1998, and the increases ranged from 59 percent (Subreach 1) to 9 percent (Subreach 3). In 1914, the estimated recurrence interval of the bankfull discharge in all of the subreaches was about 2 years, but in 1998 the recurrence intervals for the subreaches approximately doubled. In Subreaches 1 and 2 the duration of the bankfull flow decreased by about 50 percent, but it was almost unchanged in Subreaches 4 and 5.

6. Quantitative data on tributary channel morphology are only available for the Tuolumne River (McBain and Trush, 1999). McBain and Trush (1998) estimated that the bankfull discharge of the historic channel was on the order of 10,000 to 11,000 cfs which had a historical (pre-water development projects) recurrence interval at the La Grange gage of about 1.6 years. The historical floodplain was inundated by a 3-year recurrence interval flood prior to the New Don Pedro project (McBain and Trush, 1998). In the lower reaches the channel is bordered by an unconfined floodplain, but the frequency of overbank flooding was dependent on the backwater caused by high stage on the San Joaquin River

7. The bankfull discharge, based on normal-depth calculations, in the lower Merced River is about 6,000 cfs. The bankfull discharge has a post-Lake McLure duration of about 4 days per year, which may explain why there has been little replenishment of the riparian forest in the lower reaches of the river. The bankfull discharge in the lower Tuolumne River is about 5,200 cfs, and it has a post-New Don Pedro Reservoir duration of about 14 days per year. The bankfull discharge in the lower Stanislaus River is about 5,450 cfs, and it has a post-New Melones Reservoir duration of about 5 days per year.

8. Comparative bridge profiles indicate that the 1997 flood caused about 3 feet of degradation at the Highway 99 Bridge across the Merced River, and about 5 feet of degradation at the Old La Grange and the Highway 99 Bridges across the Tuolumne River. Comparative bridge profiles on the Stanislaus River showed little or no change in the bed elevations.

9. The average annual runoff volume during the pre-Friant Dam period (1913-1940) in the mainstem San Joaquin River study reach varied from about 1.8 million acre-feet in the upstream portion of the reach (Subreach 4) to about 3.7 million acre-feet in the portion of the reach downstream from the Stanislaus River (Subreach 1). The average annual runoff volume during the post-New Melones Dam period (1979-1997) was essentially the same as the earlier period, varying from about 1.8 million acre-feet in Subreach 4 to 4.0 million acre-feet in Subreach 1.

10. Annual flow-duration curves for the pre-Friant and post-New Melones time periods show that

the median discharge increased from about 640 to 740 cfs between the two time periods in Subreach 4, a difference of about 16 percent. In Subreach 1, the median discharge increased from about 2,160 to about 2,320 cfs, a difference of about 8 percent. In the April-May period when seed dispersal occurs, the median discharges decreased in Subreach 4 from about 3,700 cfs during the earlier period to about 970 cfs during the recent period, a difference of nearly 75 percent.

11. Between 1983 and 1997, there have been four significant flood events (1983, 1986, 1995, 1997) on the San Joaquin River. The extensive bank erosion along the subreaches is probably related to the occurrence of these morphogenetically-significant flood events. The magnitude and duration of the 1997 flood appears to have been significant with respect to regeneration of riparian vegetation in all of the subreaches.

12. Comparison of the historic and present annual bed material transport capacities, indicates that the transport capacities have increased by about 60 percent in Subreach 3 to about 185 percent in Subreach 1 between 1914 and 1998. The available information suggests that the channel may be aggrading in Subreach 2, where concern has been expressed over the channel capacity, and is continuing to degrade in Subreaches 3 and 4.

13. Recruitment and regeneration of riparian habitat has not occurred throughout most of the higher floodplain surfaces for many decades, and even oak saplings are uncommon. Grazing and competition with non-native weeds and grasses are probable limiting factors, but the primary limiting factor appears to be caused by the reduction of overbank flow frequency and duration, especially during the spring season of seed dispersal and growth.

