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Abstract

The San Joaquin River and its principal tributaries, the Merced, Tuolumne, and Stanislaus Rivers in the Central Valley of California, once supported spring and fall runs of chinook salmon (*Oncorhynchus tshawytscha*) numbering in the hundreds of thousands. As a result of dam construction, aggregate mining, water diversions, clearing and filling for agriculture, fishing and other human activities, the populations of these fish have declined dramatically. The spring run, formerly the most abundant salmon in the San Joaquin system, was extirpated by 1942 because dams cut off access to cold-water habitat upstream. The fall run has been reduced to a small remnant in the tributaries -- in 1992, only 1,250 adults returned upstream to spawn, including returns to a hatchery on the Merced River.

In response to the near extinction of salmon in the Sacramento-San Joaquin River system, a number of efforts are planned or underway to restore fish populations. State and federal laws call for a doubling of salmon populations by early in the 21st century. Tens of millions of dollars have been allocated (and more are anticipated) for these efforts through the Bay-Delta Accord, the Central Valley Project Improvement Act, the Four Pumps Agreement, and other funding mechanisms. One focus of these efforts is the physical modification of river channels to create or improve spawning habitat. Of these efforts, only the Four Pumps Agreement has funded projects that have already been built in the Central Valley. The purpose of this study was to assess the projects implemented under the Four Pumps Agreement with respect to their conformance with stated the goals of the Agreement, and with respect to the physical performance of three of the projects in the field. The assessment is based on document reviews, interviews, field surveys, and hydrologic and hydraulic analysis.

Of the total $33 million allocated under the Four Pumps Agreement between 1986 and 1995 for projects in the Sacramento-San Joaquin River system, 45% was directed to increase populations of striped bass (*Morone saxatilis*), an introduced species that prey on juvenile salmon. The remaining $18.3 million (55% of the total) was directed toward chinook salmon and steelhead trout (*Oncorhynchus mykiss*). Of this amount, nearly a third ($5.6 million) was allocated for hatcheries, in apparent conflict with the Agreement's guideline that funds are to be used for natural production over hatchery production, particularly since hatchery fish are known to have a deleterious effect on natural runs through competition and genetic introgression. $3.8 million was allocated for habitat improvement projects, of which $2.2 million went to spawning habitat enhancement projects on the Sacramento River, and $1.2 million went to spawning habitat enhancement projects on the Merced, Tuolumne, and Stanislaus Rivers.

Our review of project documents showed that the riffle reconstruction projects have been planned and designed without recognition of the geomorphic and ecological effects of upstream

dams, which have modified flows and eliminated the supply of gravel from upstream, and gravel mining, which has left large pits in the river, trapping gravel and inducing channel downcutting, and also providing habitat for largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*), principal predators of juvenile salmon. The agencies conducting the environmental review and issuing permits for these projects also did not recognize these effects.

The riffle reconstruction projects involved excavation of the irregular pre-project river bed and back-filling with imported gravels of a size deemed suitable for salmon spawning to create a flat channel cross section over which the designers expected suitable water depths and velocities to occur during the controlled releases in the fall spawning season. No analyses were conducted to determine whether the projects would remain stable during the higher flows that occur during other seasons in most years. It was generally assumed the projects would remain stable. However, application of a tractive force equation predicts that these imported gravels should be mobile at the higher flows experienced most years. Our survey of three reconstructed riffles shows that the bed had eroded and gravels washed away within 1 to 4 years of project construction. In some places, the channel bed is now lower than it was before the projects, implying that the projects have not simply failed to improve spawning habitat, but may have made it less suitable in places. These projects failed because their design approach was limited temporally and spatially, focusing only on the site without recognizing the larger context, and taking a short-term "snapshot" view without analyzing historical changes or projecting future changes at the site. Moreover, by replacing the undulating natural bed topography with a flat bed, the projects eliminate the morphologic features that help produce intragravel flow, an important attribute of natural spawning beds.

The only assessments of project performance, other than this study , have been the annual counts of redds (spawning nests) conducted by the Department of Fish and Game as a continuation of an ongoing program, and the monitoring of vegetation plantings at one project site. Redd counts show that actual spawning usage of the constructed riffles has been 10% of that predicted by the project proponents. Although useful, redd counts are an imperfect measure of project performance because spawning usage reflects a host of other factors (such as upstream passage, downstream flow conditions, marine conditions, and commercial harvest) unrelated to physical habitat at the site. Assessment of project performance should include objective documentation of the variables the project is designed to modify, such as channel depth and bed material size, which can be measured through channel surveys and bed material sampling.

Despite explicit language in the Four Pumps Agreement calling for reviews of project performance, no such reviews had been conducted as of 1995. Permitting agencies have not required post-project evaluations, with the exception of vegetation surveys at one site. In the absence of objective, post-project evaluation, lessons have not been learned from the projects already constructed.

The decision to fund any spawning habitat reconstruction projects in the San Joaquin River system appears inconsistent with previous agency statements about the factors limiting salmon populations. The Department of Fish and Game (CDFG 1987) has stated that spawning habitat was *not* limiting salmon populations in the San Joaquin River system, and the Department of Water Resources (CDWR 1994b) has concluded that gravels in these rivers were generally of good quality for salmon spawning. The factors found to limit salmon populations in these rivers include low instream flows, high water temperature, reversed flows in the Delta (drawing juveniles into large diversion pumps), loss of fish into unscreened agricultural diversions, predation (especially by warm-water fish species), and lack of rearing habitat.

Given the precarious position of the remnant salmon populations in the San Joaquin River system and the considerable funds intended for future restoration actions, it is important that our future efforts be informed by the experience of early projects and result in benefits to the salmon. Accordingly, we recommend that funds provided for restoration efforts address the factors actually limiting salmon populations, that uncertainties in the habitat requirements of Central Valley salmon stocks be recognized and addressed through targeted research, that objective evaluation of project performance be an integral part of every project so that we can learn from our experience, and that the considerable allocation of funding for striped bass production under the Four Pumps Agreement be reconsidered in light of the serious condition of the salmon and the predation on salmon by the striped bass.

We also recommend that if channel modification projects are to be undertaken, their design should be based on a sound understanding of the site's larger geomorphic context, which requires a historical geomorphic study, and analysis of potential sediment transport at the site. Evaluation of project performance should include documentation of physical channel conditions which are directly modified by the project in addition to measures of biological use.

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Chapter 1. Introduction

THE SAN JOAQUIN RIVER BASIN

The San Joaquin River drains 35,058 km^2 (13,537 mi^2) along the western flank of the Sierra Nevada Mountains and the eastern flank of the Coast Range in central California, flows northward through the Central Valley to its confluence with the Sacramento River in the Sacramento-San Joaquin Delta, which then flows westward through the San Francisco Bay to the Pacific Ocean (figure 1). Most of the discharge in this basin derives from the Sierra Nevada Mountains, in the eastern part of the catchment, whose upper elevations are forested by conifers and underlain by Mesozoic granitic rocks. At the Sierra's lower elevations, the foothills are vegetated by oak woodland and grassland and are underlain by Paleozoic marine metasedimentary and metavolcanic rocks. The valley floor is underlain by Quaternary alluvial deposits. On the western side of the catchment, several small, intermittent streams drain the Coast Range but rarely reach the San Joaquin River because of the paucity of precipitation on this flank of the Coast Range.

In this report, the San Joaquin River Basin refers to the San Joaquin River and its tributaries. It is bounded by the Sierra Nevada Range to the east, the Coast Range to the west, the Sacramento-San Joaquin River Delta to the north, and the Tulare Basin drainage divide to the south. The San Joaquin River Basin experiences a Mediterranean climate, with wet winters and dry summers. Approximately ninety percent of the annual precipitation falls between November and April. Precipitation, which is orographically controlled, is predominantly snow at high elevations (above 1200 m) of the Sierra Nevada Range, and rain in the middle and lower elevations of the Sierra Nevada and in the Coast Ranges. Prior to the construction of dams in the river basin, the San Joaquin River and its eastern tributaries experienced rain-generated high flows between October and March and sustained, snowmelt-generated high flows throughout the spring and early summer.

The Sacramento and San Joaquin Rivers and the Sacramento-San Joaquin Delta have been extensively modified by the development of water resources, in-channel mining, and land use practices. Together, these modifications have caused significant loss of ecological resources, as evidenced by the severe declines in salmon populations this century. In response to these declines, state and federal agencies have begun large-scale efforts to rehabilitate salmon habitat.

EXTENT AND EFFECTS OF DAMS AND DIVERSIONS

The rivers of the San Joaquin River Basin have been extensively dammed, as illustrated in a plot of large reservoirs by elevation (figure 2). The mainstem San Joaquin River and its principal tributaries have experienced flow diversions for irrigation since the turn of the century,

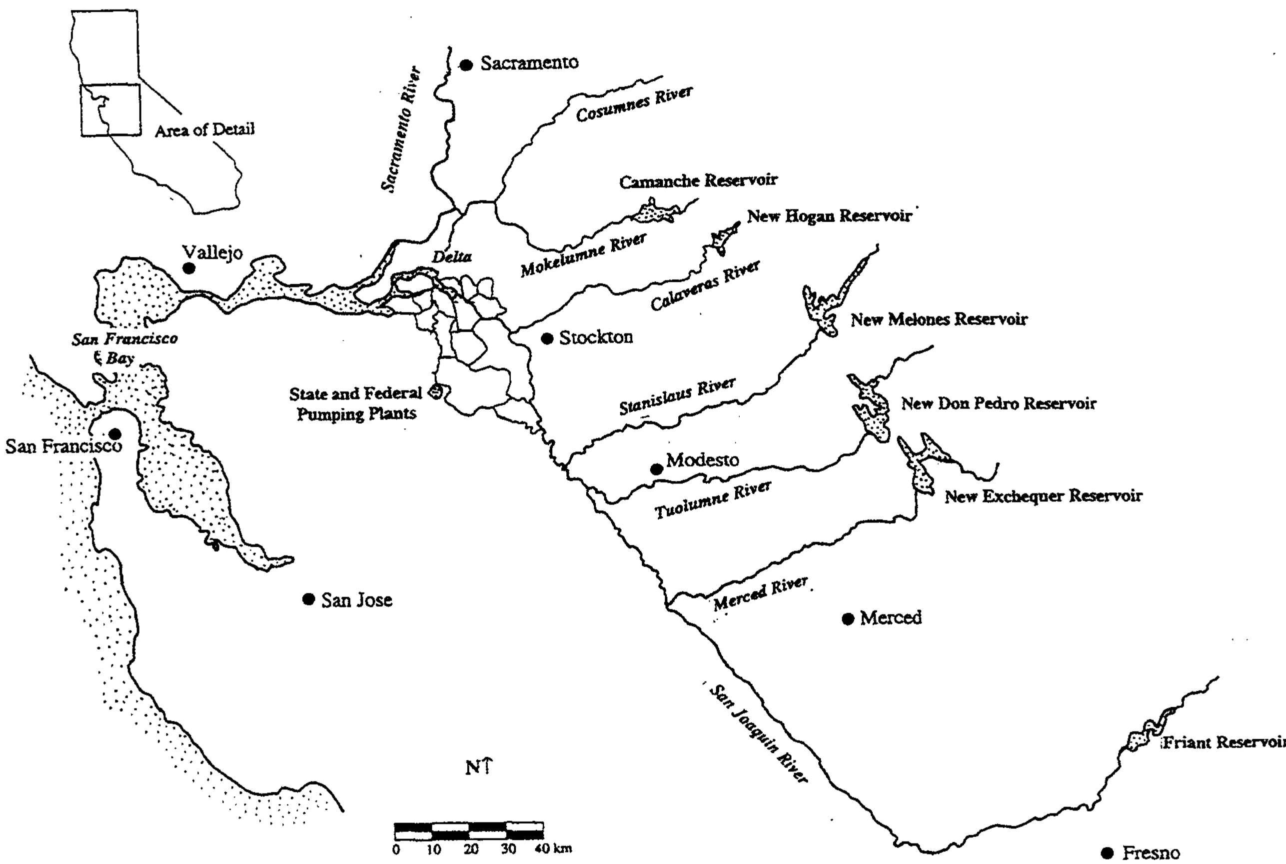

Figure 1. Map of the Stanislaus, Tuolumne, and Merced rivers in the context of the San Joaquin River basin and the San Francisco Bay-Delta system.

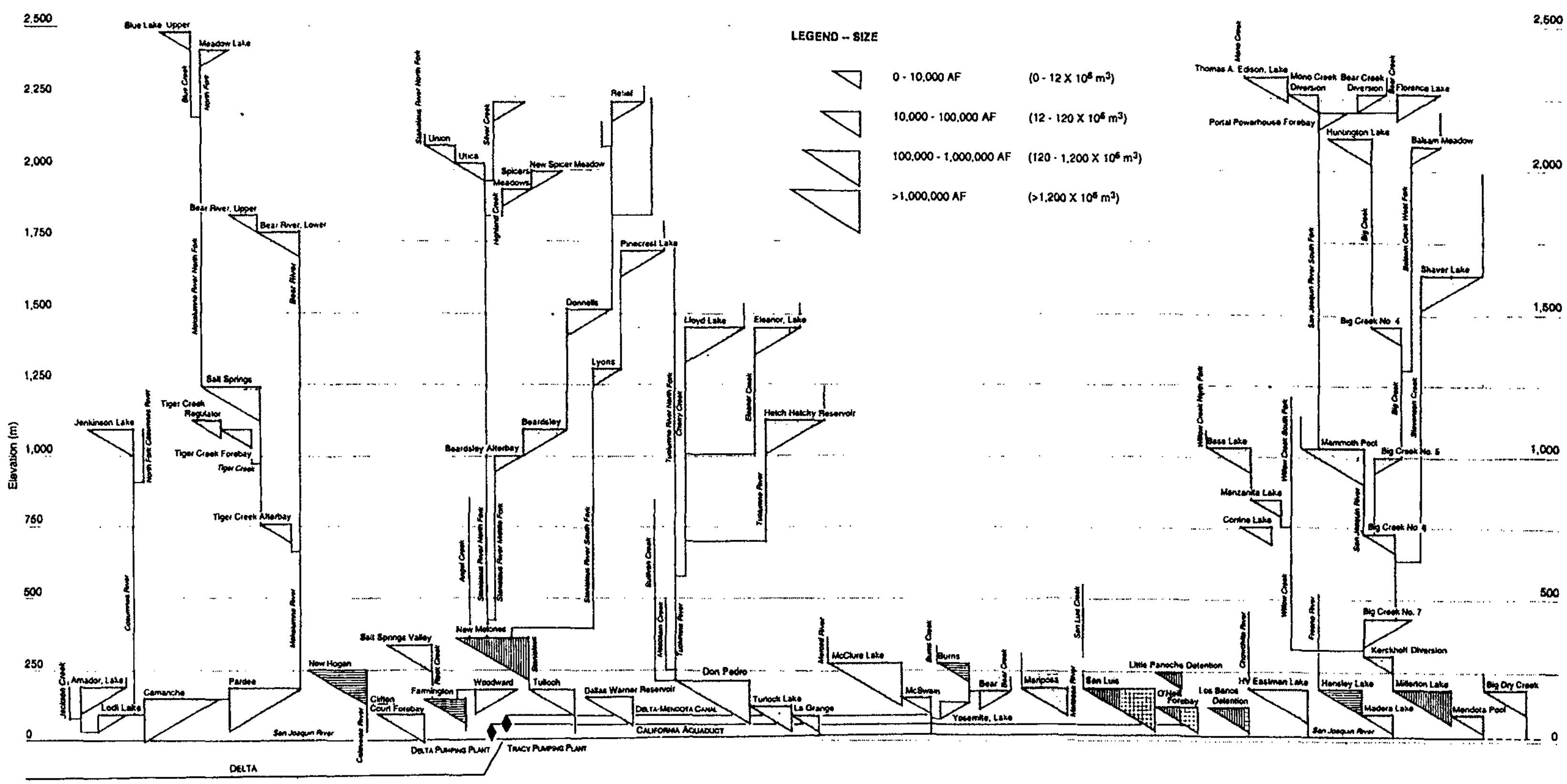

Figure 2 Schematic diagram of reservoirs in the San Joaquin River system and southern Sierra Nevada. Key to ownership: vertical lines, U.S. Bureau of Reclamation; horizontal lines, U.S. Army Corps of Engineers; cross-hatched, California Department of Water Resources; gray shading, water districts, municipalities, and utilities. (adapted from a prepared by the California State Water Resources Control Board, Graphic Unit)

with large reservoir construction in 1923-1926, and substantial increases in reservoir capacity in 1967-1979 (table 1). On the San Joaquin River and tributaries, there are now 82 dams large enough to fall under the jurisdiction of the California Department of Water Resources (CDWR) Division of Safety of Dams[1] (table 2). There are also many smaller dams, most of which are diversion structures. Kondolf and Matthews (1993) counted twelve of these smaller diversion dams in the Stanislaus River Basin, in addition to 28 larger dams (table 2). The dams affect geomorphic and ecological processes within the basin by reducing peak flows, altering seasonal flow patterns, and intercepting bed material transported from the upper watershed. Together, dams control runoff and intercept bed material from more than 40% of the total San Joaquin River Basin.

In the Sacramento-San Joaquin Delta, two major distribution systems export water to service areas to the south. The Central Valley Project, administered by the U.S. Bureau of Reclamation, diverts flows at the Tracy Pumping Plant into the Delta-Mendota Canal. The State Water Project, administered by the CDWR, diverts flows at the Harvey O. Banks Delta Pumping Plant into the California Aqueduct. As of 1975, diversions into these two systems measured 5,900 million m^3 (4.8 million acre-feet) annually, with annual diversions projected to total over 8,100 million m^3 (6.6 million acre-feet) by the year 2000 (SWRCB 1990). In addition to these major diversions, 1,600 small diversions have been identified in the Sacramento-San Joaquin Delta (SWRCB 1990).

The large-scale diversion of flows affects Delta hydrology and ecosystem function by reducing the flow of freshwater into the Delta from the Sacramento and San Joaquin Rivers and by causing flows to periodically reverse from their normal downstream direction during periods of low freshwater inflow. The Delta experiences tidally driven flow reversals twice daily. Under natural conditions, net flow was always downstream toward San Francisco Bay, but when the diversion pumps are operating at a high rate and inflow from the Sacramento and San Joaquin Rivers is low, flows in parts of the Delta reverse and net flow is upstream toward the pumps. This reversal draws saline water from San Francisco Bay up the Delta's channels (increasing salinity in parts of the Delta) and disorients juvenile salmon in their migration toward San Francisco Bay, leading large numbers of young fish to the pumping plant (SWRCB 1990).

EXTENT AND EFFECTS OF AGGREGATE MINING

Downstream of the dams, the river channels and floodplains of the San Joaquin River Basin have been excavated extensively to produce sand and gravel for construction aggregate. The removal of bed material by in-channel mining coupled with the reduction of sediment supply

[1] Dams over 7.6 m (25 ft) in height or impounding more than 61,700m^3 (50 acre-feet)

Table 1
Major Downstream Dams of the San Joaquin Basin

River	Dam (reservoir name)	Date	Drainage area above dam (km^2)	Capacity ($10^6 m^3$)	Reservoir capacity as % of annual runoff
San Joaquin mainstem	Friant (Millerton Lake)	1942	4,341	642	29
Stanislaus	Melones	1926	2,784	139	10
	New Melones	1979	2,784	2,960	216
Tuolumne	Don Pedro	1923	4,880	308	24
	New Don Pedro	1971	4,880	2,504	114
Merced	Exchequer	1926	3,297	347	28
	New Exchequer (Lake McLure)	1967	3,297	1,273	100

source: CDWR 1984, USGS 1989

Table 2
Mainstem and Tributary Dams in the Stanislaus, Tuolumne, Merced, and San Joaquin Rivers

River Basin	Number of DSD[1] reservoirs in the basin	Number of non-DSD reservoirs in the basin	Total reservoir capacity in basin ($10^6 m^3$)	Percent of Basin Controlled by Dams
Stanislaus	28	12	3,542	90.3
Tuolumne	27	NR	3,343	81.8
Merced	8	NR	1,288	81.7
San Joaquin	19	NR	1,415	NA

adapted from Kondolf and Matthews 1993

[1]Division of Safety of Dams
NR = not reported by Kondolf and Matthews 1993
NA = not applicable

due to the trapping of sediment behind the dams has created huge sediment deficits in the mined reaches of the rivers. Lacking adequate bed material supply, the rivers have no mechanism to recover their pre-mining channel morphology.

Aggregate mining involves excavation of the active river channel or of the adjacent river terrace creating large pits. These pits are separated from the active river channel by a narrow, unengineered berm, which often fail, resulting in incorporation of the pits into the active channel. Excavated pits in the active channel have significant effects on physical and biological processes in the river. Physically, the pits trap sediment (inhibiting downstream transport of bed material and wash load) and create nickpoints in the channel bed that may migrate upstream, inducing channel incision downstream and upstream of the pit (see Chapter Two). Biologically, the pits create large, warm, lake-like zones in the active river channel that provide habitat for introduced species, such as largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*), which prey on native fish (Reynolds et al. 1993; EA 1992). In addition, the steamflow velocity in these pits is near zero, and may be disorienting for which depend on streamflows for navigation during migration. Adult salmon migrating upstream and juveniles migrating downstream are increasingly vulnerable to predation and temperature-induced physiological stress as a result of the altered habitat created by the pits.

SALMON IN THE SAN JOAQUIN RIVER SYSTEM

The large-scale modifications to channel hydrology, sediment supply, and sediment transport resulting from water resource development projects and in-channel mining have caused ecological degradation throughout the San Joaquin River Basin. Declines in chinook salmon (*Oncorhychus tshawytscha*) populations provide a general indicator of this loss. Historically, the San Joaquin River and its principal tributaries supported spring and fall runs of chinook salmon that numbered in the hundreds of thousands (Reynolds et al. 1993). Spring-run chinook adults migrated upstream in the spring and remained in the rivers over the summer until they spawned in the fall. Fall-run adults migrated upstream in the fall and spawned from October through December; fry emerged in early spring, developed into smolts, and migrated ocean-ward between April and June.

The spring run, once the most abundant race of chinook salmon in the San Joaquin River Basin, was eliminated from the Stanislaus, Tuolumne, and Merced Rivers by 1930 as a result of dam construction, which eliminated access to upstream spawning grounds and cold-water holding areas. The remaining spring-run population was eliminated from the San Joaquin River in 1950 by closure of the Friant Dam (Skinner 1962). The fall-run still occurs in the three major tributaries though it has been eliminated from the San Joaquin River mainstem upstream of the confluence with the Merced River. Despite hatchery production at the Merced River Fish

Facility, fall-run escapement levels are critically low, with only 1,250 and 2,627 adults returning to the tributaries in 1992 and 1993, respectively (CDFG 1995).

Downstream of the dams, in the reaches still available to the fall-run salmon, spawning and rearing habitats have been degraded by the elimination of bed material supply and armoring of the bed with material that is too coarse for spawning (CDWR 1994b). Rearing habitat also has been lost or degraded by increased water temperatures; clearance of bank vegetation and filling of side channels, sloughs, and other floodplain aquatic habitats for agriculture; loss of channel area and channel complexity due to channel change downstream of the dams; and by the creation of deep in-channel pits by aggregate mining (Reynolds et al. 1993). Although no figures are available specific to the San Joaquin River Basin, the California Department of Fish and Game (CDFG) estimates that 95% of the spawning and rearing habitat in the Sacramento-San Joaquin system has been lost since 1850 (Reynolds et al. 1993).

The ability of salmon to migrate and reproduce is hindered further by flow other alterations. Many adult salmon migrating upstream in the San Joaquin River or its tributaries are attracted by the large discharges from canals that carry agricultural return flows to the rivers. The CDFG estimates that 31% of the 1991 San Joaquin River Basin chinook salmon run was lost to straying up agricultural return flow canals. The fish swim up and perish in the canals without reproducing because these canals have no spawning habitat. Adult and juvenile salmon are also entrained (pulled by strong currents) into unscreened agricultural diversions. The CDFG has identified 148 small diversions on the Stanislaus, Tuolumne, and Merced Rivers, none of which are adequately screened; losses are believed to be significant, but the number of fish entrained in these diversions has not been measured (Reynolds et al. 1993).

In the Delta, large-scale flow diversions affect chinook salmon by reducing instream flows, causing periodic flow reversals, and entraining fish into the diversion system. In an attempt to mitigate fish loss at the Harvey O. Banks Delta Pumping Plant, the CDWR conducts a trap-and-truck salvage operation in which fish are captured in the Clifton Court Forebay at the Skinner Fish Facility and transported by truck to other parts of the Delta, where they are released. Despite this program, fish are still killed at the pumps due to poor screen efficiency for small fish, increased predator efficiency in the Clifton Court Forebay, and stress and injury incurred during the salvage operation (CDWR and CDFG 1986).