14. Riparian vegetation does not appear to be a factor limiting the conveyance capacity of the floodway. The position of vegetation along the channel margins has changed over time as a result of channel migration and meander cutoffs, but the overall extent and density of vegetation has remained approximately the same since the 1976 river atlas photographs were taken. The density and extent of vegetation on the historic floodplain, which represents most of the land area within the levees, is greatly reduced since 1914 due to type conversion to annual grassland and oak savannah which have low hydraulic roughness compared to other riparian habitats.

8.2. Recommendations

On the basis of the results of this investigation, and on items in the scope of work, the following recommendations are provided that address sediment issues and the potential for riparian restoration.

8.2.1. Sediment Sampling Program

Recommendations for a sediment sampling program (bed and banks) to support future comprehensive modeling of the San Joaquin River system, with particular emphasis on the locations for bed material load and suspended sediment load measuring stations was requested in the scope of work.

Within the project reach of the San Joaquin River and the lower reaches of the tributaries, the bed samples collected for this investigation (Table 2.1) are probably sufficient to characterize the bed material load. Additional bed material samples may be required immediately upstream of the Merced River confluence on the San Joaquin River to better characterize the in-flowing sediment load to the project reach. Based on the field reconnaissance of the project reach of the San Joaquin River and the size changes in the bed material from Subreach 4 downstream to Subreach 1, it may be necessary to acquire at least 10 samples of bank materials in each of the subreaches. The samples should be divided between the more cohesive flood basin, and less cohesive floodplain, sediments that form the eroding banks.

Within the tributaries there is a distinct upstream coarsening trend in the bed material sediments. The existing samples (Table 2.1) are representative of the sand bed materials in the lower reaches, but further sampling is required upstream in all of the tributaries. It is recommended that a bed material sample be collected every 5 miles. Where the bed materials are sufficiently fine a bulk sample will suffice. However, in the coarser bed material reaches both a surface and subsurface gradation will be required at each sampling site. The surface gradation can be established with a Wolman pebble count (Wolman, 1954), but the subsurface gradation, which represents the parent materials, will need to be bulk sampled. Bar and bank samples which are indicative of materials being transported by the flows and sediment source areas, respectively should be sampled at the same locations.

Measurements of bed material load and suspended sediment loads should be carried out at the gage locations that were used to characterize the hydrology of the San Joaquin River and the major tributaries (Table 4.3). This will ensure that the sediment measurements can be used to establish long-term trends within the project reach.

8.2.2. Riparian Habitat on the San Joaquin River

This study includes a qualitative assessment of opportunities and approaches to enhance the natural environment of the river corridor, particularly where measures to reduce flood risk could also serve to restore or protect riparian and aquatic habitats. Recommended environmental enhancement measures presented below fall into three general categories: measures related to flow management, measures related to floodway capacity, and measures related to bank and berm protection.

8.2.2.1. Environmental measures related to flow management

A previous study of the SJR from Friant to Merced (JSA and MEI, 1998) recommended a feasibility evaluation to determine if managed flood flow releases below Friant Dam and the Chowchilla Bifurcation Structure could be modified to increase the frequency of occurrence of bankfull discharge, particularly during the spring, without adding risk to levees and farmland. The ecological purpose of increasing the frequency of overbank flows is to wet the floodplains and to deliver fine sediments and seed to promote greater riparian vegetation establishment. Floodplain inundation also suppresses non-native annual grasses and other weeds that compete with native plants, including valley oak trees, and recharges the local water table available to phreatophytes (i.e., riparian plants that tap shallow water tables to survive the dry season). A similar hydraulic evaluation is proposed for the lower SJR and its tributaries. This measure could be combined with reservoir reoperation scenarios intended to afford greater attenuation of large flood events by increasing the discharge rate of flood pool releases, such as reoperation implemented on the American River at Folsom Dam. This potential measure is complicated by the large capacity of the mainstem river channel, and the need to coordinate the flood storage release schedules of the reservoirs on all three major tributaries.

8.2.2.2. Environmental measures related to floodway capacity

The most important factor maintaining the natural meander scroll topography and riparian habitat of the mainstem SJR has been the significant width of the floodway retained within the primary outer levees and terraces. Some encroachment of the floodway may have resulted from the expansion of agricultural fields towards the river, requiring the construction of local levees or berms to reduce nuisance flooding and sand splays. However, since 1993 some of the expanded agricultural fields suffered damage from flooding and deposition during the 1995 and 1997 floods, and have since retreated their boundaries to positions with lower risk of overtopping during high flows. Detailed hydraulic analysis of floodway capacity may demonstrate that additional adjustments to local levees and outer levee setbacks may be needed to preserve a comfortable floodway capacity throughout its length. Such measures offer the added environmental benefit of conserving or restoring low and intermediate floodplain surfaces within bendways available for recolonization by riparian vegetation or oak woodland. Of equal importance is conservation of the natural river migration process that drives most natural succession on the river, because setbacks of fields and local levees within bendways eliminates the incentive to harden river banks with revetment. Greater floodway width and capacity also lessens any concern that vegetation in the river corridor has reduced hydraulic capacity to a point where local levee districts and landowners have in the past pressed for vegetation removal projects.

Another potential environmental measure related to enhanced floodway capacity is the reconnection of historic sloughs and oxbows to the river in areas that would allow these former channels to convey a portion of high flows similar to natural flow bifurcations through basin and slough complexes. Two river segments where this approach could be evaluated are Finnegan=s Cut (RM79 to RM 83) and Laird Slough (RM 87 to RM 90.5). The basin lands and abandoned river channels adjoining the river are still present and support primarily natural topography and vegetation. However, earthen berms and training levees have been constructed that appear to prevent most overbank flow from entering or flowing through these oxbow complexes. Improving the inflow and exit capacity of these large slough complexes could enhance the rate and extent of riparian regeneration, and would contribute to intermittent floodplain aquatic habitats favored by resident native fish such as splittail, or as nursery and velocity refugia favored by outmigrating juvenile salmonids. The potential for undesirable channel shortening should also be evaluated, but potential meanderbelt width is considerable in these two segments.

8.2.2.3. Environmental measures related to bank and berm protection

The river segment with the least amount of riparian vegetation and the largest gaps in the continuity of riparian habitat occurs in lower Reach 1 where levees are placed close to the river banks. The proximity of levees close to eroding channel banks has triggered an ongoing need to armor the steep banks with revetment, which removes riparian vegetation and discourages or prevents the recolonization of riparian habitat in this subreach. Natural meander succession is unavoidably terminated where armored levees flank the river banks, and it leaves a low margin of safety between unrevetted banks and narrow remnant berms adjoining levees. Therefore, measures described above that preserve or expand the width of the available floodway and meanderbelt also serve to avoid or significantly reduce the future need to construct additional bank revetment at the expense of riparian and shaded riverine aquatic habitats.

In some locations a revetted bank protects a levee close to the river on one side, but the land beyond the opposite bank supports a wide floodplain of natural or ruderal habitat and is uncultivated (for example, RM 80 to 81). These channel segments could be evaluated as sites where dikes could be constructed to deflect high flow away from the levee and promote channel migration towards the opposite bank where erosion and deposition would have positive environmental benefits. Additionally, sand deposition that would likely occur within the dike field would become a new riparian seedling regeneration site, creating a willow scrub vegetation type that would add to the reduction of near bank velocities at high flows.

8.2.3. Environmental Measures to Enhance Riparian Habitat on the Tributaries

Riparian habitat restoration measures have been implemented recently on the tributaries, and more are under planning, particularly within the gravel mining and dredger tailing-affected subreaches of the Tuolumne and Merced Rivers. Recommendations for environmental enhancement in this report focus on the downstream leveed subreaches where a stronger nexus exists with local, state, and federal flood control projects and planning.