FACTORS LIMITING SALMON POPULATIONS IN THE SAN JOAQUIN RIVER BASIN

Because chinook salmon have been affected by many human influences, the relative contribution of various factors in the decline of salmon populations must be understood as a basis for devising effective strategies to restore these fish and the ecosystem of which they are an integral part. The chinook salmon is an anadromous fish, having a complex life cycle and dependent on a variety of physical habitats for survival. Populations are affected by availability of spawning habitat, fishing pressure, impediments to passage, availability and quality of downstream rearing habitat, predation, conditions in the marine environment, streamflows and water temperature. A *limiting factor* analysis can be used to identify the life stages of the fish at which populations are limited and the causes of that limitation. Based on the analysis, actions necessary to correct the limiting conditions can be identified. For example, it would yield little benefit to enhance rearing habitat and passage if populations were limited by lack of spawning habitat, which would result in inadequate numbers of juveniles to populate the rearing habitat or take advantage of the improvements in passage.

The CDFG has determined that the factors limiting salmon populations in the San Joaquin River Basin are inadequate streamflows, elevated water temperatures, losses to unscreened diversions, losses at the state and federal pumping plants in the Delta, and predation (CDFG 1987, Reynolds et al. 1993). The single greatest problem cited by the CDFG is *inadequate streamflow*:

> "Under present conditions streamflow requirements for fall-run salmon below the major tributary reservoirs in this drainage are not adequate. All existing Licenses or Agreements fail to provide acceptable streamflow levels for young salmon emigrating to the ocean." (CDFG 1987:3)
>
> "In 1972 the Department of Fish and Game...concluded that *spring flows were the most important factor controlling the size of salmon populaion* in the Stanislaus River, with survival being proportional to flow...A similar relationship existed on the Tuolumne River...spring flows are still a key factor determining the number of adults produced in the San Joaquin River tributaries." (CDFG 1987:34) [emphasis added]
>
> "The number of San Joaquin drainage adult salmon produced is largely determined by the spring flows in the San Joaquin River...during the period young salmon emigrate to the ocean." (CDFG 1987:36)

High water temperatures, resulting from inadequate streamflows, are another significant factor limiting salmon populations.

> "Up to half the production of San Joaquin chinook salmon smolts can be subjected to high chronic thermal stress in the south Delta in most (62%) years when Vernalis flows are 5,000 cfs [140 m^3/s] or less." (CDFG 1987:29)

Predation on juvenile salmon is substantial, especially in artificially created habitats where introduced warm-water species thrive. The Clifton Court Forebay provides habitat for predators, whose ability to capture juvenile salmon is increased by the disorientation of the salmon upon entering the relatively quiet water of the Forebay. Predators tend to concentrate around artificial structures, such as dams, old bridge piers, and irrigation diversion structures

(SJRMPAC 1993). As described in chapter 2, abandoned gravel pits provide excellent habitat for warm-water predators. On the Tuolumne River, a 1987 study by CDFG estimated that nearly 70 percent of outmigrating smolts were lost to predation en route to the San Joaquin River (EA 1992).

Losses to unscreened diversions are believed to be large, especially among outmigrating juveniles, with over 148 unscreened diversions on the Merced, Tuolumne, and Stanislaus Rivers, but have never been measured. Similarly, over 30 percent of upstream migrating adult salmon in the San Joaquin River Basin stray up irrigation return canals, where they perish without reproducing (Reynolds et al. 1993).

Spawning habitat does not appear to be limiting salmon at present population levels, because the other factors in the system are limiting. In a study of the San Joaquin River Basin chinook salmon runs, the CDFG reported that spawning habitat was *not* limiting these salmon populations, stating that

> "[r]edd (or nest) overlap problems...were not documented...[t]he spawning adults were dispersed throughout the available spawning habitats...spawning area capacity does not appear to be the most important factor limiting recovery of escapements to near historic levels" (CDFG 1987:12).

This conclusion was subsequently supported by a field study conducted by the CDWR which concluded that gravel in Merced, Tuolumne, and Stanislaus Rivers was generally of good quality for spawning by chinook salmon (CDWR 1994b). If other limiting factors in the system are removed and larger numbers of adult spawners return to these streams, or if the area of available spawning gravels decreases, spawning habitat may become a limiting factor.

Based on the above analysis, it is clear that the factors now limiting salmon populations in the San Joaquin River Basin include inadequate streamflow, water temperature, predation, and losses to unscreened diversions. Spawning habitat is *not* limiting salmon populations at present.

EFFORTS TO RESTORE SALMON POPULATIONS

In recent years, federal and state agencies have recognized the severity of salmon population declines in the Central Valley and have begun to fund and implement habitat restoration efforts with primary focus on the improvement of salmonid population levels. At least thirteen state and federal actions have funded or continue to fund salmon rehabilitation in the state. Funding actions include the Fish and Game Preservation Fund; Commercial Stamp Act; Steelhead Catch and Restoration Card; Public Resources Account (Proposition 99); California Wildlife, Coastal and Park Land Conservation Fund of 1988 (Proposition 99); Boscoe-Keene Renewable Resources Restoration Fund; Keene-Nielson Fisheries Restoration Account; Davis-Grunsky Act; Federal Aid in Sport Fish Restoration Act; Bureau of Reclamation's Agreement to Reduce and Offset Direct Fish Losses Associated with the Operation of the Tracy Pumping Plant and Tracy Fish Collection Facility; Central Valley Project Improvement Act; Four Pumps Agreement;[2] and Category III of the Bay-Delta Accord (Reynolds et al. 1993). Several of these programs are slated to continue well into the future with additional expenditures.

The most recent habitat rehabilitation projects completed in the San Joaquin River Basin emerged from the Four Pumps Agreement. Signed in 1986, the Four Pumps Agreement (CDWR and CDFG 1986) provides funds to offset the direct losses of chinook salmon, steelhead (*Oncorhynchus mykiss*), and striped bass (*Morone saxatilis*) caused by the large flow diversion at the Harvey O. Banks Pumping Plant in the Sacramento-San Joaquin Delta, a component of the State Water Project. Administered by the CDWR, the agreement provides an annual fund as well as a $15 million lump sum fund to compensate for continued losses of fish.

Between 1986 and 1995, the Four Pumps program approved $9.1 million for projects to increase chinook salmon production in the San Joaquin Valley (table 3). All projects were designed and constructed by the CDWR under the auspices of CDFG. $2.5 million (27%) was allocated for physical habitat rehabilitation, $1 million of which was spent on spawning riffle rehabilitation projects and a large-scale channel reconstruction project. The riffle rehabilitation projects involved excavating the existing channel bed, installing boulder grade control and gravel retaining structures, and backfilling the site with gravel of a size deemed suitable for spawning use while achieving bed slope, flow depth, and flow velocity deemed optimal for chinook salmon spawning. The channel reconstruction project was a large-scale effort to enhance spawning and rearing habitat at the Ruddy Site on the Tuolumne River. This project involved the realignment 0.9 km (2,900 ft) of river channel to create a broader, less sinuous channel flanked by a floodplain low enough to be inundated under the river's present flow regime.

---

[2]The Four Pumps Agreement is officially titled, "Delta Pumping Plant Fish Protection Agreement between the California Department of Water Resources and the California Department of Fish and Game, 1986"

Table 3
Projects Approved for Funding under the Four Pumps Program to Increase Chinook Salmon Production in the San Joaquin Valley, 1986-1995

Projects[1]	**Date approved**	**Allocated funds ($)**	**habitat change[2]?**
ANNUAL FUND PROJECTS			
Merced River Fish Facility Modernization	January 1989	922,500	N
Merced River Gravel Phases I and II [1]	June 1989	136,000	Y
Merced River Gravel Phase II [1]	June 1989 reauthorized January 1991	194,000	Y
Tuolumne River, M.J. Ruddy Site[1]	January 1991	334,000	Y
San Joaquin River Fish Barrier I	July 1992	67,600	N
Tuolumne River, LaGrange Site[1]	September 1992	176,400	Y
Stanislaus River Gravel, River Miles 47.4, 50.4, and 50.9[1]	December 1992	176,200	Y
San Joaquin River Fish Barrier II	August 1993	37,000	N
Merced River Fish Facility Emergency Equipment	December 1994	60,000	N
San Joaquin River Fish Barrier III	January 1995	916,890	N
Tuolumne River, Reed Site[1]	March 1995	133,650	Y
Merced River, Magneson Site	September 1995	361,100	Y
LUMP SUM FUND PROJECTS			
Merced River Water Hyacinth	April 1990	25,000	Y
Tuolumne River Hatchery Appraisal	July 1994	20,000	N
Tuolumne River Salmon Restoration Center	December 1994	4,500,000	N
San Joaquin River Predator Isolation Projects	December 1994	1,000,000	Y
	1986-1995 total	9,060,340	
	1986-1995 total for projects resulting in changes to physical habitat	2,536,350	

source: CDFG Mitigation Fund Expenditures (1994 unpublished report)

[1]Gravel rehabilitation projects
[2]Indicates whether project involved change to physical habitat; y=yes, n=no

PURPOSE AND ORGANIZATION OF THE REPORT

To date, approximately $2.5 million has been spent on spawning habitat rehabilitation in the San Joaquin River Basin under the Four Pumps Agreement. Additional funds are slated to be expended in the future. The purpose of this study is to assess the project implemented under the Agreement with respect to their conformance with the stated goals. In addition, this report provides an assessment of the physical performance of three riffle reconstruction projects constructed to date. Finally, based on our findings we make recommendations for improving habitat rehabilitation project selection, planning, design, and assessment.

In 1994, when the research described in this report was initiated, the CDWR and CDFG had yet to conduct a systematic evaluation of the performance of the habitat rehabilitation projects, and similar additional projects were being proposed based on the assumption that the completed projects were performing adequately. Over the course of our study, the CDWR and CDFG have become more sensitive to the importance of projects performance and evaluation. In the fall of 1995, CDWR initiated a field survey of the Merced River Riffle 1B project to evaluate physical changes to the project resulting from the high flows of 1995. The most recent round of project proposals received more rigorous in-house agency review, and the proposals themselves have included more rigorous, quantitative analysis. By providing an objective, third party review of project planning, environmental review, and actual project performance from 1986 to 1995, we hope that this report will contribute to increased effectiveness of efforts to restore salmon populations in the San Joaquin River system.

This report is organized as follows: Chapter Two briefly reviews the effects of dams and aggregate mining on river systems; Chapter Three discusses the details of the Four Pumps Agreement, how its funds have been allocated, and the requirement for review of project performance; Chapter Four describes the planning and design process for the spawning habitat rehabilitation projects completed to date; Chapter Five describes the environmental reviews, as required by the National Environmental Policy Act and the California Environmental Quality Act, conducted for each of the spawning habitat rehabilitation projects; Chapter Six provides a geomorphic analysis of the performance of the Riffle 1B reconstruction on the Merced River; Chapter Seven provides geomorphic analyses of the performance of the Riffle 1B reconstruction on the Tuolumne River and the Riffle RM 50.4 reconstruction on the Stanislaus River; Chapter Eight presents a historical geomorphic analysis for the Lower Merced River, illustrating the kinds of information that should be taken into account in planning habitat rehabilitation projects; and Chapter Nine presents the conclusions of this report and recommendations for improving habitat rehabilitation planning and design.

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Chapter 2. Geomorphic Effects of Dams and Aggregate Mining on Rivers

As water flows from high elevation to sea level, its potential energy is converted to other forms as it sculpts the landscape, developing complex channel networks and a variety of associated habitats. In natural channels, the excess energy of rivers is dissipated in many ways: in turbulence at steps in the river profile; in the frictional resistance of cobbles and boulders and vegetation along the bank; in bends; in irregularities of the channel bed and banks; and in sediment transport. An understanding of the transport of sand- and gravel-sized sediment by rivers, and the response of river channels to a reduction in the supply of these sediments, is crucial to understanding the effect of dams and aggregate mining.

SEDIMENT IN RIVER SYSTEMS

The terms "sediment" and "sedimentation" are often viewed negatively because to non-geologists they may connote *fine sediment.* However, the term *sediment* encompasses particles ranging in size from clay (<0.0039 mm) to boulders (>256 mm) (Vanoni 1975). Gravel and cobble-sized sediment has tremendous ecological importance, as habitat for benthic macroinvertebrates, and as spawning habitat for salmon and trout (Kondolf and Wolman 1993).

Sediment is transported as *suspended load* (clay, silt, and sand held aloft in the water column by turbulence), *bedload* (sand and gravel moving by rolling, sliding, and bouncing along the bed), and as *dissolved load* (products of chemical weathering of rocks carried in solution) (Leopold et al. 1964). Most sediment is carried as suspended load, with bedload ranging from a few percent in lowland rivers to perhaps 15% in mountain rivers (Collins and Dunne 1990) to over 60% in some arid catchments (Schick and Lekach 1993). Although a relatively small part of the total sediment load, the arrangement of bedload sediments (sand and gravel) constitutes the architecture of sand- and gravel-bed channels.

The size of sediment grains mobilized and the amount of sediment that can be moved depend on the *shear stress* (the force per unit area) exerted on the bed by the flow, which is a function of water depth and channel gradient (Leopold et al. 1964). The rate of sediment transport typically increases as a power function of flow; that is, a doubling of flow typically produces more than a doubling in sediment transport (Richards 1982), and most sediment transport occurs during floods.

The sediment transported by rivers consists of the soil and rock fragments eroded from the watershed (catchment or drainage basin). The amount of sediment transported from a watershed (its *sediment yield*) can be used to compute the rate at which the landscape is being lowered by erosion (the *denudation rate*) and is governed by precipitation and runoff characteristics, rock and soil resistance to erosion, basin topography, and land cover (Knighton

1984). Denudation rates range widely. The Appalachian Mountains of North America are being denuded about 0.01 mm per year (Leopold et al. 1964), the steep, rapidly uplifting Southern Alps of New Zealand about 11 mm per year (Griffiths and McSaveney 1983), and the rapidly uplifting southern Central Range of Taiwan over 20 mm per year (Hwang 1994). The central and southern Sierra Nevada have relatively low denudation rates of about 0.1 mm per year or less, based on sedimentation rates in Don Pedro and Lake McClure reservoirs in the 1920s through 1940s (Kondolf and Matthews 1993). These low denudation rates reflect the glaciated granitic bedrock underlying much of the range, although denudation rates are probably higher now because of substantial increases in timber harvest, road construction, and other land uses in these watersheds.

CONTINUITY OF SEDIMENT TRANSPORT IN RIVER SYSTEMS

The idealized watershed can be divided into three zones: that of *erosion* or sediment production (steep, rapidly eroding headwaters), *transport* (through which sediment is moved more or less without net gain or loss), and *deposition* (Schumm 1977) (figure 3). The steep, upper watershed can be viewed as a sediment "factory" and the river channel as a "conveyor belt", which transports the erosional products downstream to the ultimate depositional sites below sea level. The size of sediment typically changes along the length of the river system from gravel, cobbles, and boulders in steep upper reaches to sands and silts in low gradient downstream reaches, reflecting diminution in size by weathering and abrasion, as well as sorting of sizes by flowing water.

Continuity is an important feature of the transport of sediment through the watershed and along the length of the river system. Land use changes producing increased sediment supply in upper reaches of the watershed may have profound consequences for the river environment many miles downstream (and for years or decades) as the increased sediment loads propagate downstream through the river network. This effect is illustrated in Redwood National Park, California, where the world's tallest trees are threatened with bank erosion caused by channel aggradation (building up of sediment in the channel), which in turn was caused by clear-cutting of timber on steep slopes in the upper part of the watershed (Madej in press; Janda 1978).

Along the river channel "conveyor belt", river forms (such as gravel bars) may appear stable, but the grains of which they are composed may be replaced annually or biannually by new sediment from upstream. Similarly, the sediments that make up the river *floodplain* (the valley flat adjacent to the channel) are typically mobile on a time scale of decades or centuries. The floodplain acts as a storage reservoir for sediments transported in the channel, alternately storing sediments, by deposition, and releasing sediment to the channel, by bank erosion. Thus, the river channel and floodplain are dynamic features that constitute a single hydrologic and geomorphic

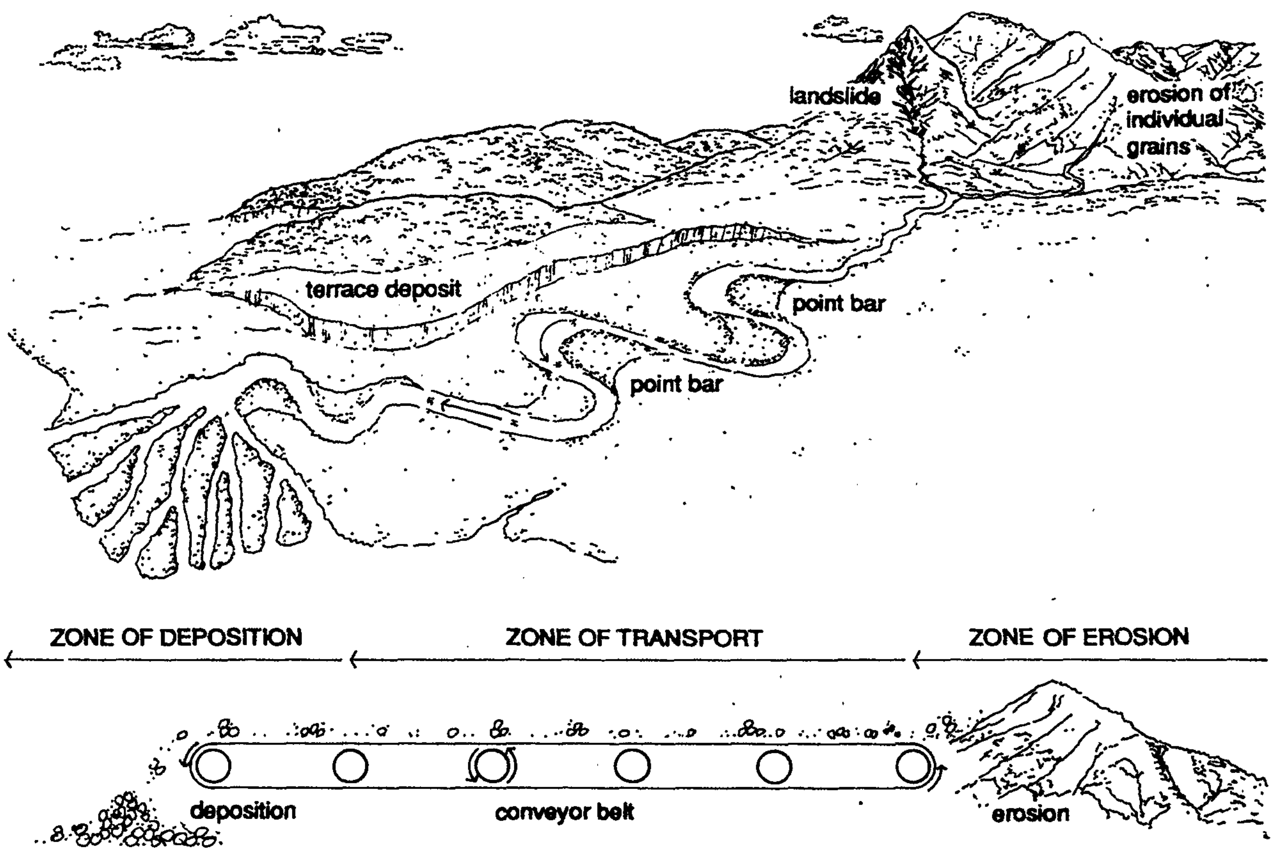

Figure 3. Zones of erosion, transport, and deposition, and the river channel as conveyor belt for sediment.

unit, characterized by frequent transfers of water and sediment between the two components. For example, the Carmel River in Monterey County, California, is flanked by alluvial terraces, the lowest of which originated as a wide channel of sand and gravel deposited by a large flood in 1911 and that now stands about 4 m above the present channel (Kondolf and Curry 1986). By 1960, the terrace had been subdivided and developed with low density housing, in apparent disregard of the recent origin of the land and of the potential for future shifts in channel position.

EFFECTS OF DAMS

Dams and diversions are constructed and operated for a wide variety of purposes including residential, commercial and agricultural water supply, flood and/or debris control, and hydropower production. Regardless of their purpose, all dams trap sediment to some degree and most alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers. To understand the nature of these changes, it is helpful to consider how dams change flow regime and sediment load, the independent variables that control the geometry of *alluvial channels* (channels in erodible alluvium, or river deposits). Changes in these variables will produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads.

Dams disrupt the longitudinal continuity of the river system and interrupt the action of the "conveyor belt" of sediment transport. Upstream of the dam, all bedload sediment and all or part of the suspended load (depending upon the reservoir capacity relative to inflow) (Brune 1953) is deposited in the quiet water of the reservoir, reducing reservoir capacity. Downstream, water released from the dam possesses the energy to move sediment, but has no (or reduced) sediment load. This "clear water" released from the dam is often referred to as *hungry water*, because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction, resulting in incision (downcutting of the bed) and coarsening of the bed material. Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing channel narrowing, or allowing fine sediments to accumulate in the bed.

Channel Incision

The magnitude of incision depends upon the reservoir operation, channel characteristics, bed material size, the occurrence of bed material sources downstream of the dam, and the sequence of flood events following dam closure. Incision below dams is most pronounced in rivers with fine-grained bed materials and where reduction of flood peaks is relatively minor (Williams and Wolman 1984). The easily eroded sand bed channel of the Colorado River below Davis Dam, Arizona, has incised up to 6 m, despite substantial reductions in peak flows

(Williams and Wolman 1984). In contrast, the gravel-bedded Mokelumne River below Camanche Dam in California has experienced such a dramatic reduction in flood regime (and consequent reduction in sediment transport capacity) that no incision has been documented, and gravel is reported to have become compacted and immobile (FERC 1993).

Reduction in bedload sediment supply can induce a change in channel pattern, as occurred on Stony Creek, a tributary to the Sacramento River 200 km north of San Francisco. Since the closure of Black Butte Dam in 1963, the formerly braided channel has adopted a single thread meandering pattern, incised, and migrated laterally, eroding enough bedload sediment to compensate for about 20% of the bedload now trapped by Black Butte Dam on an annual average basis (Kondolf and Swanson 1993).

Bed Coarsening and Loss of Spawning Gravel

Channel erosion below dams is frequently accompanied by a change in particle size on the bed, as gravel and finer materials are winnowed from the bed and transported downstream, leaving a coarse *lag* deposit of large gravel, cobbles, or boulders, known as an *armor layer*. Development of the cobble-bed is an adjustment by the river to changed conditions because the larger particles are less easily mobilized by the hungry water flows below the dam. The armor layer may continue to coarsen until the material is no longer capable of being moved by the reservoir releases or spills, thereby limiting the ultimate depth of incision (Williams and Wolman 1984; Dietrich et al. 1989).

The increase in particle size can threaten the success of spawning by salmonids (salmon and trout), which use freshwater gravel to incubate their eggs. In spawning, the female uses abrupt upward jerks of her tail to excavate a small *pit* in the gravel bed, in which she deposits her eggs and the male releases his milt. The female then loosens gravel from the bed upstream to cover the eggs and fill the pit. The completed nests, or *redds*, constitute incubation environments with intragravel flow of water past the eggs and relative protection from predation. The size of gravel that can be moved to create a redd depends on the size of the fish, ranging in median diameter from about 15 mm for small trout to about 50 mm for large salmon (Kondolf and Wolman 1993).

Below dams, the bed may coarsen to such an extent that the fish can no longer move the gravel. The Upper Sacramento River, California, was once the site of extensive spawning by chinook salmon, but massive extraction of gravel from the river bed, combined with trapping of bedload sediment behind Shasta Dam and release of sediment-starved water, has resulted in coarsening of the bed such that spawning habitat has been virtually eliminated in the reach (Parfitt and Buer 1980). In extreme cases of bed coarsening, virtually all of the alluvial material is removed, leaving only boulders and bedrock, reducing habitat for aquatic invertebrates and juvenile fish (Erman and Erman 1984; Andrews 1986). The availability of spawning gravel can also be reduced by incision below dams when formerly submerged gravel beds are isolated as terrace or flood plain deposits. Encroaching vegetation can also stabilize banks and further reduce gravel recruitment for redds (Hazel et al. 1976).

Gravel Replenishment Below Dams

Gravel has been artificially added to enhance available spawning gravel supply below dams on at least 12 rivers in California besides the Merced, Tuolumne, and Stanislaus Rivers (Kondolf and Matthews 1993). The largest of these efforts is on the Upper Sacramento River, where from 1979 to 2000 over U.S.$ 22 million will have been spent on importation of gravel derived mostly from mines on tributaries (figure 4). While these projects can provide short-term habitat improvement, the amount of gravel added is but a small fraction of the bedload deficit below the dam, and gravel placed in the main river has typically washed out during high flows.