Extreme high flows on the tributaries during the January 1997 flood overtopped and damaged levees, agricultural fields, and infrastructure, triggering a reevaluation of flood readiness and floodway capacity in the region. Regional solutions may contemplate projects to expand the capacity of the floodway through measures such as channel clearing, levee raising, setting back of levees, creating flood bypass systems, or increased flood storage from reoperation of existing reservoirs. Levee raising and channel clearing and widening generally result in unavoidable loss of riparian and aquatic habitat, and may cause higher flood peaks farther downstream by concentrating flow or raising design water surface levels. However, measures that widen the available floodway by setting levees back in overly confined segments of the tributaries would increase overall conveyance capacity and reduce levee damage in the future without adversely affecting riparian vegetation and aquatic habitats. Inspection of 1998 post-flood aerial photography covering the lower tributaries (scale 1:10 000, USACE) reveals a pronounced variation in the floodway width between local levees, including sparsely populated rural agricultural valley segments unconfined by adjoining terraces. Areas where distance between the adjoining levees are wider also typically support the largest, least disturbed, and most botanically diverse stands of riparian vegetation and have more continuous shaded riverine aquatic habitat.

As observed earlier in this report (Section 7.2), closed canopy riparian forest and shrub is very common along the lower Stanislaus River, and occupies most of the non-agricultural land within the project levee system of the river. Riparian cover is least well developed on the Tuolumne River, followed by the Merced, where many large gaps or very narrow vegetated strips are found. This diminished condition is most often found where levees are close to the active river banks on both sides. Therefore, riparian restoration and environmental enhancement measures within the tributary floodways seems to be a higher priority on the Tuolumne and Merced Rivers, whereas forest conservation may be important along the Stanislaus, and where large remaining forest nodes are found on the other two tributaries.

Floodway Widening - Widening the distance between adjoining levees would allow greater room for riparian and oak woodland vegetation to establish naturally or be planted without compromising hydraulic capacity needed to control major flood flows on the lower tributaries. The template for floodway width is the existing pattern of large nodes of mature riparian forest and oak savannah found sporadically along the lower segments of all three tributaries. Floodway widening can be accomplished in several possible ways, including levees setbacks (probably the most expensive alternative), lowering the top elevation of local earth berms constructed on the river side of adjacent agricultural fields, or designating more substantial levees often found at greater distances from the river banks as the primary flood control levees, thereby allowing the removal or abandonment of more at-risk private local levees that only protect individual fields close to the river. To be practical, this restoration measure would require the local cooperation of private landowners supported by incentive programs (public-funded grants and technical services), purchase of floodway easements, land acquisition from willing sellers, or state- and federal-sponsored floodway improvement projects which reduce local flood risk but also set aside more riparian lands for reversion to natural habitat. As both a restoration and floodway widening planning tool, hydraulic modeling of each of the lower tributaries (subreaches 1 and 2) is recommended to show areas having the greatest constrictions, the least freeboard capacity, and the highest flow velocity near the banks and levee foundations. A related measure is to evaluate the level of protection or risk of existing riparian forest found in the notably wide floodway nodes of the lower tributaries, and then develop policies and easement programs that ensure that private local levees will not be moved or built closer to the river banks. Agricultural practices could continue within widened floodways, but this measure also affords an opportunity to establish larger forest nodes within the floodway, to connect fragmented habitat patches, provide greater shade of the channel, and in appropriate locations provide greater opportunity for river-related recreational uses. Wider floodways also tend to be more self-maintaining because they have greater sediment storage capacity on the floodplain, and levees can be placed away from the high velocity channel flows and unstable river banks, thereby eliminating the need for expensive rock revetment or controversial channel clearing in the future.

Restoration of Historic Sloughs and Interfluves - A variation of the concept of flood bypasses is reuse of abandoned and disconnected sloughs and interfluve channels to convey a portion of high flows in the confined rivers. This would also offer ecological benefits by expanding the extent of riparian forest and oak savannah nodes, and creating greater connectivity between the lower tributaries, the mainstem river corridor, and upland and agricultural habitats. Potential natural bypasses worthy of investigation include remnant sloughs on the east side of the San Joaquin River that appear on the CDC 1914 maps to have conveyed overbank flows from the lowermost two miles of the tributaries, when the mainstem river was running at high stage. Examples of natural remnant sloughs associated with the lower tributaries include Walthall, Red Bridge, and Riley sloughs and several other unnamed remnant channels.

Control of Invasive Non-native Vegetation - This report has noted the presence of potentially invasive, non-native species of woody vegetation colonizing the riparian corridor of the lower tributaries, particularly along the Stanislaus and Tuolumne Rivers, including within mature native forest groves at Caswell Memorial State Park. Non-native species (e.g., edible fig, mulberry, locust, eucalyptus, tamarisk, giant reed, German ivy) are known to sometimes displace native riparian habitats in the Central Valley under certain conditions and often spread following disturbance events such as wildfires, channel clearing, or flood scour. Eradication is probably not a feasible strategy, but removal of incipient populations in new areas and reduction of large infestations over several years can limit the expansion of their range. Many of these non-native riparian species have other undesirable characteristics such as noxious agricultural weeds and many, such as eucalyptus, tamarisk, and giant reed, represent risks to fire safety and floodway capacity where they occur in dense, monocultural stands. An initial step in support of this measure is to inventory and map the distribution and extent on the lower tributaries of the larger stands of these undesirable invaders of valley riparian habitats.

Revegetate Abandoned Fields on Low Floodplains - During the aerial and ground level reconnaissance surveys for this study, several locations were observed on all three tributaries where agricultural fields found on river floodplains within the levees appeared to be abandoned or idle. Many of these sites are found adjacent to, and at the same apparent elevation as, natural riparian forests and valley oak woodlands, implying restoration potential. Some of these fields may be idle or abandoned because of the greater risk of flooding of crops and deposition of sand splays on fields from high water events. Under current hydrologic conditions on the tributaries, these sites may not flood often enough during the spring season of riparian seed dispersal for natural recolonization to occur. However, planting, flood irrigation, and seeding projects have been used successfully throughout the valley by The Nature Conservancy and others to reestablish riparian habitats on historic floodplains once cleared for agricultural uses. Fields close to the river banks could also be graded closer to the local water table (i.e., lowered in elevation) where a local need exists for soil borrow material for floodway or transportation improvement projects.

Deferred Grazing and Riparian Pasture Management - Although not strictly related to floodway projects, another restoration measure that could be employed on the sparsely vegetated floodplains of the lower rivers is deferred grazing or more intensive range management of seasonal riparian pastures. This measure, which could be used in conjunction with floodway easement acquisition, is particularly applicable to the lower few miles of the Merced River and its confluence with the San Joaquin River corridor, an area heavily grazed, but where fewer crop fields and orchards are found. Annual livestock grazing of riparian corridors during the growing season, over many years and at high stocking rates, can suppress natural recruitment of oaks and riparian trees because animals will browse seedlings and saplings extensively once the annual grassland forage dries out or is over utilized. A few years of reduced, limited seasonal duration, or no grazing of riparian pastures could allow recolonization and subsequent growth of woody vegetation to exceed the normal browse height, when grazing pressure becomes less threatening to forest succession.

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Table 4.1. Summary of stream gages used to develop the mean daily flow-duration curves.