On the border between France and Germany, a series of hydroelectric dams was constructed on the River Rhine (progressing downstream) after 1950, the last of which (the Barrage Iffezheim) was completed in the 1970s. To address the sediment deficit problem downstream of Iffezheim, an annual average of 170,000 tonnes of gravel (the exact amount depending on the magnitude of the year's runoff) are added to the river (figures 5-7). This approach has proved successful in preventing further incision of the river bed downstream (Kuhl 1992). The quantity of gravel added each year is not equivalent to the unregulated sediment load of the Rhine, but satisfies the river's current capacity to transport sediment, which has been reduced because peak discharges have been reduced by reservoir regulation.

Sediment Sluicing and Pass-Through from Reservoirs

Sediment pass-through involves passing inflowing sediment through the reservoir through the dam outlets, and delivering sediment to downstream reaches in essentially the same concentration and seasonal pattern as prevailed in the pre-dam regime, thereby reestablishing the continuity of sediment transport. This approach was employed at the old Aswan Dam on the River Nile and on the Bhatgurk Reservoir on the Yeluard River in India (Stevens 1936). Similarly, on the River Inn in Austria and Germany, floodwaters with high suspended loads are passed through a series of hydropower reservoirs (Hack 1986, Westrich et al. 1992).

Sediment pass-through is most easily accomplished on small diversion dams (such as those used to divert water in run-of-the-river hydroelectric generating projects) in steep V-shaped canyons. With adequately sized low-level outlets, these small reservoirs (or forebays) can easily be drawn down so that the river's gradient and velocity are maintained through the dam at high flow and the reservoir behaves essentially as a reach of river.

Figure 4. Gravel replenishment to the Sacramento River below Keswick Dam. (Photograph by Kondolf, January 1991)

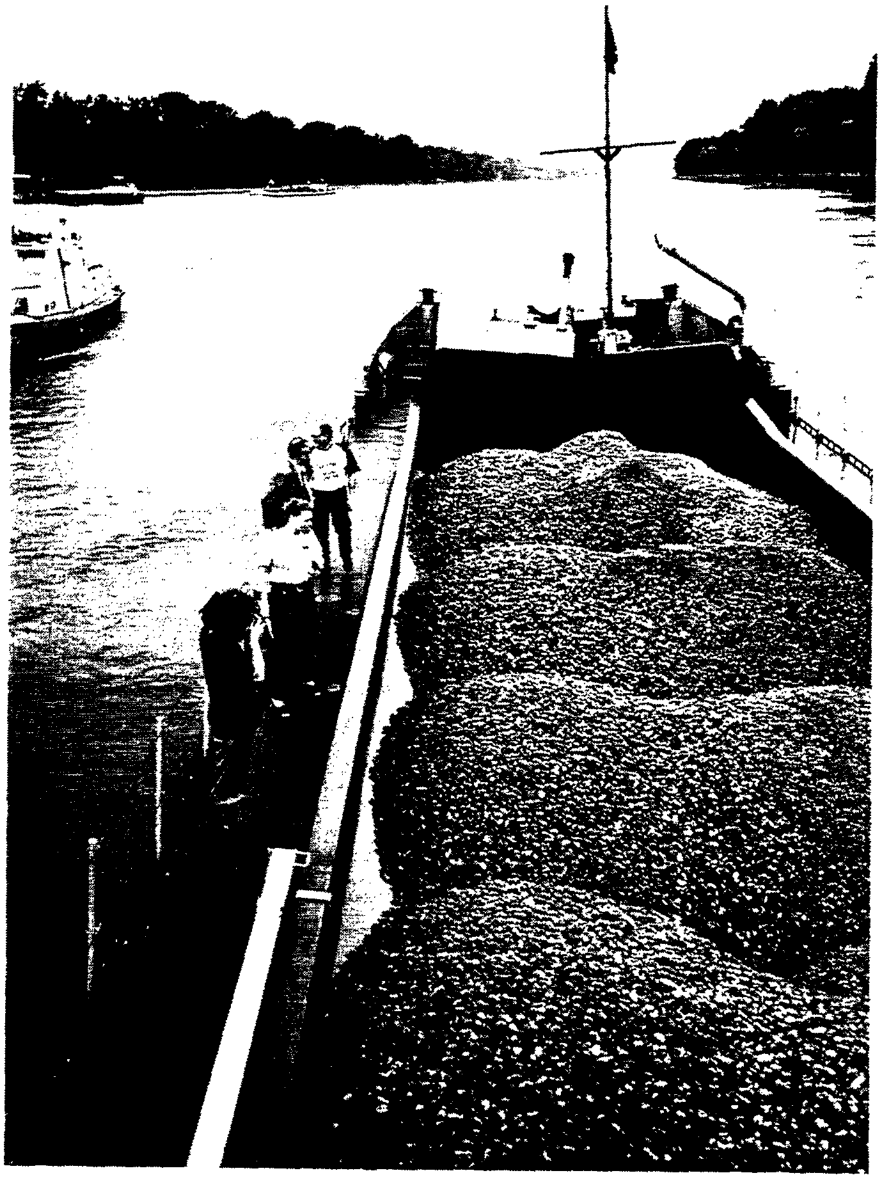

Figure 5. Artificial gravel feeding into the River Rhine downstream of the Barrage Iffezheim, showing the barge beginning to empty.

Figure 6. The barge, mostly empty, feeding gravel in to the River Rhine downstream of the Barrage Iffezheim.

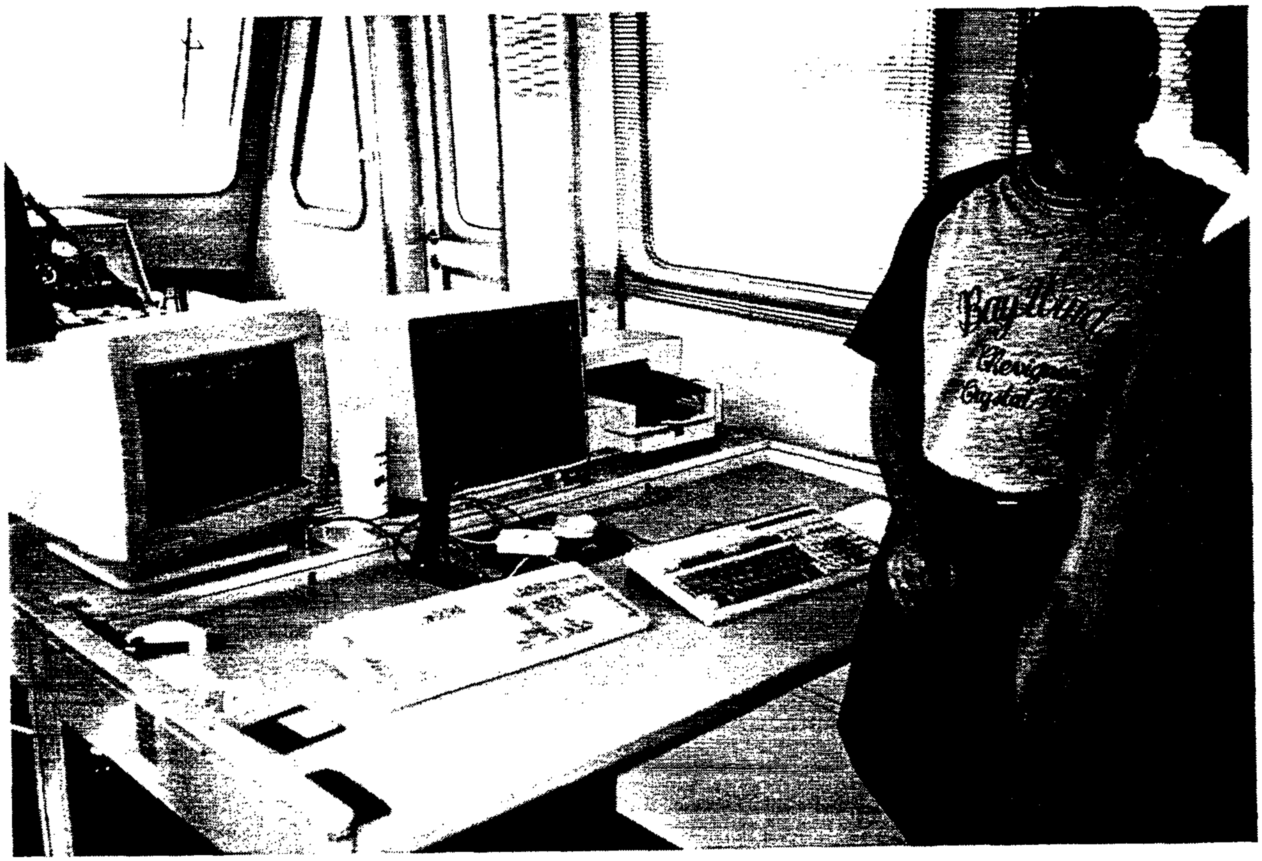

Figure 7. The pilot boat directing the barge to the location of the gravel dumping, in the River Rhine downstream of the Barrage Iffezheim. (Photograph by Kondolf, June 1994)

If sediment is permitted to accumulate in the reservoir and is subsequently discharged as a pulse (sediment *sluicing*), the abrupt increase in sediment load may alter substrate and aquatic habitat conditions downstream of the dam. The most severe effects are likely to occur when sediment accumulated over the flood season is discharged during baseflow (by opening the outlet pipe or sluice gates and permitting the reservoir to draw down sufficiently to resuspend sediment and move bedload), when the river's transporting capacity is inadequate to move the increased load. On the Kern River, Southern California Edison Company (an electric utility) obtained agency permission to sluice sand from Democrat Dam in 1986, anticipating that the sand would be washed from the channel the subsequent winter. However, several years of drought ensued, and the sand remained within the channel until high flows in 1992 (figure 8) (Dan Christenson, California Department of Fish and Game, Kernville, personal communication, 1992).

Channel Narrowing and Fine Sediment Accumulation Below Dams

While many reservoirs reduce flood peaks, the degree of reduction varies considerably depending on reservoir size and operation. The larger the reservoir capacity relative to river flow and the greater the flood pool available during a given flood, the greater the reduction in peak floods. Flood control reservoirs typically contain larger floods than reservoirs operated solely for water supply. Downstream of the reservoir, encroachment of riparian vegetation into parts of the active channel may occur in response to a reduction in annual flood scour and sediment deposition (Williams and Wolman 1984). Channel narrowing has been greatest below reservoirs with capacity to contain the large infrequent floods. In some cases, fine sediment delivered to the river channel by tributaries accumulates in spawning gravel because there are no more natural floods to flush the river bed clean.

On the Trinity River, California, construction of Trinity Dam in 1960, reduced the Q_2 (the peak flow occurring every two years on average) from 450 m^3/s (15,900 cfs) to 9 m^3/s (318 cfs). As a result of the dramatic change in flood regime, encroachment of vegetation and deposition of sediment has narrowed the channel to 20-60% of its pre-dam width (Wilcock et al. 1995). Accumulation of tributary-derived decomposed granitic sand in the bed of the Trinity River has led to decline of invertebrate and salmonid habitat (Fredericksen, Kamine and Associates 1980). Experimental, controlled releases were made in 1991, 1992, and 1993 to determine the flows required to "flush" the sand from the gravel (Wilcock et al. 1995). Additional experimental releases were made in 1995 and 1996. Such *flushing flows* increasingly have been proposed for reaches downstream of reservoirs to remove fine sediments accumulated on the bed and to scour the bed frequently enough to prevent encroachment of riparian vegetation and narrowing of the active channel (Kondolf and Wilcock 1996). In April 1996, a deliberate discharge was released

Figure 8. Sand deposited in the bed of the Kern River as a result of sluicing from Democrat Dam in 1986. (photograph by Kondolf, December 1990)

from Glen Canyon Dam in an attempt to scour sand from pools and deposit sand on marginal sand bars along the Colorado River in Grand Canyon National Park, Arizona.

AGGREGATE MINING IN RIVERS

Sand and gravel are used as construction aggregate for roads and highways (base material and asphalt), pipelines (bedding), septic systems (drain rock in leach fields), and concrete (aggregate mix) for highways and buildings. In California, virtually all aggregate is derived from alluvial deposits, either from pits in river floodplains and terraces, or from *instream gravel mining*, which involves the removal of sand and gravel from river beds with heavy equipment.

Sand and gravel that have been subject to prolonged transport in water (such as active channel deposits) are particularly desirable sources of aggregate because weak materials have typically been eliminated by abrasion and attrition, leaving durable, rounded, well-sorted gravel (Barksdale 1991). Instream gravel thus requires less processing than many other sources, and suitable channel deposits are commonly located near the markets for the product or on transportation routes, reducing transportation costs (which are the largest costs in the industry). Moreover, instream gravel is typically of sufficiently high quality to be classified as PCC-grade aggregate, suitable for use in production of Portland Cement concrete.

Aggregates can be obtained from a variety of sources other than active channel and floodplain deposits including dry terrace mines, quarries (from which rock must be crushed, washed, and sorted), tailings from gold dredging, reservoir deltas, and recycled concrete rubble. These alternative sources usually require more processing and often require longer transportation over long distances. Although their production costs are commonly higher, these alternative sources avoid the adverse effects associated with riverine extraction and may provide other benefits, such as partially restoring reservoir capacity lost to sedimentation and providing opportunities for ecological restoration of sterile dredger tailings.

EFFECTS OF INSTREAM GRAVEL MINING

Instream mining directly alters river channel geometry and bed elevation and may involve extensive clearing of riparian vegetation, diversion of flow, stockpiling of sediment, and excavation of deep pits (Sandecki 1989). In addition to these direct alterations of the river environment, instream gravel mining may induce channel incision, bed coarsening, and lateral channel instability.

Channel Incision and Bed Coarsening

By removing sediment from the channel, instream gravel mining disrupts the preexisting balance between sediment supply and transport capacity, typically inducing incision upstream and downstream of the extraction site. Excavation of pits in the active channel alters the equilibrium profile of the streambed, creating a locally steeper gradient upon entering the pit. This over-steepened point (with its increased stream power) commonly erodes upstream in a process known as *headcutting* or *nickpoint migration.* This incision may propagate upstream for kilometers on the main river (Scott 1973; Stevens et al. 1990) and up tributaries (Harvey and Schumm 1987). Incision is also induced downstream of the gravel mine, because much of the incoming sediment load is trapped in the pit, creating hungry water downstream, which typically erodes the channel bed and banks to regain at least part of its sediment load (figure 9).

Incision can also induce channel instability, triggering bank erosion in formerly stable reaches. With continued extraction, the bed may degrade down to bedrock or older substrates under the recent alluvium (figure 10). Just as below dams, gravel-bed rivers may become armored, limiting further incision (Dietrich et al. 1989), but eliminating spawning habitat. In many rivers, gravel mining has been conducted downstream of dams, combining the effects of both activities to produce an even larger sediment deficit.

Incision of the river bed typically causes the alluvial aquifer to drain to a lower level, resulting in a loss of aquifer storage, as documented along the Russian River (Sonoma County 1992). The Lake County (California) Planning Department (1992) estimated that incision from instream mining in small river valleys could reduce alluvial aquifer storage from 1 to 16%, depending on local geology and aquifer geometry.

Undermining of Structures

Direct effects of incision include undermining of bridge piers and other structures, and exposure of buried pipeline crossings and water supply facilities. Mining-induced incision of over 7 m has occurred on the Kaoping River, Taiwan, directly downstream of the Kaoping Bridge. The bridge piers have been extended and its downstream margin protected with gabions and massive concrete jacks (of the type often used to protect coastlines from energetic ocean waves) to protect the bridge from undermining by headcutting from the instream gravel mine downstream (figure 11). Mining-induced incision has exposed buried aqueducts, gas pipelines, and other utilities in the bed of the San Luis Rey River, California (Parsons et al. 1994). Municipal water supply intakes have been damaged or made less effective on the Mad (Lehre et al. 1993) and Russian (Marcus 1992) Rivers in California as the layer of overlying gravel has decreased due to incision.

Channel Instability

Instream mining can cause channel instability through disruption of the existing equilibrium channel form or undercutting of banks caused by incision. Gravel mining in

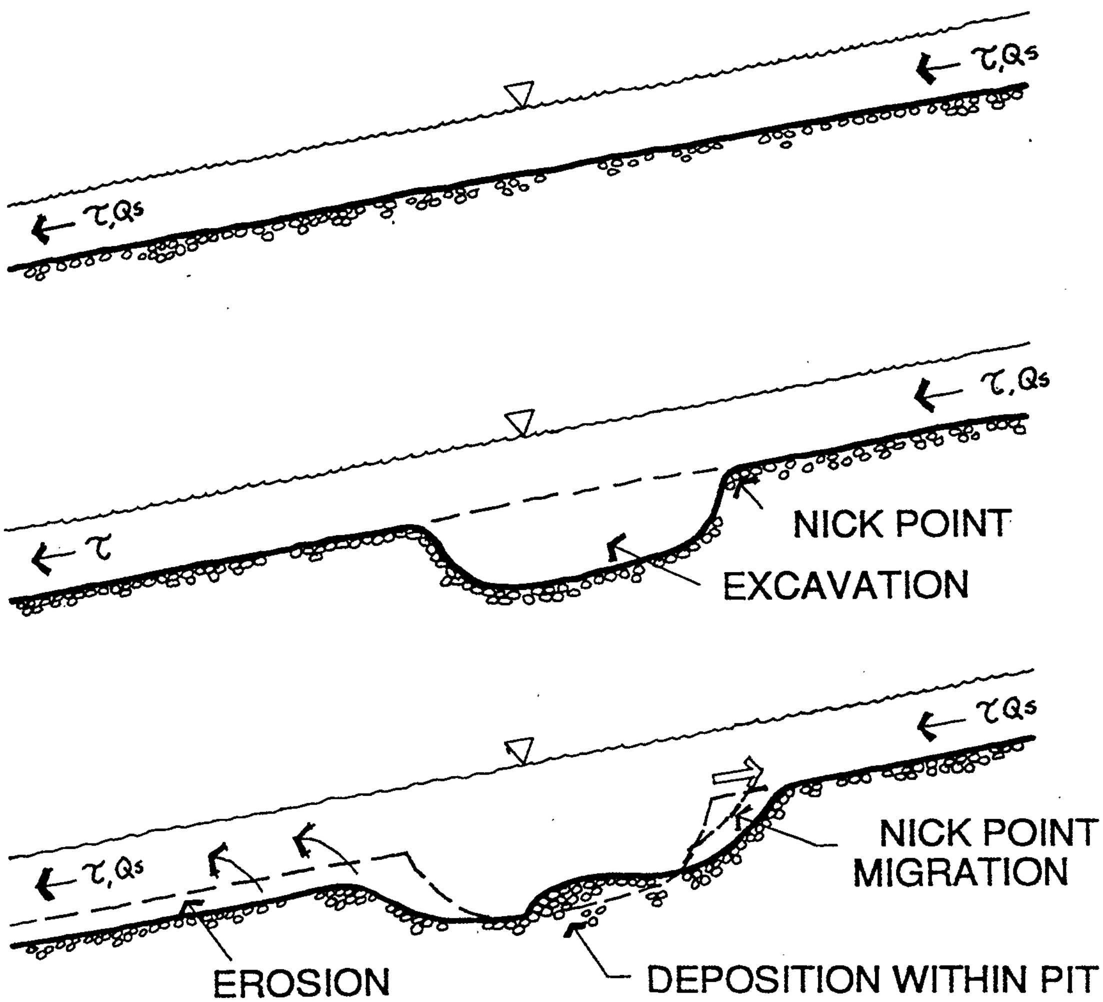

Figure 9. Incision produced by instream gravel mining. (a.) The initial, pre-extraction condition, in which the river's sediment load (Q_s) and the shear stress (τ) available to transport sediment are continuous through the reach. (b.) The excavation creates a nickpoint on its upstream end and traps sediment, interrupting the transport of sediment through the reach. Downstream, the river still has the capacity to transport sediment (τ) but no sediment load. (c.) The nickpoint migrates upstream, and hungry water erodes the bed downstream, causing incision upstream and downstream.

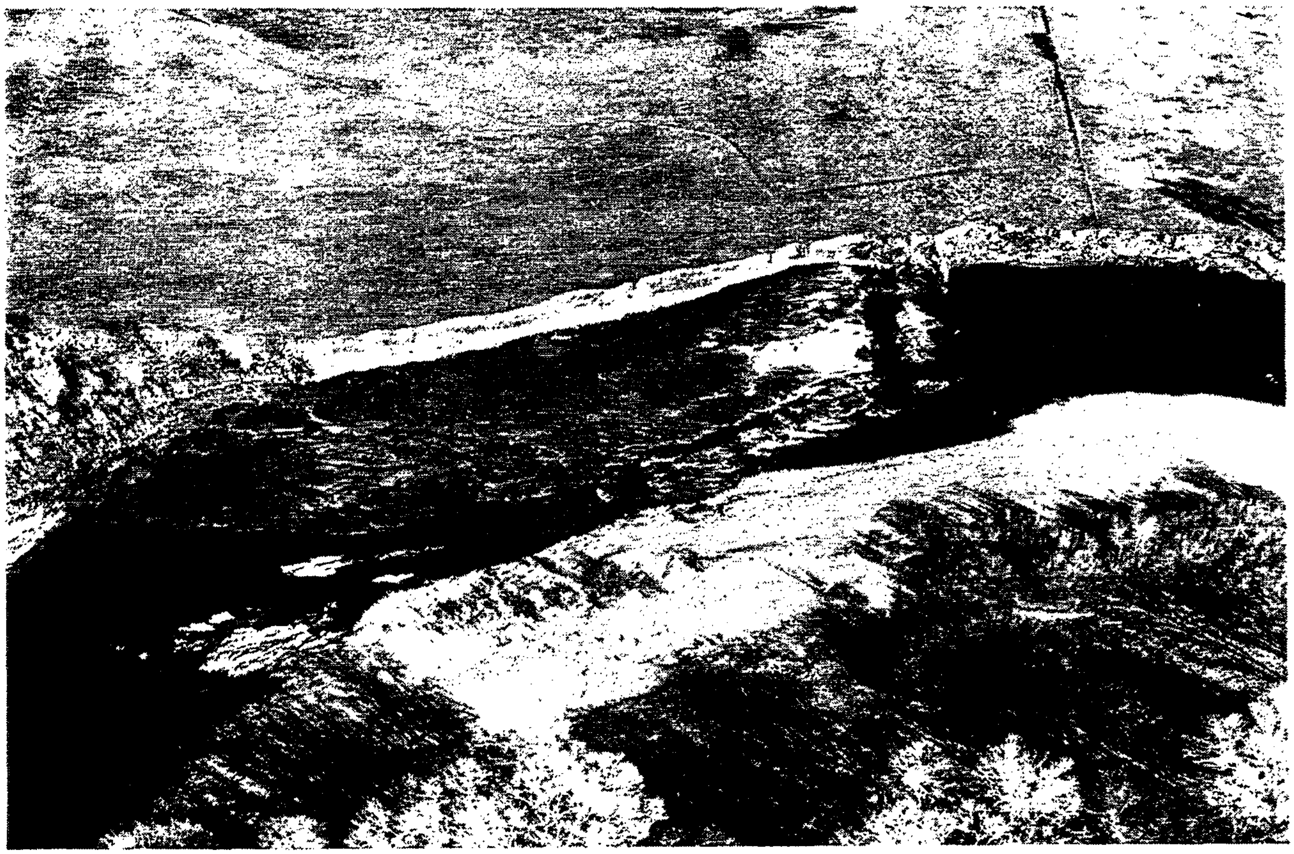

Figure 10. Tributary to the Sacramento River near Redding, California, eroded to bedrock as a result of instream mining. (photograph by Kondolf, January 1989)

Figure 11. Bed erosion and massive grade control structures installed downstream of the Kaoping Bridge, Kaoping River, Taiwan. (photograph by Kondolf, October 1995)

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Blackwood Creek, California, caused incision and channel instability upstream and downstream, increasing the stream's sediment yield fourfold (Todd 1989). As a nickpoint migrates upstream, its incision and bank undercutting release additional sediment to downstream reaches, where the channel may aggrade and thereby become unstable (Sear and Archer 1995). A more subtle but potentially significant effect is the increased mobility of the gravel bed if the active coarse surface layer (the *pavement*) (Parker and Klingeman 1982) is disrupted. Similarly, removal of gravel bars by instream mining can eliminate the hydraulic control for the reach upstream, inducing scour of riffles and thus washout of incubating salmon embryos (Pauley et al. 1989).

EFFECTS OF FLOODPLAIN PIT MINING

Floodplain pit mining transforms riparian woodland or agricultural land into open pits, which typically intersect the water table at least seasonally. Floodplain pit mining has effectively transformed large areas of floodplain into open-water ponds, whose water level commonly tracks that of the main river closely, and which are commonly separated from the active channel by only narrow strip of unmined land. Because the pits are in close hydrologic continuity with the alluvial water table, concerns are often raised that contamination of the pits may lead to contamination of the alluvial aquifer. Most pits in California are steep-sided and offer relatively limited wetlands habitat, but with improved pit design (gently sloping banks, irregular shorelines, etc.) it should be possible to increase wildlife benefits upon reclamation.

In many cases, floodplain pits have *captured* the channel during floods, in effect converting formerly off-channel mines to in-channel mines. Pit capture occurs when the narrow neck of land separating the pit from the channel is breached by lateral channel erosion, or more commonly, during large floods when overbank flows erode the upstream end of the pit (by headcut migration) or the downstream end of the pit (by water draining from the pit on the receding limb of the flood). In general, pit capture is most likely when the path through the pit offers the river a shorter course than the current active channel. Pit capture has been common along the upper San Joaquin River mainstem and tributaries. For example (as described in Chapter Eight), the Merced River now flows through at least fifteen gravel pits, seven of which were excavated in the active channel and eight of which were excavated on the floodplain or point bars, and subsequently captured the river.

When pit capture occurs, formerly off-channel pits are converted to in-channel pits, and the effects of instream mining can be expected, including the propagation of incision up- and downstream of the pit. Capture of the channel by an off-channel pit on the alluvial fan of Tujunga Wash near Los Angeles, California, created a nickpoint that migrated upstream to undermine highway bridges in 1969 (Scott 1973). The Yakima River, Washington, was captured by two floodplain pits in 1971, and began undercutting the interstate highway for whose construction the pits had been excavated (Dunne and Leopold 1978). High flows on the Clackamas River, Oregon, in 1995-1996 resulted in capture of an off-channel pit, inducing incision of more than 2 m half a kilometer upstream of the pit.

In rivers of the Central Valley of California, gravel pits tend to heat up in the summer, creating ideal habitat for warm-water fish that prey on juvenile salmon. When these pits capture the river, juvenile salmon migrating towards the ocean swim into the pits, become disoriented in the quiet water, and suffer high losses to predation. A study by the California Department of Fish and Game in 1987 estimated that nearly 70% of the out-migrating salmon smolts in the Tuolumne River were lost to predation in the three days required for them to pass through the 82-km (52-mi) length of river from the La Grange Dam to the San Joaquin River confluence, and most of the predation was concentrated in old gravel pits (EA 1992).

Chapter 3. Salmonid Habitat Rehabilitation Under the Four Pumps Agreement

The Sacramento-San Joaquin provides one of California's most important areas of natural habitat and fisheries production. The channels and marsh complexes of this system provide migratory corridors and essential habitat for several important species. Adult chinook salmon (including the federally-listed endangered winter-run, and the spring-run, which is currently under review for listing) and steelhead trout migrate through the Delta on their way to freshwater spawning areas in Central Valley streams. Juvenile salmon and steelhead depend on the Delta as transient rearing habitat where they may spend several months during their migration to the Pacific Ocean. In addition, all life stages of American shad (*Alosa sapidissima*) and striped bass are found in the Delta as well as such special status species as the Delta smelt (*Hypomesus transpacificus*), which is federally-listed as threatened, and the Sacramento splittail (*Pogonichthys macrolepidotus*), which is proposed for federal listing as threatened.

The Delta also plays a major role in state and federal water resource development projects. Flows in the Delta are greatly modified by dams and diversions of the State Water Project and the federal Central Valley Project. Both projects use the Delta channels to transport water from storage reservoirs in the north to the Clifton Court Forebay in the southern Delta, from which water is pumped into diversion canals to service areas in south San Francisco Bay, the San Joaquin Valley, and southern California. Two large pumping plants are located in the southern Delta. The Tracy Pumping Plant (Central Valley Project) diverts flows into the Delta-Mendota Canal, and the Harvey O. Banks Delta Pumping Plant (State Water Project) diverts flows into the California Aqueduct (figure 1).

In 1986, the CDWR installed four new pumps, increasing its pumping capacity at the Harvey O. Banks Delta Pumping Plant from 180 m^3/s (6,400 cfs) to 292 m^3/s (10,300 cfs). The pumping plant kills fish by directly entraining in the diversion system, and indirectly by increasing predation in the Clifton Court Forebay, by reducing freshwater flows in the Delta, and by periodically reversing flow direction in the Delta channels.

To reduce fish losses at the Delta Pumps, the CDWR conducts a "trap-and-truck" salvage operation in which fish are removed at the Skinner Delta Fish Protective Facility after passing through the Clifton Court Forebay and are transported in trucks to the Delta, where they are released. Despite this salvage operation, fish continue to be killed at the Delta Pumps due to poor screening efficiency for fish less than 2.5 cm (1 inch) in length, enhanced predator efficiency, and stress and injury incurred during the salvage operations. Estimates of loss of chinook salmon in the Clifton Court Forebay range from 63 to 97% (Kano 1990). Recognizing these losses, the CDWR and CDFG have sought to improve striped bass, steelhead, and chinook salmon stocks.

THE FOUR PUMPS AGREEMENT

On December 30, 1986, the CDWR and CDFG entered into an agreement to offset the direct losses of striped bass, chinook salmon, and steelhead caused by the diversion of water at the Harvey O. Banks Delta Pumping Plant (CDWR and CDFG 1986). Formally known as the "Agreement between the Department of Water Resources and the Department of Fish and Game to offset direct losses in relation to the Harvey O. Banks Delta Pumping Plant," the agreement is commonly referred to as the *Four Pumps Agreement*, since it was designed to address fish losses resulting from the addition of the four new pumps to the state Delta Pumping Plant. The Four Pumps Agreement (hereafter referred to as the *Agreement*) defines direct losses of fish as those which occur from the time fish are drawn into Clifton Court Forebay until the surviving fish are returned to the Delta.

To offset the direct losses, the Agreement established two separate accounts to fund fishery mitigation projects, an *Annual Account* and a *Lump Sum Account*. The Annual Account is funded annually, based on estimated annual losses of the target species -- striped bass, steelhead, and chinook salmon -- at the Delta Pumping Plant (Agreement §I(A)). The CDWR estimates these losses based on the number of fish salvaged at the Skinner Delta Fish Protective Facility adjusted by factors influencing survival to age one year. The adjustment for striped bass is based in the observed survival rate for specific length groups and ranges from 49% to 100%. For young-of-the-year steelhead and salmon, survival is estimated as 17%. The estimated annual loss is the basis for a dollar amount which must be paid from the Annual Account.

The Lump Sum Account was established in recognition that operation of the pumps prior to the 1986 Agreement resulted in reduced abundance of striped bass, steelhead, and chinook salmon and that, since these species are less abundant, the direct losses of these fish experienced in a given year is likely to be less than would be experienced had flow diversion not occurred in previous years (Agreement §I(B)). It is not the purpose of this account to mitigate losses incurred prior to 1986 *per se*, but rather to initiate immediate mitigation measures and to increase the likelihood of quickly demonstrating increased fish populations as a result of the Agreement.

Project Selection Guidelines

The Agreement set forth six guidelines for the selection of mitigation projects to be funded under the Annual and Lump Sum Accounts (Agreement §I(D)). These guidelines are:

- Guideline One: Project Costs and Benefits - Project selection is to be based on (1) magnitude of the project's potential benefits; (2) evidence of the probability of achieving these benefits; (3) project costs (capital, operation, maintenance and replacement) in relation

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to other mitigation projects and to the project's expected benefits; (4) ability and cost to evaluate project performance; and (5) environmental considerations.

- Guideline Two: Favor Natural Production over Hatcheries - Priority is to be given to habitat restoration and other non-hatchery measures which help protect the genetic diversity of fishery stocks and that avoid over-reliance on hatcheries.

- Guideline Three: Priority to the San Joaquin River Basin - In selecting mitigation projects for steelhead and chinook salmon, priority is to be given to measures in the San Joaquin River system.

- Guideline Four: Deadline for Spending the $15 Million Lump Sum Account - The $15 million Lump Sum Account is to be expended over a period not more than ten years from the date of execution of the Agreement (December 31, 1986), i.e. December 31, 1996. In 1994 this deadline was extended to the year 2001.

- Guideline Five: Compensation for Annual Losses - Although mitigation obligations for annual fish losses are expected to be met as soon as practicable after the losses occur, compensation for these obligations may be accumulated over a period of up to ten years. Compensation funds can also be spent in advance based on the expectation of losses. Advance expenditures are not to exceed the obligations expected over a ten year period.

- Guideline Six: Maximum Allowable Per Fish Project Cost - The average amount paid for fish replaced under the Annual Account is not to exceed the cost of replacing fish with hatchery-reared yearling fish. At the time of the Agreement, the cost of hatchery fish was estimated to be $1.65 per striped bass and $0.55 per yearling steelhead and chinook salmon. In 1991, the per fish cost for yearling steelhead and chinook salmon was increased to $1.05 to include capital costs not recognized in the 1986 estimate. Adjusted for inflation, the 1996 value is approximately $1.60 per yearling steelhead and chinook salmon. The per fish cost constraint does not apply to allocations from the Lump Sum Account.

Project Selection Process

The Agreement specifies that the CDWR and CDFG jointly appoint and seek input from an advisory committee, which provides assistance in estimating annual direct losses as well as identifying, selecting, and implementing mitigation projects (Agreement §I(F)). The committee consists of interest groups concerned with fishery resources affected by the State Water Project,

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and includes representatives from commercial and sport fishing organizations, State Water Project contract holders, and environmental interest groups.

Under the Agreement, the CDWR and CDFG review proposed mitigation projects using the six guidelines set out by the Agreement then submit the projects to the advisory committee at which point the committee or agency staff may modify the project proposal. The agency directors then select mitigation projects for implementation based on the recommendations of the advisory committee and agency staff.

Annual Review of Project Performance

The Agreement requires that the performance of funded projects be reviewed and the results reported annually:

> "By December 31, 1989, and by December 31 of each year thereafter, Water Resources and Fish and Game shall, with input from the advisory committee set forth in Section I.F, review the success of this agreement in offsetting the direct effects of diversions by the Pumping Plant on the fisheries dependent on the Delta ... The parties will provide an annual report describing the results of the annual review" (Agreement §VI).

METHODS

We evaluated the allocation of mitigation funds from the Annual Account and the Lump Sum Account between 1986 and 1995 in light of the overall intent of the Four Pumps Agreement and evaluated the extent to which required annual project reviews were carried out. We defined the Agreement's intent based on guidelines two and three (§I(D)(2) and I(3)) which state that priority should be given to (1) improving natural production over stocked or hatchery production, and (2) for salmon and steelhead projects, to measures that are located in the in the San Joaquin River Basin over those located in the Delta or Sacramento Basin. We chose these two guidelines because they represent the general purpose of the Agreement whereas Guideline One is specific to selection of individual projects and Guidelines Four through Six are specific to payment schedules and per fish project costs. We also added a third criterion which was not explicitly stated in the Agreement, that priority should be given to projects intended to provide long-term rather than short-term benefits, because short-term projects are not capable of meeting the stated purpose of the Agreement, the protection and improvement of fish habitat and preservation of the genetic diversity of fish stocks (CDWR and CDFG 1986:4). In addition, to provide a general assessment of the focus of the Four Pumps mitigation funding on specific target species, we compared funding allocation for striped bass relative to allocations for steelhead and chinook salmon. We did not evaluate funding allocation with respect to cost-benefit analyses (Guideline

One), time constraints on funding allocation (Guidelines Four and Five), or per fish expenditure constraints (Guideline Six).

We obtained project descriptions and funding allocations for each project funded under the Agreement between 1986 and 1995 from the CDFG and the CDWR. From this information, we categorized each project based on target species, targeted benefit, estimated life of the benefit, and project location. Targeted benefits included habitat, passage, hatchery, or enforcement.

In July 1995, we submitted written requests to the Directors of the CDFG and the CDWR for copies of the annual reports "describing the results of the annual review[s]" of project performance and for copies of supporting documentation relevant to reviewing the performance of the riffle rehabilitation projects funded under the Agreement.

RESULTS

Allocation of Funds Under the Agreement

A total of $33 million was allocated from the Annual and Lump Sum Accounts for striped bass, steelhead, and chinook salmon mitigation projects. Of this, $18.3 million (55%) was allocated for projects directed at improving steelhead and chinook salmon stocks. The remaining $14.7 million (45%) was allocated for projects directed toward increasing populations of striped bass, an introduced species which preys on juvenile salmon.

As detailed in table 4, $3.8 million (21% of the total steelhead and salmon allocation) was allocated for habitat improvement projects, including spawning riffle rehabilitation and gravel enhancement, predator isolation, and water hyacinth eradication. $5.7 million (31% of the total steelhead and salmon allocation) was allocated for improving fish passage through the Delta and Central Valley. Passage improvement projects included barriers and screens in the Delta and San Joaquin River Basin as well as flow acquisition in the Sacramento Basin. $5.6 million (31% of the total steelhead and salmon allocation) was allocated for upgrades to existing hatcheries on the Feather River (a tributary to the Sacramento River) and the Merced River, and a new hatchery on the Tuolumne River. $3.1 million (17% of the total steelhead and salmon allocation) was allocated for improved enforcement of CDFG fishing regulations.

Funding allocations differed markedly between the two accounts. From the Annual Account, 24% of total steelhead and salmon funds went to habitat improvement; 16% went to passage improvement; 17% went to hatcheries; and 44% went to enforcement. From the Lump Sum Account, 21% of total steelhead and salmon funds went to habitat improvement; 31% went to passage improvement; 31% went to hatcheries; and 2% went to enforcement.

53% of the Annual Account and 74% of the Lump Sum Account steelhead and salmon funds (66% of the total steelhead and salmon allocation under the Agreement) were allocated for projects intended to provide benefits lasting more than five years. These long-term projects

Table 4
Expenditure of Funds for Chinook Salmon and Steelhead Projects under the Four Pumps Agreement
(in unadjusted U.S. Dollars)

	allocation	habitat	passage	hatchery	enforcement	long-term (>5 years)	short-term (<5 years)	San Joaquin	Sacramento	Delta
ANNUAL ACCOUNT PROJECTS										
Mill Creek gravel restoration	$83,000	$83,000				$83,000			$83,000	
Steelhead rearing (Feather River Hatchery)	$100,000			$100,000			$100,000		$100,000	
Warden overtime for enforcement (spring run)	$91,000				$91,000		$91,000		$91,000	
Stanislaus River Gravel Enhancement	$176,200	$176,200				$176,200		$176,200		
Tuolumne River, MJ Ruddy	$334,000	$334,000				$334,000		$334,000		
Tuolumne River Gravel Riffles 1B, 3A, and 3B	$176,400	$176,400				$176,400		$176,400		
Tuolumne River, Reed Site	$133,650	$133,650				$133,650		$133,650		
Merced River Fish Facility* Modernization	$922,500			$922,500		$922,500		$922,500		
Merced River Fish Facility Equipment	$60,000			$60,000		$60,000		$60,000		
Merced River Gravel Phase I and II	$136,000	$136,000				$136,000		$136,000		
Merced River Gravel Phase II	$194,000	$194,000				$194,000		$194,000		
Merced River, Magneson Site	$361,102	$361,102				$361,102		$361,102		
San Joaquin River, Hills Ferry Fish Barrier I	$67,600		$67,600				$67,600	$67,600		
San Joaquin River, Hills Ferry Fish Barrier II	$37,000		$37,000				$37,000	$37,000		
San Joaquin River, Hills Ferry Fish Barrier (15 yrs)	$916,890		$916,890			$916,890		$916,890		
Delta-Bay Enhanced Enforcement (I)	$1,641,405				$1,641,405		$1,641,405			$1,641,405
Delta-Bay Enhanced Enforcement (II)	$1,119,536				$1,119,536		$1,119,536			$1,119,536
Annual Account Subtotal	$6,550,283	$1,594,352 24%	$1,021,490 16%	$1,082,500 17%	$2,851,941 44%	$3,493,742 53%	$3,056,541 47%	$3,515,342 54%	$274,000 4%	$2,760,941 42%
LUMP SUM ACCOUNT PROJECTS										
Sacramento River Gravel, Initial Phase	$2,200,000	$2,200,000					$2,200,000		$2,200,000	
Mill Creek Pump Project	$424,000		$424,000			$424,000			$424,000	
Deer Creek Water Exchange Project	$1,650,000		$1,650,000			$1,650,000			$1,650,000	
Salmon Transfer Mobile Net Pen	$194,592		$194,592				$194,592		$194,592	
Georgiana Slough Acoustical Barrier	$400,000		$400,000				$400,000			$400,000
Tuolumne River Hatchery Appraisal	$20,000			$20,000		$20,000		$20,000		
Tuolumne River Salmon Restoration Center*	$4,500,000			$4,500,000		$4,500,000		$4,500,000		
Merced River water hyacinth eradication	$25,000	$25,000					$25,000	$25,000		
San Joaquin River Predator Isolation Projects	$1,000,000		$1,000,000			$1,000,000		$1,000,000		
Delta-Bay Enhanced Enforcement Project	$258,204				$258,204		$258,204			$258,204
Suisun Marsh Wetland Diversion Screening	$1,000,000		$1,000,000			$1,000,000				$1,000,000
Grizzly Island Screen	$58,000		$58,000			$58,000				$58,000
Lump Sum Account Subtotal	$11,729,796	$2,225,000 19%	$4,726,592 40%	$4,520,000 39%	$258,204 2%	$8,652,000 74%	$3,077,796 26%	$5,545,000 47%	$4,468,592 38%	$1,716,204 15%
Total	$18,280,079	$3,819,352 21%	$5,748,082 31%	$5,602,500 31%	$3,110,145 17%	$12,145,742 66%	$6,134,337 34%	$9,060,342 50%	$4,742,592 26%	$4,477,145 24%

* Hatchery

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included hatchery upgrades and investment in a new hatchery as well as habitat and passage improvement.

Of the total funds allocated for steelhead and salmon-related projects, 50% was allocated to projects located in the San Joaquin River Basin, 26% to projects in the Sacramento Basin, and 24% to projects in the Delta. Of the San Joaquin River Basin allocation, $5,502,500 (61%) was allocated to hatchery improvements and a new hatchery.

Annual Review of Project Performance

In response to our request for annual reviews of project performance, we received ten tabulations of funds expended, entitled Mitigation Fund Expenditures from October 1988 to June 1994 and two tabulations covering the fiscal years 1989-1990 and 1990-1991. These tabulations all listed total expenditures to date from the Annual and Lump Sum Accounts. Some listed specific projects funded, and some reports listed projects approved and funds encumbered.

We also received eleven balance sheets listing the number of striped bass, salmon, and steelhead estimated to have been killed annually at the pumps and the number of fish "replaced" through projects funded by the Four Pumps Agreement. Use of the term "replacement" is problematic because it implies that actions affecting other life stages of these fish in other places can truly "replace" fish lost at the pumps. Although we do not agree that the concept of replacing the lost fish is valid, the term has taken on a technical meaning in the accounting performed by the CDWR and CDFG, and it is used here consistent with that meaning. The balance sheets (dated from October 1988 to July 1994) were variously titled as shown in table 5.

The narrative accompanying the numbers was limited to footnotes to some of the entries. These footnotes broke the total replacement values into components, but despite their seeming precision, many of the numbers were derived from negotiation between the CDFG and CDWR rather than objective evaluation of project performance. For example, the July 1994 balance sheet listed estimated replacement of salmon in 1993 as 520,695. The accompanying footnote read, "Mill Creek Gravel 78,125; Merced River Gravel 8,329; SJR Barrier 116,860; Merced River Fish Facility 101,562 yearlings = 317,381 smolts. Total 520,695." Mill Creek Gravel and Merced River Gravel refer to gravel enhancement (i.e., spawning riffle reconstruction) projects, the 'SJR Barrier' is a barrier across the San Joaquin River to prevent fish from continuing upstream past the confluence of the Merced River, and the 'Merced River Fish Facility' is a hatchery. No evaluation of project performance was presented, implying that the projects were assumed to be successful.

The July 1994 balance sheet listed the estimated replacement of salmon in 1994 as 272,444. The accompanying footnote read, "1993 Redd Survey for Merced River counted 63 redds, 22,444 smolts and DBEEP 250,000 smolts. Total 272,444 smolts." DBEEP refers to the

Table 5
Estimated Salmon Losses at Pumping Plant and Replacement by Report Date

Estimated Salmon Losses

Report and Date	Salmon Losses Reported (thousands)[a] 1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Fish Loss Account July 1994	1973.2	1536.9	1609.6	1486.0	1349.2	709.7	510.5	500.0[b]	500.0[b]	500.0[b]
Fish Loss/Replacement Account April 1993	1973.2	1536.9	1609.6	1486.0	1349.2	709.7				
Fish Loss Account May 1992	1973.2	1536.9	1609.6	1486.0	1349.2	1000.0[b]	1000.0[b]	1000.0[b]	1000.0[b]	1000.0[b]
Fish Loss Account July 1991	1973.2	1536.9	1609.6	1486.0	1349.2					
Offset Losses Account February 1991	1973.2	1536.9	1609.6	1486.0						
Mitigation Losses Account Nov 1990	1973.2	1536.9	1609.6	1486.0						
Mitigation Losses Account June 1990	1973.2	1536.9	1609.6	1486.0						
Mitigation Losses Account Mar 1990	1973.2	1536.9	1609.6							
Pumping Plant Fish Mitigtn Agmt Losses Acct July 1989	1973.2	1536.9	1609.6							
Pumping Plant Fish Mitigtn Agmt Losses Acct Mar 1989	631.4	491.8								
Fish Agreement Mitigation Losses Account Oct 1988	631.4	491.8								

Estimated Salmon Replacement

Report and Date	Salmon Replacement Reported (thousands)[a] 1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Fish Loss Account July 1994			78.1	15.6	15.6	79.6	598.9	520.7	272.4[c]	630[b]
Fish Loss/Replacement Account April 1993			78.1	15.6	15.6	79.6	598.9	228[d]		
Fish Loss Account May 1992			78.1	15.6	15.6	79.6	260.0	270.0	280.0	290.0
Fish Loss Account July 1991			0.0	78.1	15.6	18.3[b]	991[b]	991[b]		
Offset Losses Account February 1991				78.1	15.6					
Mitigation Losses Account Nov 1990				78.1	15.6					
Mitigation Losses Account June 1990				78.1	78.1					
Mitigation Losses Account Mar 1990				78.1						
Pumping Plant Fish Mitigtn Agmt Losses Acct July 1989		78.1								
Pumping Plant Fish Mitigtn Agmt Losses Acct Mar 1989			78.1							
Fish Agreement Mitigation Losses Account Oct 1988			78.1							

[a]smolt equivalents [c]through July
[b]projected [d]through March

Delta Bay Enhanced Enforcement Project, whose purpose is to reduce illegal take of fish, and which supports ten existing enforcement positions in the Sacramento and San Joaquin Rivers and Delta (notes for 6 September 1995 meeting of the Four Pumps Advisory Committee, Sacramento). In this case the value for replacement on the Merced River was a multiple of the number of redds observed at the Merced River riffle reconstruction sites. However, the credit accorded to the DBEEP program of 250,000 smolts was "negotiated" according to a table accompanying a letter from the CDWR to Kondolf. Using the values provided in this table, the number of smolts at Mossdale per redd would be 181 for the Merced River, 232 for the Tuolumne River, and 248 for the Stanislaus River. Assuming that for every two adults whose illegal take is prevented, one additional pair of salmon will successfully spawn and construct a redd, this implies that the DBEEP program must prevent the illegal take of 2,016 to 2,752 adult salmon per year to produce an additional 250,000 smolts annually at Mossdale from the San Joaquin River tributaries. None of the materials we received provided objective evidence that this number of adult salmon were saved from illegal harvest by DBEEP.

These balance sheets present an accounting of fish replaced, but with the exception of redd counts for some projects, they provide no evidence that the constructed habitat (or other action) was actually producing fish. Thus, the balance sheets do not provide a review of the performance of the funded projects in actually mitigating the losses of fish at the pumping plants, as required by the Agreement. Even if the validity of the estimates of fish losses and replacement in the balance sheets is accepted, this accounting indicates that replacement of fish has not kept pace with losses. As of July 1994, the CDWR had accumulated an obligation to replace 7.6 million salmon smolts lost at the pumps, an unmitigated balance that was projected to increase in the future.

Following subsequent conversations with the CDWR staff, we received annual reports from 1992 to 1995 on the performance of extensive riffle rehabilitation and gravel importation projects on the Upper Sacramento River near Redding, California, which were partially funded by the Agreement. These projects involved importation of 120,000 m^3 (165,000 yd^3) of gravel from 1978-1995, and are reported to have performed with "mixed" results (CDWR 1995a:6). We received no comparable reports for the San Joaquin Basin gravel projects, and we understand that none have been prepared.