Gage Operator	Gage I.D.	Gage Name	Period of Record	Drainage Area (mi^2)
San Joaquin River				
USGS	11274000	San Joaquin River near Newman CA	1912-present	9,520
DWR		San Joaquin River at Maze Road Bridge	1966-1968, 1970-1980, 1983, 1986, 1995, 1997	12,400
USGS	11303500	San Joaquin River near Vernalis CA	1924, 1930-present	13,536
Merced River				
USGS	11270900	Merced River Below Merced Falls Dam, near Sneller CA	1911-present	1,061
USGS	11272500	Merced River near Stevinson CA	1941-present	1,273
Tuolumne River				
USGS	11288000	Tuolumne River above La Grange Dam, near La Grange C	1896-1970	--
USGS	11289650	Tuolumne River below La Grange Dam, near La Grange C	1971-present	1,538
USGS	11290000	Tuolumne River at Modesto CA	1941-present	1,884
Stanislaus River				
USGS	11302000	Stanislaus River below Goodwin Dam, near Knights Ferry	1957-present	986
USGS	11303000	Stanislaus River at Ripon CA	1941-present	1,075

Table 5.3. Summary of reach-average hydraulic conditions for the San Joaquin River, based on cross sections surveyed in 1998.

Total Discharge (cfs)	Reach				Topwidth (feet)	Reach			
Profile	1	2	3	4	Profile	1	2	3	4
1	460	190	130	100	1	200	110	90	70
2	780	430	270	200	2	230	220	120	80
3	1320	900	600	420	3	290	250	140	100
4	2320	1750	1120	740	4	300	280	160	130
5	4030	3220	1800	1220	5	320	310	170	140
6	7330	5920	2900	2390	6	360	330	180	170
7	10450	8700	4230	3840	7	410	350	200	190
8	13530	11280	5880	5700	8	410	370	210	210
9	16040	13700	7940	7970	9	420	380	220	220
10	24150	22270	13990	13340	10	420	390	230	230
Main channel velocity (fps)	Reach				Hydraulic depth (feet)	Reach			
Profile	1	2	3	4	Profile	1	2	3	4
1	0.8	0.4	0.3	0.8	1	1.8	1.4	1.0	0.5
2	0.9	0.5	0.8	0.9	2	2.2	2.2	1.2	1.2
3	1.0	0.8	1.1	0.9	3	3.2	3.3	1.9	2.1
4	1.2	0.9	1.2	1.0	4	4.1	4.3	2.9	3.0
5	1.3	1.1	1.4	1.1	5	5.1	5.3	4.1	3.8
6	1.8	1.7	1.8	1.5	6	8.0	8.1	6.9	5.5
7	2.2	2.2	2.0	1.8	7	11.2	10.6	9.1	6.7
8	2.4	2.3	2.2	2.0	8	12.9	11.6	10.2	7.4
9	2.5	2.4	2.2	2.1	9	13.9	12.5	10.6	7.8
10	2.6	2.5	2.3	2.1	10	14.5	13.0	10.8	8.0
Energy gradient	Reach								
Profile	1	2	3	4					
1	0.00019	0.00015	0.00011	0.00011					

Table 5.1. Summary of reach-averaged hydraulic conditions from the HEC-RAS results based on cross sections surveyed in 1914.

Total Discharge (cfs)	Reach				Topwidth (feet)	Reach			
Profile	1	2	3	4	Profile	1	2	3	4
1	230	60	40	30	1	170	110	110	60
2	390	200	120	90	2	200	170	120	80
3	810	500	300	190	3	250	200	140	100
4	1370	910	560	340	4	280	230	160	120
5	2110	1570	980	640	5	310	270	170	150
6	5060	4250	2710	2010	6	360	310	220	240
7	9670	8160	4650	3990	7	390	360	250	320
8	13100	11200	6060	5570	8	420	410	280	380
9	15130	12730	6860	6660	9	430	410	290	420
10	16660	13910	7490	7490	10	430	410	300	440
Main channel velocity (fps)	Reach				Hydraulic depth (feet)	Reach			
Profile	1	2	3	4	Profile	1	2	3	4
1	0.8	0.4	0.3	0.8	1	1.8	1.4	1.0	0.5
2	0.9	0.5	0.8	0.9	2	2.2	2.2	1.2	1.2
3	1.0	0.8	1.1	0.9	3	3.2	3.3	1.9	2.1
4	1.2	0.9	1.2	1.0	4	4.1	4.3	2.9	3.0
5	1.3	1.1	1.4	1.1	5	5.1	5.3	4.1	3.8
6	1.8	1.7	1.8	1.5	6	8.0	8.1	6.9	5.5
7	2.2	2.2	2.0	1.8	7	11.2	10.6	9.1	6.7
8	2.4	2.3	2.2	2.0	8	12.9	11.6	10.2	7.4
9	2.5	2.4	2.2	2.1	9	13.9	12.5	10.6	7.8
10	2.6	2.5	2.3	2.1	10	14.5	13.0	10.8	8.0