In the fall of 1995, the CDWR initiated a field survey of the Merced River Riffle 1B project to evaluate physical changes during the high flows of 1995. As of May 1996, we were unaware of a report of the results of this evaluation nor reviews of the performance of other Four Pumps projects in the San Joaquin River system. However, as a result of the evaluation, the Riffle 1B project is scheduled for maintenance in the summer or fall of 1996 (Stephen Ford, Department of Water Resources, personal communication, 1996).

DISCUSSION

The $15 million (45% of the total Four Pumps allocation) allocated for striped bass production could be viewed as inconsistent with the goals of increasing salmon populations inasmuch as the striped bass is an introduced species that preys on salmon. Of the 55% of funds allocated for steelhead and salmon-related projects for the overall project area (which includes the San Joaquin and Sacramento Basins, and the Sacramento-San Joaquin Delta), 69% of the allocated steelhead and salmon funds went to projects intended to benefit natural production of steelhead and chinook salmon consistent with the Agreement's guideline that natural production be favored over hatcheries, including reconstruction of spawning and rearing habitat (21%), predator isolation and passage improvements (31%), water hyacinth eradication (0.1%), and increased enforcement of CDFG regulations (17%).

Half of the total funding for salmon and steelhead projects was allocated to projects in the San Joaquin River Basin, indicating at least equal treatment, if not a priority for this region, consistent with the intent of the Agreement. However, in the San Joaquin River Basin, only 39% of the funds allocated went to projects intended to improve natural steelhead and salmon production while the remaining 61% went to improvements to an existing hatchery on the Merced River and investment in a proposed new hatchery on the Tuolumne River. Funding for projects intended to improve natural steelhead and salmon production in the San Joaquin River Basin included spawning riffle reconstruction (7.6%), reconstruction of spawning and rearing reaches (5.2%), predator isolation on the San Joaquin and Merced Rivers (15%), a barrier to prevent salmon from straying up the San Joaquin River upstream of the Merced River confluence (11%), and water hyacinth eradication (0.3%)[3]. The preferential funding for hatcheries indicates that, while allocation of Four Pumps funds was consistent with the goal of improving natural over hatchery production in the overall project area, allocation of funds for the San Joaquin River Basin was not consistent with this goal.

Of the funds allocated for habitat-related projects in the San Joaquin River Basin, 99% went to projects intended to provide long-term benefits. These include the electrical barrier at Hills Ferry on the San Joaquin River, which is designed to prevent adult migrants from swimming up the San Joaquin River upstream of its confluence with the Merced River (where they would encounter a dry channel and no spawning habitat), and can be expected to provide benefits for the 15-year funding period. However, as reported in Chapters Six and Seven, the

[3] Four of the spawning riffle reconstruction projects (which modified nine riffles) have been completed and are discussed in further detail in Chapters Four through Seven. One spawning and rearing reconstruction project (the Ruddy Site on the Tuolumne River) has been completed and is discussed in Chapters Four and Five. Another authorized spawning and rearing reconstruction project (the Reed Site on the Tuolumne River) and predator isolation projects on the Merced River (the Magneson Site) and on the San Joaquin River have not been constructed.

available data indicate that the spawning riffle rehabilitation projects on the Stanislaus, Tuolumne, and Merced Rivers will not provide the long-term benefits expected by the CDFG and the CDWR. Therefore, although the funds were allocated with the intent to provide long-term benefits, they have actually failed to do so. We did not conduct a detailed evaluation of the Ruddy Site, the only rearing and spawning project constructed thus far. No other physical habitat improvement or predator isolation projects have been constructed as yet.

More importantly, the projects funded by the Agreement do not address the issue of low instream flows in the Merced, Tuolumne, and Stanislaus Rivers, which is identified by the CDFG as the principal factor limiting salmon populations (Chapter One) and recognized by the CDWR (1991) as the "single most important factor" affecting chinook salmon in the Tuolumne River. Thus far, the main purpose of the funded projects has been to improve and construct hatchery facilities ($5,502,500); increase the area of spawning habitat in the Stanislaus, Tuolumne, and Merced Rivers ($1,150,250); isolate predator habitat from the main channels in the San Joaquin and Merced Rivers ($1,361,102); and prevent inmigrating adults from straying up the San Joaquin River upstream of the Merced River confluence ($1,021,490).

There is no evidence that the availability or quality of spawning habitat is limiting chinook salmon production in the San Joaquin River Basin. Studies conducted by the CDFG (1987) and the CDWR (1994b) conclude that spawning habitat is *not* limiting these populations. In addition to inadequate flows, the CDFG has identified predation as a major factor affecting juvenile migration, and unscreened diversions a major factor affecting both adult and juvenile migration (Reynolds et al. 1993). Only 26% of the funds allocated under the Agreement (for predator isolation and the Hills Ferry Barrier) address factors that have been identified as limiting, while 10% has been allocated for improving spawning habitat, which has been specifically identified as not limiting, and 61% has been allocated for hatcheries, which do not improve, and are probably detrimental, to natural stocks.

Despite the unambiguous language of the Agreement requiring an annual "review [of] the success" of the actions funded under the Agreement, and preparation of "an annual report describing the results of the annual review," as of 1995 no such annual review reports were completed for salmon and steelhead-related projects, with the exception of four annual reports on the Sacramento River gravel enhancement. A potential opportunity to use lessons from the performance of past projects in design of future projects has been forgone.

CONCLUSION

Only 26% of the mitigation funds allocated in the San Joaquin River Basin meet the intent of the Agreement to augment natural production and actually to address factors identified as limiting the San Joaquin River Basin chinook salmon populations. 71% of the funds were allocated for hatcheries, which do not meet the intent of the Agreement, and spawning habitat improvements, which do not address limiting factors. The failure to address the most important issues affecting the salmon runs and the decisions to fund hatchery projects severely limit the Agreement's ability to improve salmon stocks in the long term. The failure to conduct annual reviews and report on project performance has contributed to the perpetuation of a process of constructing projects whose benefits to target salmon populations are unproven.

Chapter 4. Planning for Salmonid Spawning Habitat Rehabilitation Projects in the San Joaquin River Tributaries Under the Four Pumps Agreement

INTRODUCTION

Of the $9.1 million authorized under the Four Pumps program to increase chinook salmon production in the San Joaquin River Basin from 1986-1995, $2.5 million was allocated for physical habitat rehabilitation (Chapter Three, table 4), including reconstruction of nine spawning riffles, large-scale channel alteration to improve both spawning and rearing habitat at two sites, and levee construction to isolate the channel from warm-water predator habitat in pits created by aggregate mining. Thus far, five of the authorized projects have been constructed at a cost of approximately $1 million and include the reconstruction of nine riffles on the Stanislaus, Tuolumne and Merced Rivers to provide spawning habitat and the reconstruction of a 0.9-km reach of the Tuolumne River to improve spawning and rearing habitat[4]. The spawning riffle rehabilitation projects were designed and constructed by the CDWR under the auspices of CDFG. The design for the large-scale channel reconstruction on the Tuolumne River was proposed by the CDWR, based on the design prepared by a consultant, and constructed in cooperation with a local aggregate mine operator.

Despite the considerable cost of these projects, and despite the requirement of the Four Pumps Agreement that annual reviews of project performance be conducted, the CDFG and the CDWR have not evaluated how well these projects have performed in improving salmon spawning and rearing habitat. Absent this review, the agencies continue to plan and design similar habitat rehabilitation projects without the benefit of performance information that would likely be useful in development of more effective projects.

In this chapter, we review the project planning and design processes for the five habitat rehabilitation projects completed thus far in the San Joaquin River tributaries. Based on this review, we provide recommendations to improve the planning and design processes.

METHODS

We reviewed project planning and design documents prepared for the five physical habitat rehabilitation projects constructed to date by the CDWR and CDFG. These documents include agency reports on the utility of restoring spawning habitat, project proposals, environmental review documents completed under the California Environmental Quality Act (CEQA), contract documents, materials submitted for permits required for construction, and the Four Pumps Agreement.

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[4]A "project" may include work at more than one site along a river.

We reviewed these documents specifically to identify factors considered in (1) the decision to rehabilitate spawning riffles, (2) site selection, (3) project design, and (4) the estimation of project benefits. To clarify some points we interviewed the CDWR and CDFG staff and submitted written inquiries to the CDWR concerning specific issues.

PROJECT DESCRIPTIONS

Merced River, Phase I - Riffle 1B (constructed September 1990)

One riffle was reconstructed 60 m (200 ft) downstream of the Crocker-Huffman Dam. The channel bed was excavated to a depth of 0.6 m (2 ft) to remove rock, cobble and silt, which were replaced with washed gravel, sized from 13-102 mm (0.5 - 4 in). Six rock weirs were constructed. This project modified 122 m (400 ft) of channel.

Merced River, Phase II - Sites Two and Three (constructed Fall 1991)

Two sites were reconstructed approximately 1.6 km downstream of the Crocker-Huffman Dam. At the upper site, Site 2, the channel bed was bedrock. Spawning gravel, measuring from 13-102 mm, was placed over the bedrock to provide spawning substrate. No weirs were constructed at the site. At the lower site, Site 3, the bed was excavated to a depth of 0.6 m and backfilled with washed gravel, sized from 13-102 mm. Two rock weirs were constructed to attain a grade of 2% "to provide the suitable ranges of water depth and flow velocities over the riffle area throughout the expected flow regime" (CDFG 1991b). This project modified 205 m (673 ft) of channel.

Tuolumne River, Ruddy Site (constructed June 1993)

A 0.9-km (0.5 mi) reach of channel and floodplain, located at river mile 39, east of Waterford, California, was realigned and reshaped to create several spawning riffles and improve rearing habitat. Prior to project construction, the channel was narrow and deep, providing "very limited" salmon spawning habitat and the floodplain was perched above existing streamflow levels (CDFG 1991a:1). The channel reconstruction created a wider, shallower channel and a floodplain that would be inundated under the river's current (post-dam) flood regime. The new channel was relocated, generally north of the pre-project channel.

Specifically, the project included reshaping and relocating 880 m (2,900 ft) of channel and floodplain. The reshaping was designed to increase the area of the bankfull channel from 13,500 m^2 (145,800 ft^2) to 32,200 m^2 (346,300 ft^2). The floodplain was designed to withstand a discharge of 310 m^3/s (11,000 cfs), a flow having a 20-year recurrence interval in the post-dam flood regime. The CDFG estimated that the project would increase the area of spawning habitat from the existing 1,500 m^2 (16,200 ft^2) to 20,900 m^2 (225,000 ft^2).

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Tuolumne River, Riffles 1B, 3A, and 3B (constructed June 1994)

Three riffles were reconstructed between river miles 49 and 50 near La Grange, California. At the upper two sites, Riffles 1B and 3A, the channel bed was excavated to a depth of 0.5 m (1.5 ft) to remove rock, cobble and silt, which were replaced with washed gravel, sized from 13-102 mm (0.5-4 in). The lower site, Riffle 3B, was determined to have "good gravel but poor channel configuration" (CDWR and CDFG 1992a). At this site, two gravel bars were leveled and the gravel was "manipulated to produce a good spawning riffle" (CDWR and CDFG 1992a).

At all three sites, rock weirs were constructed to "maintain the desired slope and prevent gravel from moving downstream" (CDWR and CDFG 1992a). As at the Stanislaus sites, the weirs were intended to establish a grade of 0.2% to 0.5%, and achieve a water depth of 0.3 to 0.6 m and flow velocity of 0.6 m/s over the site throughout the spawning season at anticipated spawning flows.

This project modified 381 m (1,250 ft) of channel, excavating 5,405 m^3 (7,070 yd^3) of bed material, placing 3,555 m^3 (4,650 yd^3) of spawning gravel in the excavated channel, and constructing seven rock weirs.

Stanislaus River, Riffles at River Miles 47.4, 50.4, and 50.9 (constructed September 1994)

Three riffles were reconstructed by excavating the channel bed to a depth of 0.5 m (1.5 ft) to remove rock, cobble and silt, and replacing the excavated material with washed gravel, sized from 13-102 mm (0.5-4 in), to a depth which produced "the desired channel depth" at the site (CDFG 1994). Rock weirs were constructed at each site to "modify the streamflow characteristics of the renovated spawning channel" by (1) achieving the "necessary grade" of 0.2% to 0.5%, (2) allowing intragravel gravel flow (to remove silts and provide oxygen circulation to the redds), and (3) holding gravel in place and maintaining grade during periods of high flows. These design characteristics were intended to limit water velocities to approximately 0.6 m/s (2 ft/s) and maintain water depths of 0.3 to 0.6 m (1 to 2 ft) over the spawning site during fall spawning flows.

This project modified 206 m (675 ft) of channel, excavating 2,370 m^3 (3,101 yd^3) of bed material, placing 2,347 m^3 (3,070 yd^3) of spawning gravel in the excavated channel, and constructing six rock weirs.

RESULTS AND DISCUSSION

The Utility of Restoring Spawning Habitat

The main purpose of the physical habitat rehabilitation projects was to increase spawning habitat. However, no evidence was presented in the planning documents to demonstrate that

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spawning habitat is limiting the chinook salmon populations in the Merced, Tuolumne, or Stanislaus Rivers. As discussed in Chapter One, the CDFG has identified low streamflows, unscreened diversions, and predation as principle factors limiting these populations (CDFG 1987; Reynolds et al. 1993; and SJRMPAC 1993). In its draft project proposal for the Ruddy Site, the CDWR states that "[i]t is widely accepted by fishery managers that the single most important factor in benefiting the chinook salmon resource in the Tuolumne River is the maintenance of adequate stream flows for adult migration in the fall and juvenile outmigration in the spring" (CDWR 1991: 37). Moreover, the CDFG has specifically stated that spawning habitat is *not* limiting salmon populations in the Stanislaus, Tuolumne, and Merced Rivers (CDFG 1987), and the CDWR (1994b) has reported that gravel in these rivers is generally of good quality for salmon spawning.

It is also notable that the CDFG previously expressed reservations about the effectiveness of gravel rehabilitation work conducted under the Davis-Grunsky Act of 1967, stating that "[g]ravel renovation work on the San Joaquin River spawning tributaries in the early 1970s did not immediately result in improved escapement" (CDFG 1987:12). Although, the CDFG left open the possibility that "[i]ncreases in spawning habitat area may be needed in the future to offset gravel depletions or vegetation encroachment" (CDFG 1987:12), the project documents did not present evidence that gravel depletion and vegetation encroachment occurring since the 1987 report now required gravel rehabilitation. Thus, it is unclear why the limited funds available under the Four Pumps Agreement were used in attempts to create or improve spawning habitat, rather than to solve the problems actually limiting fish populations, such as low instream flows, unscreened diversions, and predation.

Site Selection

The planning and design documents did not state the basis for the selection of specific riffle rehabilitation projects. In response to our written inquiries regarding the criteria used for site selection, the CDWR stated that the CDFG identified sites that were considered for spawning rehabilitation projects based on "established methods and related to biology and use" and that the CDWR assisted in prioritizing these sites based on engineering criteria as described in a report titled *Comprehensive Needs Assessment for Chinook Salmon Habitat Improvement Projects in the San Joaquin River Basin* (CDWR 1994a) (Kevin Faulkenberry, CDWR, personal communication, 1995). The report presents proposals for future projects and was published after construction of the existing projects. It states that the CDFG prioritizes sites based on historical use by salmon, bed slope, channel width, water depth, flow velocity, bank vegetation, substrate condition, potential for habitat diversity, adjacent land use, construction access, and potential for quantifiable benefits, and that the CDWR prioritizes sites based on engineering cost and feasibility (CDWR 1994a).

Project Design

At the nine riffle rehabilitation sites, the basic design approach was to reconfigure the channel to produce flow depth, velocity, and slope believed to be preferred by spawning chinook salmon at flows expected during the spawning season. Riffle reconfiguration included excavation of the existing channel bed to a specified depth and backfilling the channel with gravel of sizes considered to be preferred by chinook salmon (Flosi and Reynolds 1991).

In designing the projects, the CDWR did not analyze important geomorphic processes, including bed mobility, the potential for erosion and transport of bed sediment out of the sites, or sediment supply to the sites for spawning season flows or for higher flows expected to occur over the project life. Instead, the CDWR designed the sites to provide the desired hydraulic conditions during the spawning season only and relied on boulder weirs to retain the imported spawning gravel at the sites during high flows.

The Ruddy Site project, however, was designed to reestablish channel function in the post-dam flow regime. This project considered available flows and flood recurrence intervals in the project design and attempted to construct a floodplain, that would be inundated at frequently occurring flows. However, it is unclear why the channel was realigned rather than reconfigured in its pre-project alignment. The decision to realign the channel has important implications, particularly because the channel recaptured its old alignment twice in the three years since project construction in 1993.

In addition to failing to address geomorphic processes, the project designs greatly simplify the physical habitat needs of spawning salmon. Chinook salmon and some other salmonids have been observed to preferentially select sites of downwelling water (flows of stream water into the gravel bed) for spawning (e.g., Vronsky 1972), while other species have (such as chum salmon, *O. keta*) have been observed to select sites of upwelling water (flows of water upwards from the gravel bed) for spawning (e.g., Tautz and Groot 1975). The absence of downwelling or upwelling currents may be at least one important reason why many seemingly excellent spawning gravels are not used by spawning fish (e.g., Burner 1951).

Dye studies in the field and laboratory have confirmed that irregularities in the bed profile tend to promote exchanges of water between the stream and the interstices of the gravel bed (Vaux 1968, Cooper 1965). The flat beds designed for this project are unlikely to experience significant upwelling or downwelling and are thus unlikely to constitute good spawning habitat.

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Estimation of Project Benefits

The Four Pumps Agreement requires the CDWR and CDFG to consider project costs and benefits in selecting projects to be funded from the Four Pumps accounts (CDWR and CDFG 1986). The agencies defined benefits as the number of smolt equivalents in the San Joaquin River at Mossdale (located on the San Joaquin River as it enters the Sacramento-San Joaquin Delta) produced by the projects over their estimated lives. Costs were defined as costs for construction, engineering and design, and limited monitoring and maintenance.

In calculating project benefits, smolt production was estimated based on the total area of spawning riffle constructed and the estimated project life. Using the CDFG benefit estimation method (CDWR and CDFG 1992a), the total bed area of the rehabilitated riffle was divided by a constant salmon redd area (6 m^2/redd) to yield the maximum number of redds that could be constructed at the site during one spawning season. The maximum number of redds was then adjusted based on the frequency of occurrence of water year types (critical, dry, below normal, above normal, and wet). Smolt production from the redds was adjusted for egg production and smolt survival to Mossdale based on published survival rates: 5,000 eggs per redd; egg-to-fry survival (0.41); fry-to smolt survival (0.48); smolt survival in the tributary (0.40), and smolt survival from the mouth of the tributary to Mossdale (Stanislaus 0.63, Tuolumne 0.59, Merced 0.46). This calculation yielded an estimated number of "smolt equivalents" expected to reach Mossdale on the San Joaquin River each year. The number of smolt equivalents was then multiplied by the expected project life to arrive at total number of smolts produced by the projects and an approximate cost per smolt.

The nine spawning riffle rehabilitation sites and the Ruddy Site project were assigned estimated lives of 15 years. The expected benefits for each project ranged from 21,539 to 51,089 smolt equivalents annually (table 6). Based on this projection, costs ranged from \$0.29 to \$0.55 per smolt. However, actual spawning usage at the sites was much lower than anticipated in the cost-benefit analyses, ranging from 4 to 28% of the expected usage (table 6). In addition, no redd counts were reported for the sites *prior to* riffle rehabilitation, without which information the added benefit of project implementation can not truly be assessed because the net benefit of the project should be only those redds over and above those occurring at the site before project implementation.

In response to a written inquiry regarding the basis for the estimated project life, the CDWR stated that sites "were not designed to for a given [flow] return period" but "were given a 15 year life for the purposes of the cost-benefit analysis, as agreed by the Four Pumps [Advisory] Committee" (Kevin Faulkenberry, CDWR, personal Communication, 1995). This statement implies that the use of the 15 years for the project life was arbitrary. Results of the evaluation of project performance (Chapters Five and Six) suggest that the rehabilitated spawning riffles are

Table 6
Estimated and Observed Spawning Usage at Riffle Rehabilitation Sites

Project	Assumed Project Life (years)	Estimated # of Redds	Estimated Annual Benefit (smolt equivalents at Mossdale)	Estimated Total Benefit (smolt equivalents at Mossdale)	Estimated Cost per Smolt Equivalent	Actual Redd Count
Stanislaus River						
Riffles at River Miles 47.4, 50.4, and 50.9	15	161	>40,000	600,000	$0.29	8 (1994)
Tuolumne River						
Riffles 1B, 3A, and 3B	15	117	27,170	407,553	$0.43	9 (1994)
Ruddy Site	15	220	51,089	766,339	$0.44	9.5 (1993-94 annual average)
Merced River						
Phase I, Riffle 1B	15	119	21,539	323,090	$0.55	33.4* (1990-94 annual average)
Phase II, Sites 2 and 3	15	160	28,969	434,534	$0.45	16.7 (1992-94 annual average)

*includes redds at Phase II sites for 1991 count

source: CDWR 1995b

not stable under the current flow regime, and experience significant erosion and transport of the imported spawning gravel out of the sites within 1 to 4 years. Thus, the estimated 15-year project life is unlikely to be realized at the project sites.

These results demonstrate that the estimates of both annual smolt production and project life employed in the cost-benefit analyses were unrealistic for the spawning riffle projects. The observed shortage of actual spawning use compared to the expected use, combined with a project life much lower than assumed, reduce the accountable benefits of these projects and render the cost-benefit ratio significantly less favorable than estimated.

CONCLUSIONS

At the nine riffle reconstruction sites, project design was limited to an attempt to create specified hydraulic conditions during spawning flows. This approach did not consider erosion and transport of bed material from the sites or supply of new material to the sites under the conditions anticipates to occur at the sites during spawning flows or higher flows. At the Ruddy Site, an attempt was made to restore channel function based on an understanding of river processes, rather than merely modifying channel form. In general, a process-based approach is likely to yield more long-term benefit to river function and habitat maintenance, not only for salmon, but for other species that use the river and riparian corridor. However, the realignment of the channel at the Ruddy Site has resulted in difficulties as evidenced by the recapture of the old channel twice between 1993 and 1996.

The design approach for the nine riffle sites ignored basic geomorphic factors (discharge, sediment supply, and sediment transport) that determine the long-term stability of the channel features at the project site. At a minimum, the project design should include an analysis of sediment transport at the site under pre-project and post-project conditions for *all* flows expected to occur at the site. Failure to address sediment transport (and, therefore, project stability) during the higher flows ignores the most critical episodes during which the project may fail, similar to designing a airplane for to withstand the forces of flying at cruising altitude but not at take-off and landing. From an adequate sediment transport analysis, the project can be designed to remain stable (or in quasiequilibrium) over the long-term, or the project design (and budget) can incorporate maintenance, such as periodic addition of spawning gravel, so that the project reach can be restored to its design condition after each high flow.

In addition to the sediment transport analysis, project planning and design should be undertaken with a recognition of the larger geomorphic context, which requires a historical geomorphic study. Field surveys and sampling provide useful information about existing conditions and can establish a baseline against which future change can be measured. However, to understand channel behavior adequately requires that the period of observation be extended into the past to identify long-term trends and cyclical behavioral patterns. A historical channel study is essential to adequate project planning and design. The historical analysis can reveal the underlying causes of channel change, document prior habitat conditions, help establish realistic habitat restoration objectives, and provide a context within which changes can be interpreted (Kondolf and Larson 1995). In the Merced, Tuolumne, and Stanislaus Rivers, the geomorphic context includes sediment starvation from upstream dam construction and instream gravel mining, reduced flood flows, and massive alterations of the channel and floodplain from gravel extraction and agriculture (Chapter Eight). Project planning and design must recognize that these channels have either adjusted to these large scale alterations or are in the process of adjustment.

In addition to adequate design, project planning should include systematic, objective evaluation of project performance. This evaluation is critically important to the long-term performance of the overall restoration program. Effective project evaluation requires clearly stated goals, adequate baseline data, good study design, commitment to the long term (a decade or more), and to learn from project failures (Kondolf 1995). Results of evaluations should be used as a basis for selecting future actions. Project evaluation should be based primarily on documented changes in physical habitat (which is directly modified by the project and its interaction with subsequent high flows), rather than changes in biological populations (which are affected by a variety of other factors besides physical habitat). The failure to conduct reviews of project performance under the Four Pumps Agreement, despite the Agreement's specific requirement for such reviews, means that the project failures documented here (Chapters Six and Seven) were undetected, and the potential lessons to be learned from them did not contribute to design of future projects.