Energy gradient	Reach			
Profile	1	2	3	4
1	0.00011	0.00011	0.00015	0.00015

Table 4.2. Summary of median discharges and runoff volumes for the Merced, Tuolumne, and Stanislaus Rivers.

Time Period	Merced River below Merced Falls Dam CA	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1902-1913, 1917-1966	860	928,600
1967-1997	1,150	1,008,000
	April-May	
1902-1913, 1917-1966	2,060	341,100
1967-1997	1,630	249,700

Time Period	Merced River near Stevinson CA	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1941-1966	200	499,400
1967-1995	270	493,800
	April-May	
1941-1966	510	1,012,700
1967-1995	300	736,700

Time Period	Tuolumne River near La Grange Dam CA*	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1912-1971	1,680	1,674,000
1972-1997	230	734,600
	April-May	
1912-1971	3,500	515,300
1972-1997	210	183,400

Time Period	Tuolumne River at Modesto CA	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1896, 1941-1971	760	1,052,300
1972-1997	370	731,800
	April-May	
1896, 1941-1971	870	1,476,000
1972-1997	400	888,000

Time Period	Stanislaus River bl Goodwin Dam CA	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1958-1978	45	525,500
1979-1997	360	578,700
	April-May	
1958-1978	140	175,000
1979-1997	750	133,100

Time Period	Stanislaus River at Ripon CA	
	Median Discharge (cfs)	Runoff Volume (acre-ft)
	Annual	
1941-1978	310	729,000
1979-1998	500	701,500
	April-May	
1941-1978	1,490	1,493,100
1979-1998	940	930,300

*Before 1971, the LaGrange gaging station was located above the TID and MID diversions.

Table 5.4. Summary of average hydraulic conditions for the downstream reach of the Stanislaus, Tuolumne and Merced RIvers, based on HEC-RAS computed normal depth, and cross sections from the 1998 topographic mapping.

Total Discharge (cfs)	Reach			Topwidth (feet)	Reach		
Profile	Stanislaus	Tuolumne	Merced	Profile	Stanislaus	Tuolumne	Merced
1	50	50	50	1	88	87	88
2	100	107	160	2	105	100	93
3	300	500	300	3	111	133	97
4	600	800	600	4	117	143	103
5	1000	1000	1000	5	123	149	109
6	2500	2500	2000	6	133	173	121
7	4000	4000	4000	7	136	183	167
8	5500	6000	5000	8	141	193	177
Main channel velocity (fps)	Reach			Hydraulic depth (feet)	Reach		
Profile	Stanislaus	Tuolumne	Merced	Profile	Stanislaus	Tuolumne	Merced
1	0.7	0.6	0.6	1	0.8	0.9	0.9
2	0.8	0.8	0.9	2	1.1	1.4	1.8
3	1.3	1.3	1.2	3	2.1	2.9	2.6
4	1.6	1.5	1.5	4	3.1	3.7	3.8
5	2.0	1.6	1.8	5	4.1	4.1	5.1
6	2.8	2.2	2.3	6	6.8	6.5	7.2
7	3.3	2.6	2.7	7	8.8	8.4	8.9
8	3.5	3.0	2.9	8	10.0	10.3	9.8
Energy gradient	Reach						
Profile	Stanislaus	Tuolumne	Merced				
1	0.00033	0.00023	0.00022				