The cost-benefit analysis methods used in project planning unreasonably constrain project design and selection by limiting the definition of benefit to the number of smolts potentially produced at the sites. As demonstrated, smolt equivalent estimates are flawed and serve as a poor tool for estimating smolt production. In general, habitat restoration objectives are best defined in terms of restoring channel function, including sediment transport and sediment supply, to produce channel conditions that will support ecosystem functions over the long term.

Chapter 5. Environmental Review Conducted for Salmonid Spawning Habitat Process Under the Four Pumps Agreement

The nine spawning riffle rehabilitation sites and the Ruddy Site project completed under the Four Pumps Agreement required environmental reviews mandated by California Environmental Quality Act of 1970 (*CEQA*) (Pub. Res. Code §§ 21000-21177) and the National Environmental Policy Act of 1969 (*NEPA*) (42 USC 4321 et seq.). The reviews mandated by these acts are intended to inform government decisionmakers and the public of the potentially significant environmental effects of proposed activities, identify ways that environmental damage can be avoided or significantly reduced, and disclose to the public the reasons why a government agency approved a project in the manner the agency chose if significant environmental effects are involved.

This chapter reviews the environmental analyses completed for the five habitat rehabilitation projects involving channel modification at a total of ten sites in the San Joaquin River Basin, each of which was constructed and funded by state agencies and required state and federal permits. The goal of this review is to determine how geomorphic information was used in the NEPA and CEQA review processes and how post-construction project monitoring was incorporated into permit requirements.

REQUIREMENTS OF THE NEPA AND CEQA REVIEW PROCESSES

The NEPA and CEQA environmental review processes incorporate a three-level environmental analysis, with the intensity of analysis increasing at each level. The three-level review processes mandated by NEPA and CEQA are similar, although their terminology differs (table 7). The three levels include (1) a *preliminary assessment*, (2) an *environmental assessment* or *initial study*, and (3) an *environmental impact statement* or *environmental impact report*. The preliminary assessment determines whether the proposed action is exempt or excluded from specific NEPA or CEQA review. Actions that are excluded from NEPA include categorical exclusions (i.e., actions that do not individually or cumulatively have a significant impact on the environment [40 CFR 1508.4]) and actions that have been statutorily exempted by Congress. Actions excluded from CEQA include those that are not defined as a project (§15378, OPR 1994), projects that have been granted exemption by statute (Article 18) or by categorical exemption (Article 19), and projects covered by the general rule that CEQA applies only to projects that have the potential to cause significant effects to the environment. If the agency responsible for conducting the NEPA or CEQA review determines a project is exempt from NEPA and CEQA, no further analysis is required and the agency either files no additional papers

Table 7
Three-level Review Processes Mandated by CEQA and NEPA

Step	NEPA	CEQA	Purpose
1	Preliminary Review	Preliminary Review	Determine whether project is exempt from NEPA/CEQA review
2	Environmental Assessment	Initial Study	Identify potentially significant environmental effects of the proposed project Identify and evaluate feasible alternatives (NEPA only)
3	Environmental Impact Statement	Environmental Impact Report	Provide detailed analysis of the potential environmental effects of the proposed project and its alternatives (CEQA and NEPA) Identify feasible mitigation measures to offset significant environmental effects

(NEPA) or files a Notice of Exemption with the California Office of Planning and Research (CEQA) (§15062, OPR 1994).

If a project is not exempt, the agency continues to the second level of analysis to determine whether the project may have "significant" environmental effects. This step requires the preparation of an environmental assessment (under NEPA) or an initial study (under CEQA). The environmental assessment, which is primarily a tool for determining whether the impacts of a proposed action *may be* significant [40 CFR 1508.9(a)] must describe the need for proposed action, feasible alternatives to the proposed action, and the environmental impacts of the proposed action and its alternatives [40 CFR 1508.9(b)]. The requirements for the initial study are similar although identification and evaluation of alternatives are not required.

The definition of "significant" is fundamental to this level of the NEPA and CEQA review. NEPA does not specifically define "significant" but states that "the definition ... is based on the context and the intensity of the action" (40 CFR 1508.27). CEQA defines a "significant" effect as "a substantial, or potentially substantial, adverse change in any of the physical conditions within the area affected by the project including land, air, water, minerals, flora, fauna, ambient noise and objects of historic or aesthetic significance" (§15382, OPR 1994). However, the CEQA Guidelines acknowledge that the determination of significance "calls for careful judgment on the part of the public agency involved, based to the extent possible on scientific and factual data" (§15064, OPR 1994). In addition, CEQA contains mandatory findings of significance, a list of projects or situations for which impacts are always considered to be potentially significant. These mandatory findings include projects that have "the potential to achieve short-term environmental goals to the disadvantage of long-term environmental goals" (§15065b, OPR 1994).

If an agency determines in its environmental assessment or its initial study that the potential for a significant environmental effect does not exist, the agency prepares a *Finding of No Significant Impact* (FONSI) under NEPA or a *Negative Declaration* under CEQA and conducts no further analysis. If the lead agency determines that the proposed action may result in significant effects to the environment, the third level of more detailed analysis is required - an Environmental Impact Statement under NEPA and an Environmental Impact Report under CEQA. These studies are required to provide detailed analysis of the potentially significant impacts of the proposed project and its feasible alternatives and must follow a detailed public review and participation process.

If members of the public do not agree with the issuance of a FONSI or Negative Declaration, they may sue the agency that conducted the NEPA or CEQA analysis upon issuance of the FONSI or Negative Declaration. In addition, the public can sue the agency conducting the

NEPA or CEQA analysis upon the agencies' adoption of the final Environmental Impact Statement or final Environmental Impact Report.

METHODS

To determine the scope and content of the environmental analyses completed for the five projects, we reviewed NEPA and CEQA documentation prepared by state and federal agencies for each project. We also reviewed permits issued for the five projects from all agencies with jurisdiction over project construction. Specifically, we sought to determine (1.) the level of CEQA or NEPA analysis completed for each project and the appropriateness of this level; (2.) whether the environmental analysis included consideration of geomorphic processes; and (3.) what specific geomorphic monitoring requirements, if any, were included in project permits and proposals.

RESULTS

Level of Environmental Analysis Completed

For all five projects reviewed, CEQA analysis was completed by the CDFG, as the project proponent, and NEPA analysis was completed by the Corps of Engineers, who issued permits under the jurisdiction of section 404 of the Clean Water Act. Permits were also issued by four additional state agencies including the Regional Water Quality Control Board, State Reclamation Board, State Lands Commission, and the California Mining and Geology Board (table 8).

Under CEQA, the nine riffle rehabilitation sites were determined to be categorically exempt from review under Class 4(d) as "minor alterations of the land, water, and vegetation existing on officially designated wildlife management areas or fish production facilities which result in improvement of habitat for fish and wildlife resources or greater fish production" [§15304(d), OPR 1994]. The Ruddy Site was not included under this exemption, and an initial study and negative declaration were prepared by the CDFG (CDFG 1991a).

The Corps of Engineers authorized the nine riffle rehabilitation sites under an existing general permit and, therefore, did not complete a NEPA assessment for the nine riffle rehabilitation sites. General permits are issued on a regional or nationwide basis for a category of activities for which individual and cumulative impacts are believed to be minimal. Although the authorization of individual projects under a general permit does not require a NEPA review for the individual project, the district engineer can assert discretionary authority to override the regional permit and require individual project review. These four projects were authorized by General Permit Number 008 - State of California - Fill for Spawning Areas which allows the placement of fill below the "ordinary high water elevation ... for rehabilitation of salmon

Table 8

Environmental Assessment of Projects Completed Under the Four Pumps Agreement on the Stanislaus, Tuolumne, and Merced Rivers

River Mile (construction date)	Project Name	Environmental Assessment under NEPA	Environmental Assessment under CEQA	CDFG[a]	RWQCB[a]	Reclamation Board	USCOE[a]	SLC[a]	CMGB[a]
Riffle Reconstruction									
Merced 39.0 (1990)	*Merced River Salmon Spawning* Gravel Improvement Project *(Phase I - Riffle 1B)*	Project authorized under General Permit Number 008 - No NEPA documentation required for individual projects	Notice of Categorical Exemption filed by CDFG with Governor's Office of Planning and Research (August 1989) based on Class 4, Section (d) of CEQA guideline 15304 ("minor alterations")	Streambed Alteration Agreement (5/90)	Notification (7/89)	Permit No. 15309 GM (11/89)	GP-008 (7/89)	Lease No. 7324.9 (8/89)	nr[b]
Merced 37.5-38.5 (1991)	Merced River Salmon Spawning Gravel Enhancement below *Crocker-Huffman Dam (Phase II -* Sites 2 and 3)	*Project authorized under General* Permit Number 008 - No NEPA documentation required for individual projects	Notice of categorical exemption filed by CDFG with Office of Planning and Research (7/91) based on Section 15304, Class 4(d) of CEQA guidelines	Streambed Alteration Agreement (8/91)	nr[b]	Permit No. 15784 GM (11/89)	GP-008 (5/91)	Amend Lease No. 7324.9 (7/91)	nr[b]
Tuolumne 49.0-50.0 (1994)	Restoration of Salmon Spawning Habitat at Riffles 1B, 3A, and 3B, Lower Tuolumne River.	Project authorized under General Permit Number 008 - No NEPA documentation required for *individual projects*	Notice of Categorical Exemption *filed by CDFG with Governor's* Office of Planning and Research (April 1994) based on Class 4, Section (d) of CEQA guideline 15304 ("minor alterations")	Streambed Alteration Agreement (3/93)	Waiver (4/93)	Permit No. 16089 (7/93)	Included under General Permit No. 8	Lease (3/94)	Exemption (7/93)
Stanislaus 47.0-51.0 (1994)	Restoration of Salmon Spawning Riffles at River Miles 47.4, 50.4, and 50.9 - Lower Stanislaus River	Project authorized under General Permit Number 008 - No NEPA documentation required for individual projects	Notice of Categorical Exemption *filed by CDFG with Governor's* Office of Planning and Research *(January 1994)* based on Class 4, Section (d) of CEQA guideline 15304 ("minor alterations")	Stream Alteration Notification #4-025-94 (4/94)	Water Quality 401 Certification (2/94)	Permit No. 16185 GM (5/94)	GP-008 (2/94)	General Lease 7739.9 (7/94)	Exemption From S.M.A.R.A. Section 2714 (f) (5/94)
Large-scale Channel Reconstruction									
Tuolumne 39.0-39.5 (1993)	Tuolumne River Salmon Habitat Enhancement (Ruddy site)	Environmental Assessment completed (No. 9100571), Finding of No Significant Impact issued, (USCOE 1991)	Initial Study completed, Negative Declaration issued (CDFG 1991a)	MOU (8/89)	Water Quality 401 *Certification* (9/91)	Permit No. 15790 GM (4/92)	191100571 (10/91)	Lease No. 7575 (9/91)	nr[b]

[a]CDFG (California Department of Fish and Game), RWQCB (Regional Water Quality Control Board), USCOE (U.S. Army Corps of Engineers), SLC (State Lands Commission), CMGB (California Mining and Geology Board)

[b]No record in information we obtained from project files

spawning areas in the Sacramento-San Joaquin River system ..." (USCOE 1993a). Actions authorized by this permit include construction of low berms to retain spawning gravel, addition of gravel to spawning sites, removal of "unsuitable habitat", loosening of compacted gravel, and modification or restoration of side channels that historically maintained salmon or steelhead spawning populations.

The Ruddy Site was not covered by the regional permit and, therefore, required individual NEPA review. For this project, the Corps of Engineers completed an environmental assessment followed by a FONSI, determining that the project would not result in significant environmental impacts.

Consideration of Geomorphic Processes in Environmental Review

For the nine riffle reconstruction sites, no CEQA or NEPA environmental review was conducted, so there was no opportunity to consider geomorphic processes in the environmental review. However, in issuing General Permit 008, the Corps of Engineers implicitly assumed that such physical modifications (undertaken with good intentions) would not have detrimental geomorphic and environmental effects. General Permit 008 presented no evidence to support the assumption that such projects would have no geomorphic or adverse environmental impacts.

For the Ruddy Site project, neither the CDFG initial study nor the Corps of Engineers environmental assessment included a geomorphic analysis or referred to an analysis completed by the project consultant during the project design phase. The CDFG initial study noted changes to channel and floodplain geometry directly resulting from excavation of the new channel but did not address future (short-term or long-term) changes in channel morphology resulting from flows and sediment transport expected to occur at the site (table 9). The Corps of Engineers environmental assessment also noted changes in the landscape directly resulting from excavation of the new channel but did not consider changes in channel morphology resulting from flows and sediment transport expected to occur at the site. In addition, the environmental assessment stated that the project would improve sediment transport through the project reach but did not provide the basis for this conclusion or establish that sediment transport at the site was a problem (table 10).

Monitoring

For all five projects evaluated, none of the funding, constructing, or permitting agencies required specific measures to monitor channel morphology and, by implication, physical habitat at the project sites in the years following project construction. At the nine riffle reconstruction sites, project monitoring was not mentioned in any project proposal or permit. The monitoring

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Table 9
CDFG Responses to CEQA Checklist for the Ruddy Site
(CDFG Proposed Negative Declaration, July 1991)

Excerpt from CEQA Review Checklist	Agency Response
Will the project result in:	
unstable earth conditions or changes in geologic substructures?	No
disruptions, displacement, compaction or uncovering of the soil?	Yes - "The existing active stream channel is narrow and relatively deep and provides little salmon spawning habitat. A new stream channel containing appropriate width and slope to achieve suitable spawning habitat will be constructed within the historic floodplain and generally north of the existing channel. The floodplain will be contoured to allow flood flows within the present flow regime to spread out onto the floodplain. This will require the movement of large amounts of gravel material to cut a new 2,330-foot stream [710 m] channel and fill the present active stream channel. The dredged material from the new stream channel will become the fill material for the old channel; no material will be removed from or transported to the site. The on-site material is largely sand, gravel and rock, and contains very little 'soil'."
change in topography or ground surface relief features?	Yes - "The general topography of the area will be unchanged. The stream channel will be realigned and the floodplain graded, however, all construction activity will take place within the existing flood channel."
the disruption, covering, or modification of any unique geologic or physical features?	No
any increase in wind or water erosion of soils, either on or off the site?	No
changes in deposition or erosion of beach sands, or changes in siltation, deposition or erosion which may modify the channel of a river or stream or the bed of the ocean or any bay, inlet or lake?	Maybe - "The existing active stream channel will be modified according to engineered plans to create suitable salmon spawning riffles and nursery areas. The floodplain will be modified according to design utilizing the past 20 years of streamflow data that will enable high flows to utilize the floodplain area."
exposure of people or property to geologic hazards such as earthquakes, landslides, mudslides, ground failure, or similar hazards?	No

source: CDFG 1991a

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Table 10
Corps of Engineers Responses to NEPA Checklist for the Ruddy Site
(USCOE Permit No. 19100571, October 1991)

Excerpt from NEPA Review Checklist	**Agency Response**
Physical/chemical characteristics and anticipated changes:	
substrate	"The river channel will be redirected and the floodplain will be recontoured, requiring relocation of large quantities of rock and gravel. A new stream channel with appropriate width and slope will be created. All material will come from on-site. No material will be removed from or transported to the construction site. Very little 'soil' will be removed according to the Negative Declaration."
currents, circulation or drainage patterns	"The existing stream channel in the project reach will be realigned. A new bankfull channel will be formed. An improved stream flow with [sic] enable natural gravel recruitment to occur. Transport of fine sediments will also improve."
suspended particulates; turbidity	"The creation of a low flow channel and properly elevated floodplain will allow improve [sic] sediment transportation. Most of the channel shaping and relocation will take place outside of the wetted steam [sic] channel. Turbidity levels are expected to increase during the period when the new channel is connected with the existing channel. Construction will occur when stream flows are low, and suspended particulates are not expected to have a substantial effect to downstream habitat..."

source: USCOE 1991

undertaken at these sites was limited to (1) annual redd counts at all sites by the CDFG, and (2) monitoring of planted riparian vegetation at the Ruddy Site.

At the Ruddy Site, no measures were specifically required and no funds were provided to complete monitoring of any geomorphic parameters, such as channel cross section, slope, or bed material size. The CDFG, in its initial study, stated that the agency "expects" the Ruddy Site to be monitored by the CDFG and the CDWR for six parameters but did not commit to a monitoring program. The CDFG also did not specifically require monitoring in their 1603 Stream Alteration Agreement for the project. The parameters "expected" to be monitored included numbers and relative proportion of spawning salmon utilizing the area, gravel quality in terms of hatching and emergent fry success, gravel quality in terms of intrusion of fine sediments, channel stability, riparian plant survival, and frequency of maintenance to maintain gravel quality (CDFG 1991a).

The permit issued by the Corps of Engineers required monitoring of the riparian vegetation planted at the Ruddy Site on the banks of the realigned channel and stated areas of vegetation types that must be attained at the site. The Corps permit required the establishment of the following "habitat types": 8.0 acres [3.2 ha] emergent/submergent, 2.3 acres [0.9 ha] oak woodland, and 4.8 acres [1.9 ha] mixed riparian. The permit stated that the CDFG "shall monitor the revegetation project and submit reports annually to the Corps of Engineers. The reports shall describe the acreage of each proposed habitat type to be established; identify deficiencies of the revegetation project, and specify corrective measures to make the revegetation project successful" (USCOE 1993b).

DISCUSSION

Consideration of Geomorphic Processes

Between 1990 and 1994, the CDWR and CDFG undertook substantial channel alterations at ten sites on the Tuolumne, Stanislaus, and Merced Rivers, including one project that moved 880 m (2,900 ft) of channel to a new location on the floodplain and four additional projects that excavated and reconstructed 1,800 m (5,900 ft) of channel at eight sites. Despite the experimental nature and the cumulative magnitude of these projects, four of the projects (involving reconstruction of nine riffles) received no NEPA or CEQA review of potential environmental impacts in general, and no review of potential interactions of the projects with geomorphic processes at the sites in particular. Rather, the funding, constructing, and permitting agencies *assumed* that the projects would be successful in creating the targeted channel parameters, that these features would persist in the long term, and that attainment of these physical parameters would improve salmonid spawning habitat. Based on these unsupported assumptions, all projects were determined to provide beneficial long-term effects to the environment and were excluded from individual project review.

The Ruddy Site project received intermediate level evaluation by the CDFG and the Corps of Engineers. However, despite the magnitude of the project (involving realignment of 0.9 km of river channel) neither agency considered geomorphic processes in their NEPA or CEQA evaluations. Again, the agencies *assumed* that the engineered, realigned channel would be successful in attaining the desired channel geometry and substrate character. Based on this assumption, the agencies determined the project would improve "natural" gravel recruitment to the channel and that the constructed channel geometry would benefit spawning salmon. However, lacking adequate geomorphic analysis, this determination could not be based on "scientific or factual data" as required by CEQA (§ 15064, OPR 1994) or on "sufficient evidence and analysis" as required by NEPA (40 CFR §1508.9).

To adequately assess the potential impacts of any project that proposes to alter channel morphology (including channel alignment, width, slope, or substrate character), the funding, constructing, and permitting agencies must consider the channel's short-term and long-term geomorphic response to channel and substrate modifications proposed by the project. Only an adequate geomorphic analysis can provide an adequate basis for the agencies to assess whether adverse environmental impacts (or the beneficial impacts expected from the project) are likely to occur. A geomorphic assessment should include (1) a historical analysis (Chapters Two and Eight) and (2) application of tractive force analyses such as the Shields criterion (Chapters Six and Seven) and/or a *geomorphically informed* application of available sediment transport models. Application of assumptions based on a channel classification system, especially by non-geomorphologist is *not* an adequate geomorphic analysis.

Although the channel response to a proposed project can be predicted in a general sense, the predictive ability of the geomorphic assessment and hydraulic modeling are limited, and considerable uncertainty will inevitably accompany any specific prediction. Thus, planning and permitting for any project which alters channel morphology also must include a program to monitor geomorphic parameters.

Monitoring

No funding, constructing, or permitting agency required or conducted monitoring of basic geomorphic parameters at any of the five project sites. The performance of the projects funded under the Four Pumps Agreement is to be reviewed and reported annually. However, no performance reviews of these projects had been undertaken as of 1995. The Agreement also states that the "ability and the cost to evaluate the success" of individual projects is one of five criteria used in selecting habitat rehabilitation projects to be implemented (CDWR and CDFG

1986). However, the Agreement does not specify who shall conduct this evaluation of project performance or how the evaluation is to be funded. The CDWR has interpreted the Agreement as making CDFG responsible for project monitoring and evaluation but has provided no Four Pumps funding to carry it out.

To date, the monitoring that has been conducted by CDFG has been limited to (1) annual redd counts, and (2) monitoring of riparian vegetation planted at the Ruddy Site. The redd count monitoring is important but not sufficient in evaluating project performance because it does not compare pre-construction to post-construction spawning at the project site or link changes in spawning usage at the site to the availability of physical habitat constructed by the projects. Moreover, changes in spawning usage and salmon populations at the sites may be affected by a host of factors other than availability of physical spawning habitat (the factor that is influenced by the project). Thus, the monitoring program may document increased spawning and fish populations at the project site, but these changes may be unrelated to (or in spite of) the effects of the project. Likewise, lack of change in spawning usage need not imply that the project failed to create adequate spawning habitat but simply may reflect overall population decline or lack of saturation of spawning habitat already available. This is especially true of anadromous fishes, where populations are affected not only by spawning habitat but also by fishing pressure, impediments to passage, availability and quality of downstream rearing habitat, predation, and conditions in the marine environment (Kondolf and Micheli 1995).

While the redd counts should continue as part of a project monitoring program, the preferred monitoring approach would also document the short-term and long-term development of the physical habitat parameters targeted by the project. For instance, for projects that seek to develop a specific channel planform, cross section, slope, and substrate character, the monitoring program should systematically evaluate the short-term and long-term development of the channel planform, cross section, slope, and substrate character. Specific components which should be incorporated into the monitoring program for spawning riffle reconstruction projects include channel cross section surveys, channel profile surveys, and pebble counts.

CONCLUSIONS

For the five projects completed to date, the agencies conducting the environmental reviews assumed the projects would have no environmental impact (or would be beneficial). No agency considered on-going geomorphic processes in its evaluation of potential project impacts. The lack of consideration of basic scientific information in the environmental review process fostered an oversimplification of project analysis and led to the unjustified assumption that constructed channel geometry and sediment character would prove to be stable under the discharge and sediment supply geomorphic conditions at the project sites. To avoid this mistake in the future, geomorphic assessments based on both historical analysis and geomorphic principles should be included in the NEPA and CEQA evaluations for projects that propose to alter channel geometry or substrate character. In addition, short-term and long-term channel response to the project should be systematically monitored to determine project performance.

Chapter 6. Post-project Evaluation of Salmonid Spawning Habitat Rehabilitation on the Merced River, Riffle 1B

In September 1990, a 122-m (400-foot) long reach of the Merced River approximately 60 m (197 ft) downstream of the Crocker-Huffman Dam was excavated and reconstructed as a spawning riffle. This project, designated as *Riffle 1B*, was the first riffle rehabilitation completed in the San Joaquin Basin with funds provided under the Four Pumps Agreement, and provided a good opportunity to evaluate the geomorphic stability of these riffle rehabilitation projects because it is representative of subsequent projects and because its condition could be observes in 1994 after four years of low flows. This chapter presents the results of field studies and tractive force analyses to determine the expected (theoretical) stability of the project site and the actual stability observed in the field.

SITE DESCRIPTION

The project site was located 25 km (16 miles) downstream of the New Exchequer Dam, originally constructed with 347 x 10^6 m^3 (281,000 acre-feet) capacity in 1926 and enlarged to its current capacity of 1.2 x 10^9 m^3 (1,032,000 acre-feet) in 1967. Downstream of New Exchequer Dam but upstream of the project site, there are three smaller dams: the McSwain Dam re-regulates flows released from New Exchequer Dam and generates hydroelectric power, and the Merced Falls and Crocker-Huffman dams divert water for agriculture (figure 12). These dams have eliminated the upstream supply of sand and gravel to the project site.

The coarsening of bed material, commonly observed below dams in response to the lack of sediment supply (Williams and Wolman 1984), has been documented on the Merced River (CDWR 1994b). At the project site, smaller gravel preferred by salmon for spawning has been transported downstream without being replaced with new gravel from upstream resulting in loss of spawning habitat. In an effort to "provide salmon spawning gravel for the purpose of increasing chinook salmon production on the Merced River" (CDFG 1989:1), the CDWR replaced the existing bed material at the site with spawning-sized gravel in 1990.

The project involved excavating a 122-m (367-foot) reach of the existing riverbed to a depth of about 0.6 m (2.0 feet) and backfilling the excavated channel with smaller spawning-sized gravel. To retain the imported gravel at the site, six lines of boulders were installed across the channel perpendicular to the flow, one of which was designated as a grade control structure (figure 13).

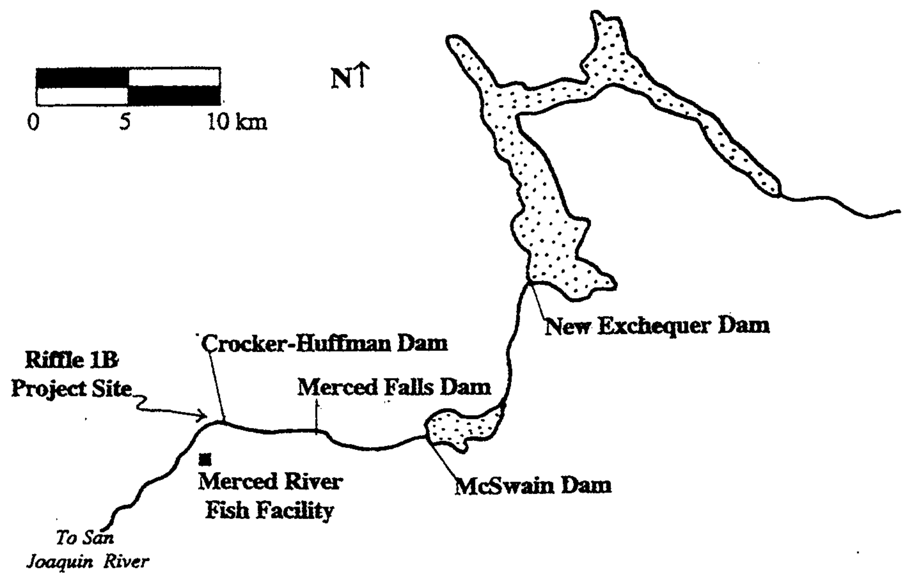

Figure 12. Map of riffle rehabilitation project at Riffle 1B in relation to four main dams on the lower Merced River.

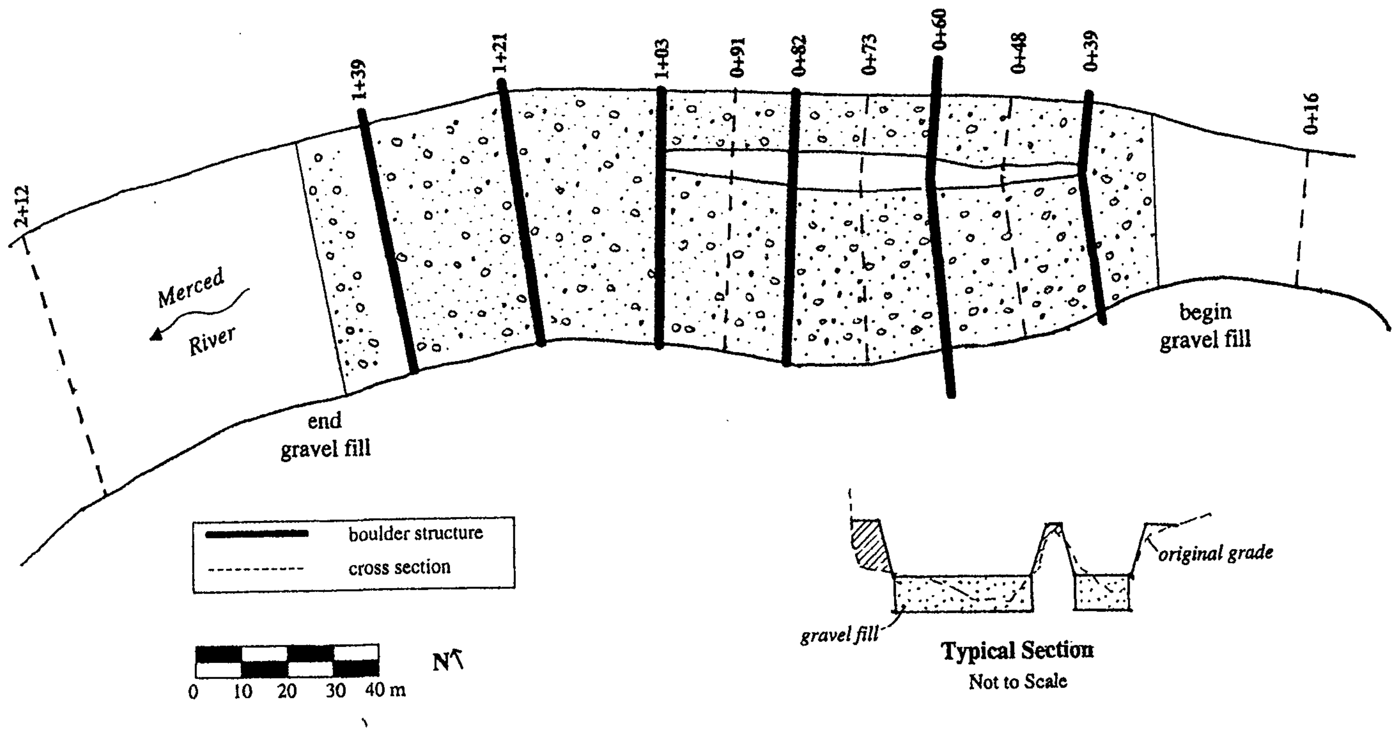

Figure 13. Site plan for riffle rehabilitation project at Riffle 1B on the Merced River, with locations of cross sections. See text for description. (adapted from plans included in CDFG 1990)

METHODS

We documented physical changes at the Riffle 1B project site since the completion of construction in 1990 by conducting channel surveys in 1994 and comparing the results with the project construction plans. Because changes in bed configuration implied movement of the imported gravel, we calculated the particle sizes that would be mobile under flow conditions experienced at the site since project completion.

Channel Surveys

We surveyed five cross sections and two longitudinal profiles (along the thalweg) of the channel bed in August and November 1994 (figure 13). An automatic level was used to measure elevations with respect to a benchmark established by CDFG at the Merced River Fish Facility (a hatchery located on the south bank of the river at the project site), and a tape was used to measure horizontal distances. We first measured distances along the channel downstream of the outlet of an artificial spawning channel leading to the hatchery and used these measured distances (stationing) to designate our cross sections and stations in our longitudinal profile. Within each cross section and in the longitudinal profiles, we measured points at 3-m (10-foot) intervals or at every slope break, whichever distance was shorter.

In August 1994, we surveyed two cross sections located 12 m (39 feet) upstream (cross section 0+16) and 65 m (213 feet) downstream (cross section 2+12) of the project boundaries. In November 1994 we surveyed three additional cross sections (0+48, 0+73, and 0+91) and longitudinal profiles of the main and side channels within the project boundaries. We plotted the 1994 surveys against the as-built project configuration as depicted in the design drawings to document changes in channel form since project construction. This approach assumes the project was built as specified in the drawings since no survey of the site was conducted immediately after project construction.

Flow Conditions

Mean daily flow records were obtained from the Merced Irrigation District's Crocker-Huffman stream gauge located approximately 200 m (655 feet) downstream of the project site. The discharge hydrograph was plotted with these values to identify periods of high flow since project construction (figure 14). To put these flows in a long-term context, we conducted flood frequency analyses for post-New Exchequer reservoir conditions (since 1967) using the annual maximum series.

In the course of surveying the channel in November 1994, we also measured the water surface elevation and gradient, flow depth, and flow velocity (by timing floats over a measured distance in the current) at a discharge of 6.2 m^3/s (220 cfs). We visited the site again in June

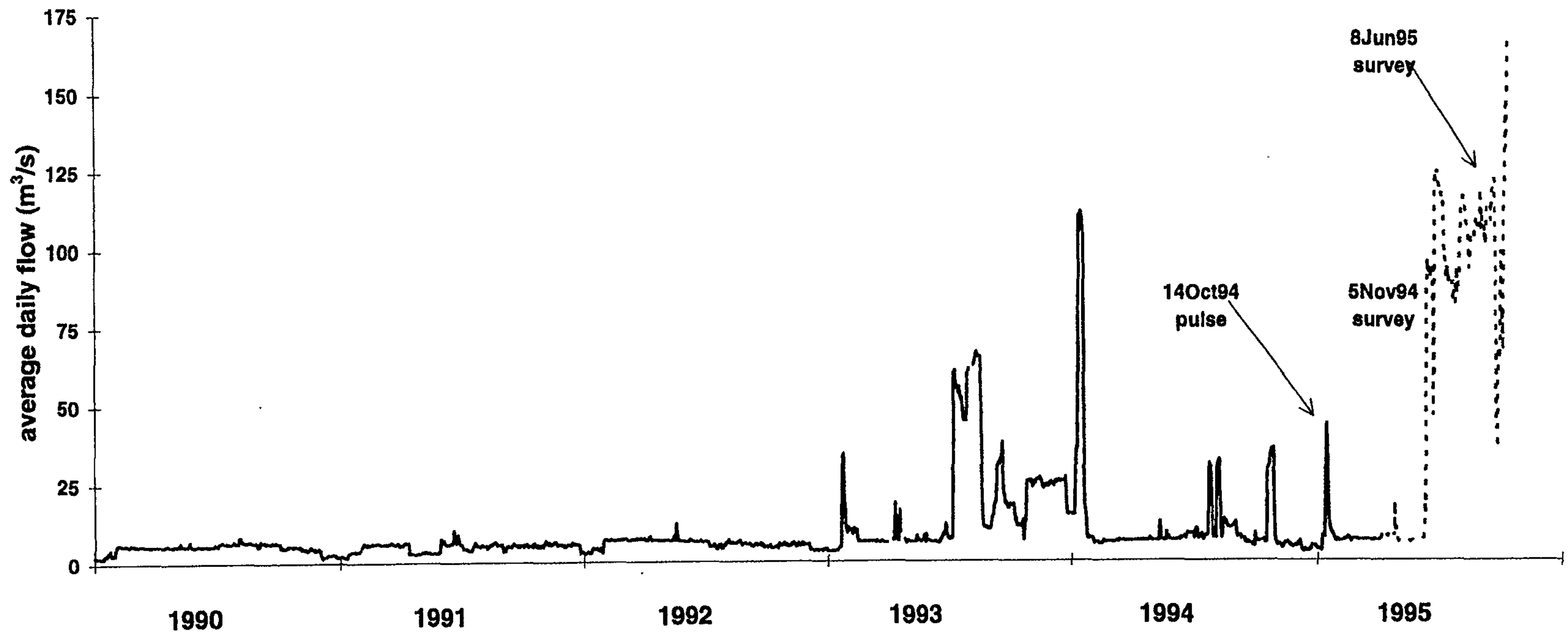

Figure 14. Hydrograph for Merced River below Crocker Huffman Dam for water years 1990 - 1995. (Water years begin October 1.) Solid line shows mean daily flows, dashed line reflects instantaneous flows at 0800 daily. (Data supplied by Merced Irrigation District, Merced, California)

1995, during a discharge of 112 m^3/s (3960 cfs) and measured water surface elevation and gradient, and flow velocity. High flow conditions prevented our conducting surveys of the channel bed at this discharge.

Because we had direct observations of flow conditions at 6.2 and 112 m^3/s we selected these discharges for bed mobility analysis. We also analyzed a third discharge, a peak flow of 43 m^3/s (1520 cfs) released in October 1994 to attract returning adult spawners into the river. Akagi (1994) placed 72 tracer gravel particles at the project site before the 43 m^3/s peak flow, providing direct observations of bed mobilization.

Bed Material Size

Unfortunately, the bed material size at the project site was not documented prior to project construction (or at least no such data were reported in project documents). To approximate pre-project bed material size, we conducted pebble counts (Wolman 1954) 12 m (39 ft) upstream of the project (at cross section 0+16). We also conducted pebble counts 65 m (213 ft) downstream of the project (at cross section 2+12) and obtained the size distribution of the gravel placed at Riffle 1B from construction specifications provided by the CDFG (CDFG 1990). From these data, we plotted cumulative size distributions for the bed upstream and downstream of the site and for the imported gravel at the site. These plots were used to estimate the d_{50} (the median grain diameter, or the size at which 50% of the sample is finer) and d_{90} (the size at which 90% of the sample is finer) of the pre-project and existing bed material.

Calculation of Shear Stress Exerted on the Bed

The assessment of gravel mobility requires the estimation of the forces applied on the channel bed by the flow (the bed shear stress) and an estimation of the force required to mobilize the particle sizes present at the site (the critical shear stress). We calculated the bed shear stress using the equation (Leopold et al. 1964),

$$\tau_b = \rho_f g R S \qquad [1]$$

where τ_b is bed shear stress
ρ_f is the density of water, for which we assume clear water at 4°C (1000 kg/m^3),
g is gravity (9.81 m/s^2),
R is the hydraulic radius (m), and
S is the energy slope, approximated by the water surface slope.

The bed shear stress (τ_b) is thus a function of the water surface slope (S) and the hydraulic radius (R). The hydraulic radius is given by A/wp, where A is the cross sectional area and wp is the wetted perimeter of the channel. For wide, shallow channels, R is commonly approximated by water depth, D.

Estimation of Slope and Depth at the 43 m^3/s Discharge

For the 6.2 m^3/s and 112 m^3/s discharges, we made direct measurements of water slope and depth. However, at 43 m^3/s we made no direct observations, nor could we find any clear high water marks afterward. Calculation of bed shear stress at 43 m^3/s, therefore, required estimation of water surface slope and depth for that discharge. To estimate slope, we plotted the water surface profiles at 6.2 and 112 m^3/s and interpolated a slope at 43 m^3/s between these profiles.

To estimate depth at 43 m^3/s, we solved the Manning and flow equations simultaneously. The Manning equation (Chow 1959) relates flow velocity to water surface slope, water depth and a roughness coefficient, n.

$$u = (1/n)\, R^{0.67} S^{0.5} \qquad [2]$$

where u is flow velocity (m/s), and
n is the Manning roughness coefficient

The flow equation (Chow 1959) relates discharge to mean velocity and cross sectional area.

$$Q = uA \qquad [3]$$

where Q is discharge (m^3/s), and
A is channel cross sectional area (m^2)

The roughness coefficient, n, is commonly estimated using photographic guides (Barnes 1967, Hicks and Mason 1991) or the incremental method (Chow 1959). To obtain a more site-specific estimate of the roughness coefficient, we back-calculated n at 6.2 m^3/s (the only discharge for which all other variables in the equations were known) and used these n values to calculate flow depth at 43 m^3/s. Although roughness typically changes with discharge, the values calculated here appeared reasonable for higher flows as well.

Calculation of Critical Shear Stress to Mobilize Gravel

We used the Shields criterion (Vanoni 1975, Richards 1982) to predict mobilization of bed material as a function of bed material size and shear stress.

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$$\tau_{ci} = \tau^*_{ci} (\rho_s - \rho_f) g d_i \quad [4]$$

where τ_{ci} is the critical shear stress (N/m^2) required to mobilize particle size d_i,
τ^*_{ci} is a dimensionless shear stress,
ρ_s is the density of the sediment, which we assume to be 2650 kg/m^3, and
d_i is the particle diameter (m)

The value of τ^*_{ci} is a function of the properties of the sediment mixture and typically ranges from 0.03 to 0.06. We assumed a value of 0.047, which was the average τ^*_{ci} back-calculated for the particles mobilized in Akagi's (1994) tracer gravel study (n=11, range in τ^*_{ci} from 0.031 to 0.075).

Using the calculated bed shear stress as τ_{ci}, we solved the Shields equation for the particle diameters mobilized (by the shear stress produced) at each of the specified discharges at the three cross sections surveyed in November 1994. Then, using the d_{50} of the pre-project gravel and the d_{50} and d_{90} of the imported gravel, we calculated the τ_{ci} necessary to mobilize the bed at each of the three cross sections surveyed. Using the d_{50} value in this calculation is consistent with Parker's theory of equal mobility (Parker and Klingeman 1982) which states that the entire channel bed is mobilized by the τ_{ci} needed to mobilize the d_{50}.

RESULTS AND DISCUSSION

Bed Material Transport Calculations

Prior to project construction, the surficial bed material at Riffle 1B, as determined by pebble counts at cross section 0+16, had a median size of 135 mm. By contrast, the gravel imported to the site for project construction had a median size of 24-31 mm (figure 15), or about 20% of the median size of the pre-project bed material at the site.

At a discharge of 6.2 m^3/s (the baseflow release during the fall spawning season), calculated bed shear stress ranged from 5.4 to 10.5 N/m^2 over the three surveyed cross sections, which is sufficient to mobilize particles 7-14 mm in diameter, or between the $<d_5$ and d_{16} of the imported gravel, or $<d_1$ of the pre-project bed material (table 11).

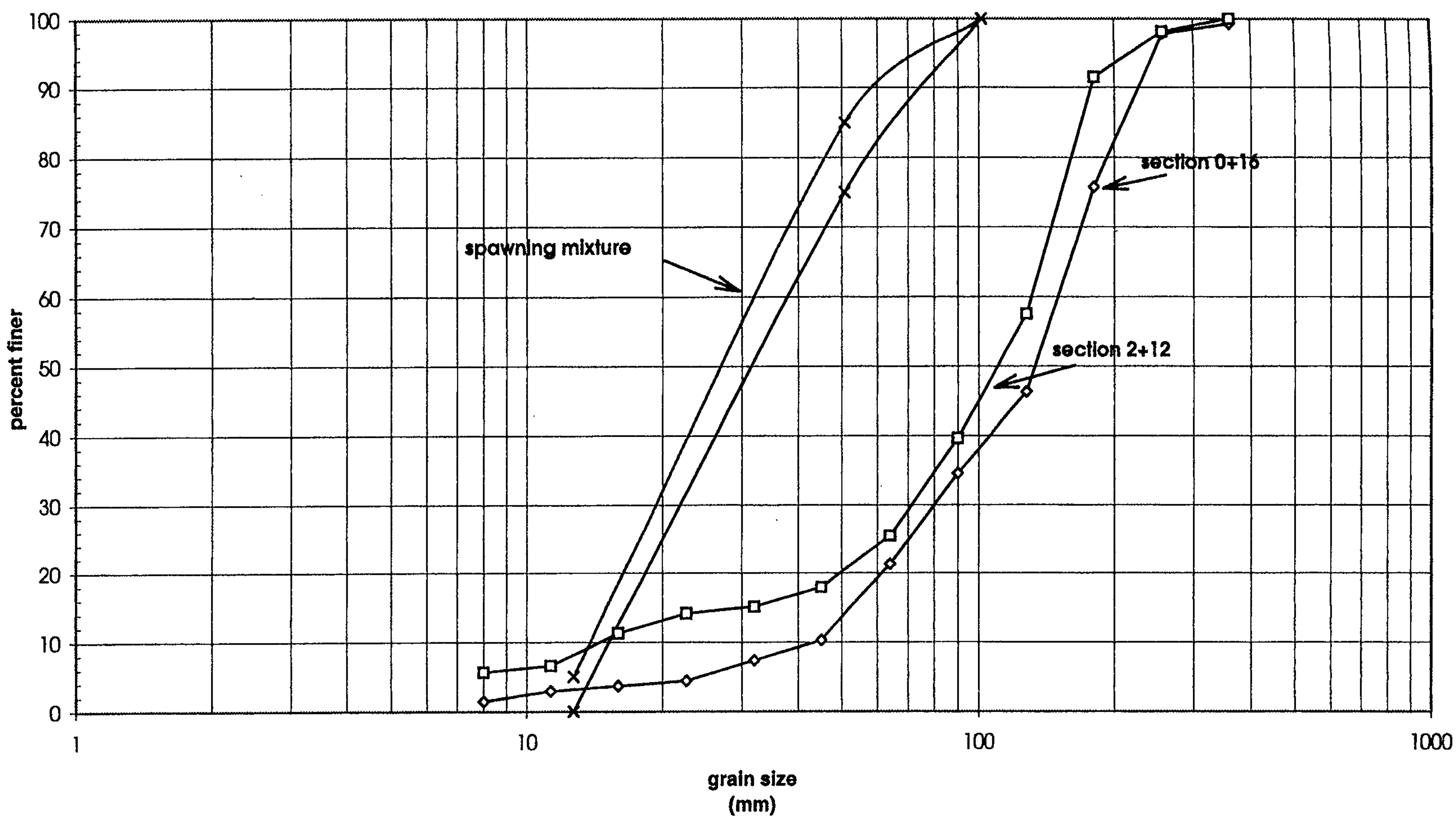

Figure 15. Cumulative size distributions for imported gravel placed in the Riffle 1B rehabilitation site (based on contract specifications) and for bed material 12 m upstream (cross section 0+16) and 65 m downstream (cross section 2+12) of the project reach, which reflect pre-project bed material in the project reach (from field measurements August 1994).

Table 11
Hydraulic Parameters for Cross Sections within the RIffle 1B Project Reach

	main channel			side channel		
	0+48	0+73	0+91	0+48	0+73	0+91
Q = 6.2 m³/s						
n	0.049	0.026	0.036	0.040	0.037	0.066
S	0.0017	0.0017	0.0030	0.0026	0.0013	0.0015
R (m)	0.52	0.33	0.36	0.33	0.49	0.49
T_b (N/m²)	8.67	5.44	10.50	8.44	6.22	7.22
d_{mob} (mm)	11	7	14	11	8	10
d_{mob} (percentile[a])	$< d_5$	$< d_5$	$d_8 - d_{16}$	$< d_5$	$< d_5$	$< d_5$
Q = 43 m³/s						
n	0.049	0.026	0.036	0.040	0.037	0.066
S	0.0029	0.0023	0.0033	0.0035	0.0021	0.0022
R (m)	1.20	0.94	1.00	1.05	0.81	1.42
T_b (N/m²)	34.08	21.11	32.27	35.90	16.64	30.59
d_{mob} (mm)	45	28	43	47	22	40
d_{mob} (percentile[a])	$d_{68} - d_{81}$	$d_{45} - d_{58}$	$d_{66} - d_{79}$	$d_{71} - d_{83}$	$d_{32} - d_{44}$	$d_{63} - d_{76}$
Q = 112 m³/s						
n	--	--	--	--	--	--
S	0.0055	0.0039	0.0039	0.0055	0.0039	0.0039
R (m)	1.89	1.65	1.72	1.75	1.93	1.87
T_b (N/m²)	101.99	63.25	65.77	94.26	73.75	71.37
d_{mob} (mm)	135	84	87	125	98	94
d_{mob} (percentile[a])	$> d_{100}$	$d_{92} - d_{97}$	$d_{94} - d_{98}$	$> d_{100}$	$d_{98} - d_{100}$	$d_{96} - d_{99}$

[a]size percentile of imported gravel

At a discharge of 43 m^3/s, the flow released in October 1994 to attract spawning salmon (return interval 1.5 years), calculated bed shear stress ranged from 16.6 to 34.1 N/m^2 over the three cross sections surveyed, which is sufficient to mobilize particles 22-47 mm in diameter, or between the d_{32} and d_{83} of the imported gravel (table 11). Mobility of the imported gravel at this discharge is also supported by Akagi's (1994) observations of tracer gravel at the project site in which particles up to 75 mm in diameter were transported during the 43 m^3/s discharge. This shear stress, however, would be sufficient to mobilize only the d_2-d_{10} of the pre-project bed material.

At a discharge of 112 m^3/s, the snowmelt season high flow observed in June 1995 (return interval 4.5 years), calculated bed shear stress ranged from 63.3 to 102.0 N/m^2 over the three cross sections (table 11). This shear stress is sufficient to mobilize particles 84-135 mm in diameter, or greater than the d_{90} of the imported gravel. This shear stress would mobilize the d_{32}-d_{50} of the pre-project bed material.

Based on the Shields analysis, the τ_{ci} for the d_{50} of the imported gravel was exceeded at 43 m^3/s at all cross sections in the main channel and two cross sections in the side channel. The τ_{ci} to mobilize the d_{90} of the imported gravel was exceeded at 112 m^3/s at all cross sections. The τ_{ci} to mobilize the d_{50} of the pre-project bed material was not exceeded at any cross section at 43 m^3/s and was reached at only one cross section at 112 m^3/s (figure 16).

Tracer Gravel Mobility

In November 1994, Akagi (1994) placed 72 painted tracer gravels at four locations within the project site, two in the main channel and two in the side channel, and returned after the 43 m^3/s flow to document movement of the tracer particles. Of the 36 particles placed in the main channel, twenty were recovered, eleven downstream of their original placement. Of the 36 particles placed in the side channel, nineteen were recovered, two downstream of their original placement. However, six of these tracer gravels were lodged under a rock, which prevented mobilization.

The tracers that were mobilized in the main channel ranged in size from 6-75 mm (0.2-3.0 in) and averaged 47 mm (2.9 in). Distance traveled ranged from 0.6-6.8 m (2-22.4 ft) and averaged 2.7 m (8.9 ft). In the side channel, tracers that were mobilized were 75 and 95 mm in diameter and were transported 2.0 and 2.4 m (6.6 and 7.9 ft), respectively.

Channel Surveys

Mobilization and transport of bed material through the project site (as predicted by the tractive force analyses) was evident in the 1994 channel surveys. Our cross sections and long profiles showed that Riffle 1B changed significantly since its construction in 1990, with scour in

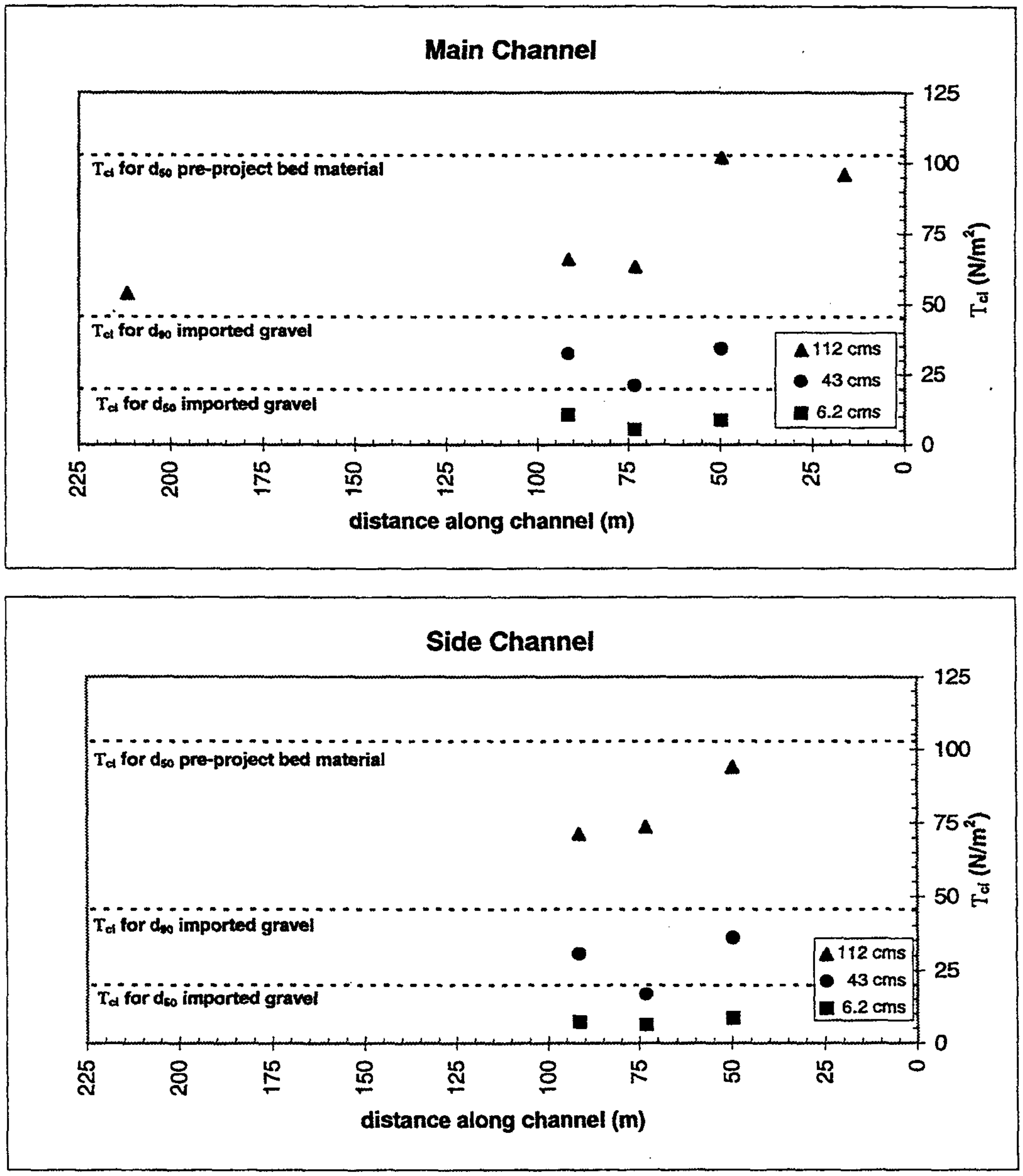

Figure 16. Plots of bed shear stress in main and side channels of Merced River in the Riffle 1B rehabilitation site at 6.2 m^3/s, 43 m^3/s, and 112 m^3/s. Horizontal dashed lines indicate the critical shear stress needed to mobilize d_{50} and d_{90} of the imported gravel and d_{50} of the pre-project bed material. The 43 m^3/s discharge is capable of moving the d_{50} of the imported gravel at five of the six cross sections, and the 112 m^3/s discharge is capable of moving the d_{90} of the imported gravel at all cross sections. The d_{50} of the pre-project bed material is immobile at all analyzed discharges.

the upper reaches and moderate scour and deposition in the lower reaches of the project site (figures 17 and 18). At cross section 0+48, both the main and side channels experienced significant scour, lowering the bed elevation by as much as 0.58 m (1.9 feet) from the constructed elevation. At cross section 0+73, sediment was deposited in the main channel, increasing bed elevation by as much as 0.42 m (1.4 feet) from the constructed elevation. The side channel at this cross section experienced both deposition and scour. At cross section 0+91, the main channel thalweg degraded (downcut) and deposition occurred along channel margins, while the side channel degraded as much as 0.11 m (0.36 feet). In addition, comparing the cumulative size distribution curves for the cross section upstream of the project (0+16) with that downstream (2+12) suggests that the fine tail of the distribution of the downstream section was augmented by 10-40 mm gravel, probably derived from the transport of imported gravel from the project reach upstream (figure 15).

It is also notable that the depth of scour in the upstream end of the project (0.6 m) is essentially the same as the depth to which the original bed was excavated, suggesting that the entire thickness of imported gravel was washed out at this location, and the channel scoured down until reaching the cobble bed at the level of excavation for the project. Thus, the channel at the project site has not simply reverted to pre-project conditions, but has actually degraded to the level to which it was excavated, 0.6 m (2.0 feet) below the original grade. Without a corresponding lowering of the effective hydraulic control for the reach, scour such as this could increase the water depth beyond the range suitable for spawning. The net result could be conversion from formerly marginal spawning habitat to no spawning habitat at all at sites of such scour.

Importantly, the scoured gravels were transported downstream despite the gravel retaining structures, with some being deposited as a bar along the right side of the main channel. This bar was above the water level at spawning flows, and thus these gravels are useless for spawning. As a deviation from the construction plans, a low flow channel was cut into at least one of the gravel retaining structures to facilitate fish migration at low flow (Kevin Faulkenberry, CDWR, personal communication 1995). Substantial downstream gravel transport occurred through this gap. Gravel was also transported over the tops of downstream grade control structures as illustrated by burial of the structures under newly-deposited mid-channel bars.

The high flows of the 1995 runoff season resulted in additional transport of gravels from the study site, beyond those reported from our field work of 1994. On a visual inspection of the study site in November 1995, we observed evidence of extensive washout of imported gravel and its deposition downstream of the project site.

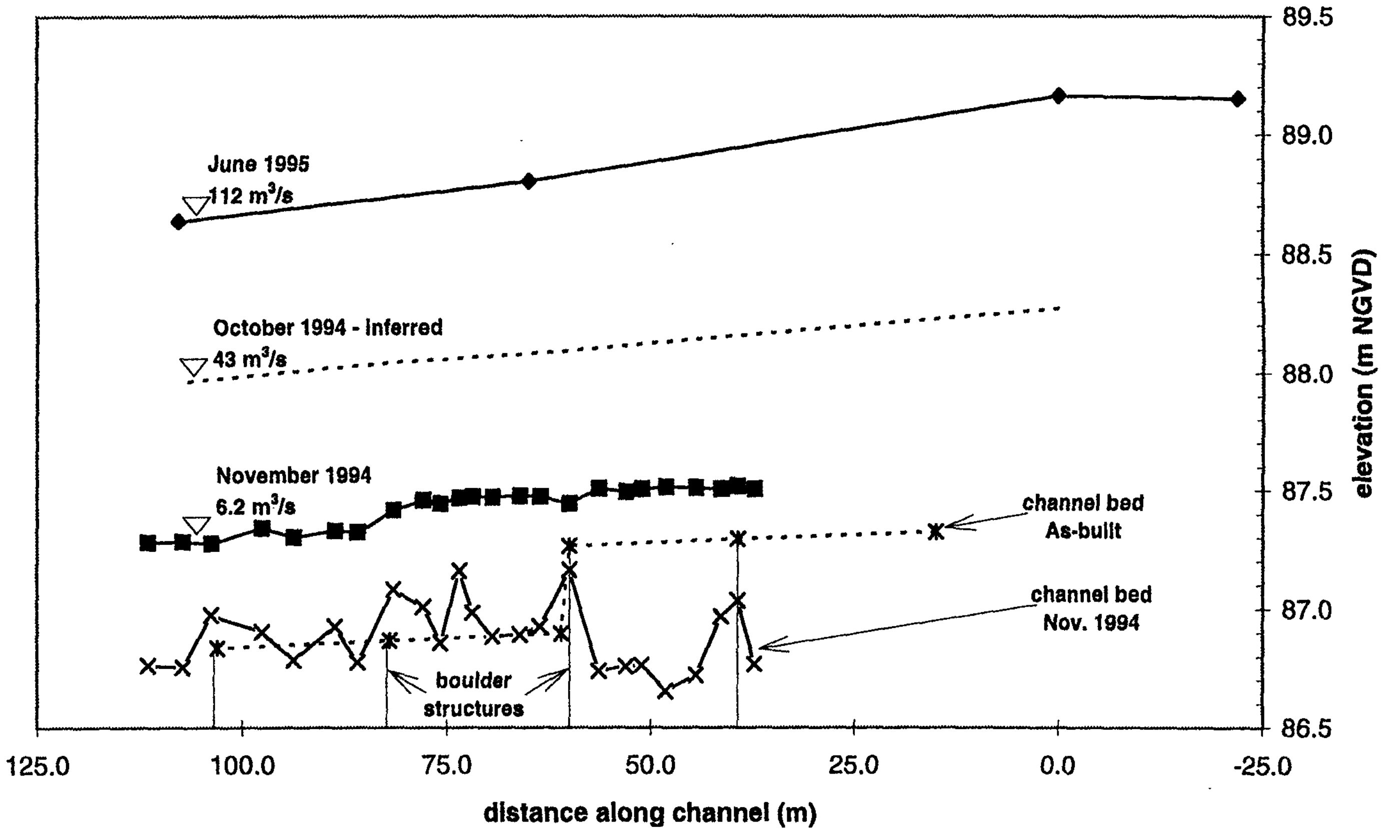

Figure 17. Surveyed water surface profiles and longitudinal bed profiles (from construction drawings and from field surveys November 1994) for the upstream 120 m (of 170 m total length) of Riffle 1B rehabilitation site (main channel only). Water surface elevation at 6.2 m^3/s surveyed November 1994, at 112 m^3/s surveyed June 1995, and at 43 m^3/s based on Manning's equation with slope interpolated between measured water surface slopes at 6.2 and 112 m^3/s.

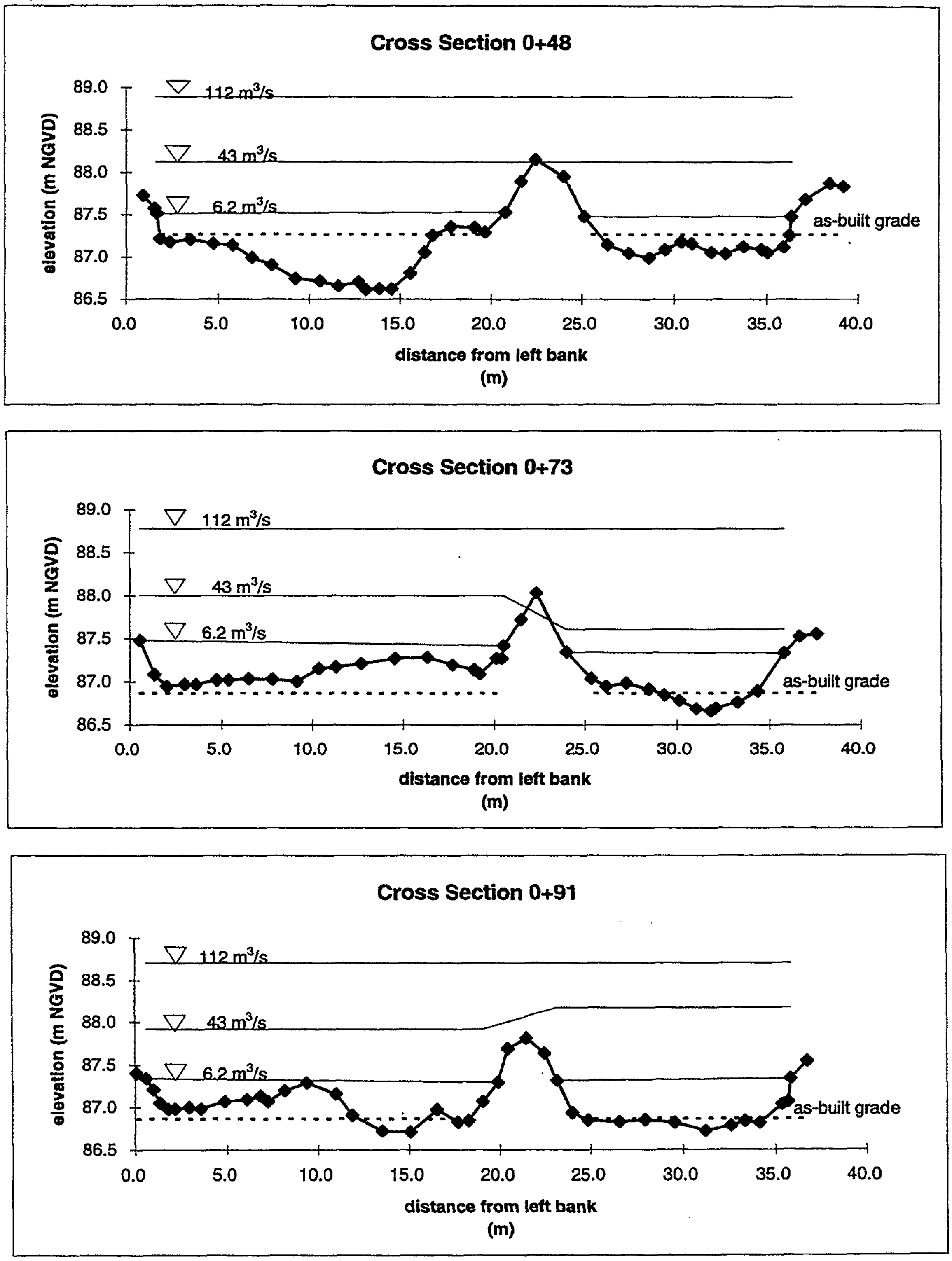

Figure 18. Channel cross sections of the Merced River in the Riffle 1B rehabilitation site. Bed elevations from surveys November 1994 and from construction plans.

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CONCLUSIONS

Our field measurements of changes in the channel form from 1990-1994, Akagi's (1994) tracer gravel observations, and our calculations of bed shear stress and particle mobilization under 1.5-year flow conditions clearly indicate that the smaller, imported gravel placed in the channel is unlikely to remain in place, even under modest flow conditions, and even with the designed grade control and drop structures in place. This bed mobility was observed in the surveyed channel changes, which showed significant scour and deposition in the project during relatively modest discharges during the drought years of 1990 to 1994. We did not resurvey the project after the higher flows of 1995, but a visual appraisal indicated further washout of the project.

While smaller, ideal spawning-sized gravel and bed mobility may be preferable for spawning habitat, these conditions must be considered in light of the geomorphic context of the project site. The pre-project bed material at this site was probably considerably coarser than under natural, pre-dam conditions because the sediment supply has been eliminated by the construction of dams upstream. Even though this coarsened condition may be undesirable for spawning habitat, it reflects an adjustment to sediment-starved conditions below the dam, and provides an indicator of the sizes of bed material likely to be stable under post-dam conditions. Replacing this bed with smaller gravels that are regularly mobilized under current conditions without addressing the lack of sediment supply does not provide a long-term solution to improving spawning habitat. Excavation of the stable channel bed may have actually further degraded the spawning habitat. If gravel importation projects are to be undertaken, our results demonstrate the need for frequent maintenance and addition of imported gravel.

Chapter 7. Post-project Evaluation of Salmonid Spawning Habitat Rehabilitation on the Stanislaus and Tuolumne Rivers

In 1994, two riffle rehabilitation projects (each involving three sites) were completed on the Stanislaus and Tuolumne Rivers. Riffles were reconstructed in a fashion similar to the Riffle 1B project on the Merced River (Chapter Six). In 1995, we resurveyed one project site on each river and calculated expected mobility. This chapter presents the results of the field surveys and calculations for the Tuolumne River Riffle 1B Site and the Stanislaus River RM 50.4 Site.

SITE DESCRIPTION

The Tuolumne River Riffle 1B is located approximately 1.7 km (1.1 miles) west of the town of La Grange and 3.2 river km (2 river miles) downstream of the La Grange Dam (figure 19). The La Grange Dam was constructed in 1894 and has a 617 $10^3 m^3$ (500 acre-foot) reservoir capacity. The New Don Pedro Dam, located 4.8 river km (3 river miles) upstream of the La Grange Dam, was originally constructed in 1923 with a capacity of 308 $10^6 m^3$ (250,000 acre-feet) and enlarged to its current capacity of 2.5 $10^9 m^3$ (2 million acre-feet) in 1971.

The Stanislaus River Riffle at RM 50.4 is located 13.3 km (8.3 miles) east of the town of Oakdale and 15.8 river km (9.8 river miles) downstream of the Goodwin Dam (figure 19). The Goodwin Dam was constructed in 1912 and has a 617 $10^3 m^3$ reservoir capacity. The New Melones Dam is located 27.4 river km (17 river miles) upstream of the Goodwin Dam. The New Meolones Dam was originally constructed in 1926 with a capacity of 139 $10^6 m^3$ and enlarged to its current capacity of 3.0 $10^9 m^3$ in 1979.

At both sites, the CDFG attributed the lack of spawning usage to a lack of gravel recruitment and the infiltration of fine sediments into the coarsened bed material downstream of the dams (CDFG 1993, 1994). The purpose of these projects was to improve spawning habitat at the sites by replacing the existing bed material with clean, spawning-sized gravel in 1994.

At the Tuolumne River Riffle 1B Site, the rehabilitation project involved excavating a 91-m (300-ft) reach of the existing riverbed to a depth of about 0.5 m (1.5 ft) and backfilling the excavated channel with 1,300 m^3 (1,700 yd^3) of spawning-sized gravel (figure 20). Two boulder weirs were constructed to establish a grade of between 0.2% and 0.5% and retain the imported gravel on the project site during high flows. At the Stanislaus River Riffle RM 50.4 Site, the project involved excavating a 61-m (200-ft) reach of the existing riverbed to a depth of about 0.5 m and backfilling the excavated channel with 757 m^3 (990 yd^3) of spawning-sized gravel (figure 21). One boulder weir was constructed to establish a grade of between 0.2% and 0.5% and retain the gravel on the site during high flows .

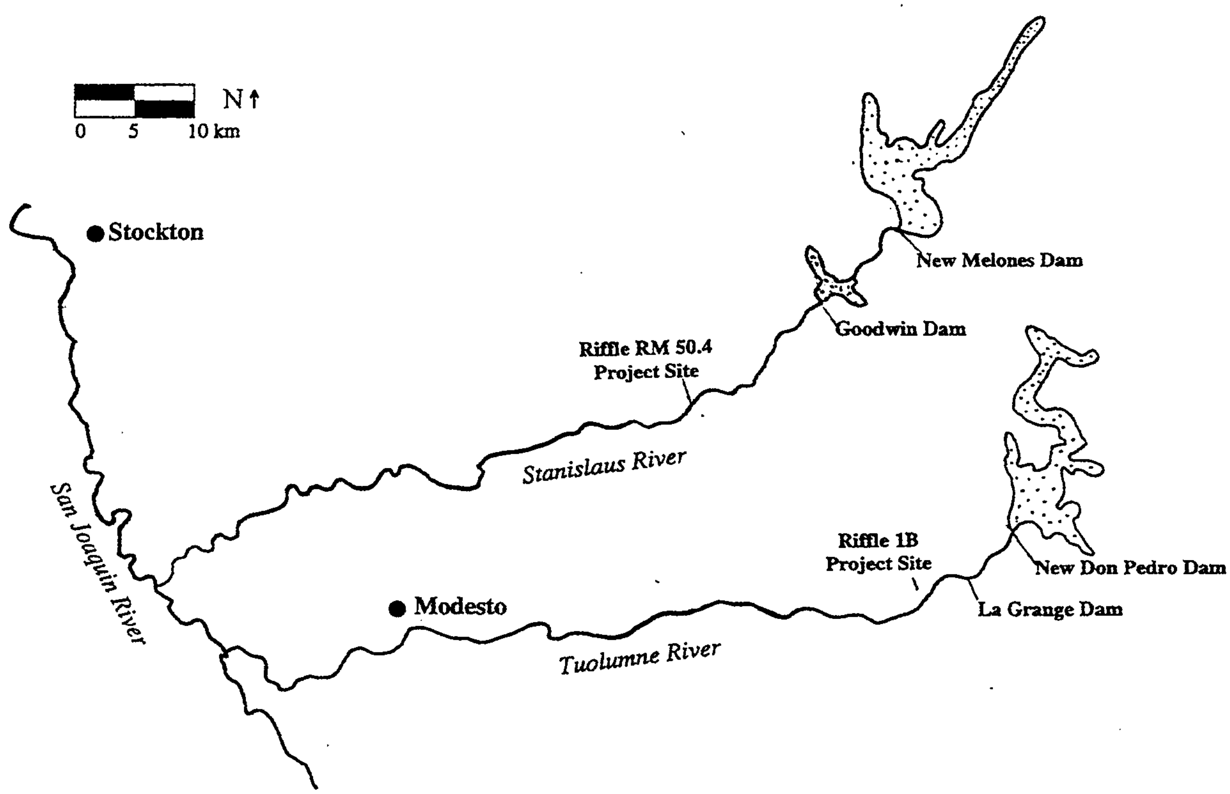

Figure 19. Map of riffle rehabilitation projects at Riffle 1B and RM 50.4 in relation to dams on the lower Tuolumne and Stanislaus Rivers.

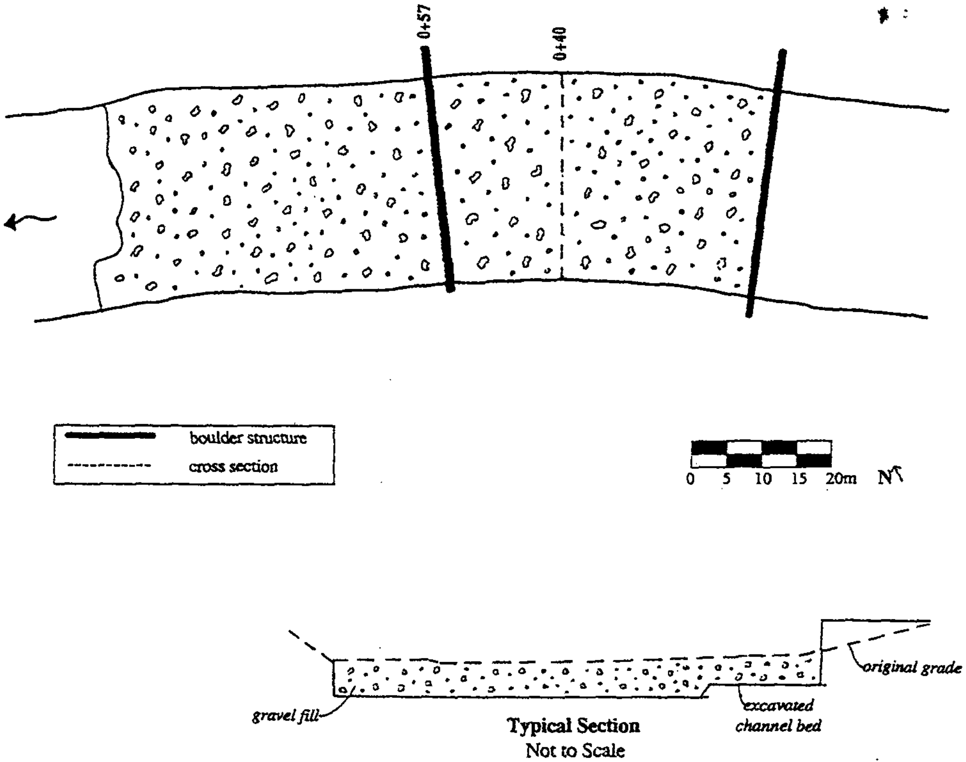

Figure 20. Site plan for riffle rehabilitation project at Riffle 1B on the Tuolumne River, with locations of our surveyed cross sections superimposed. See text for description.

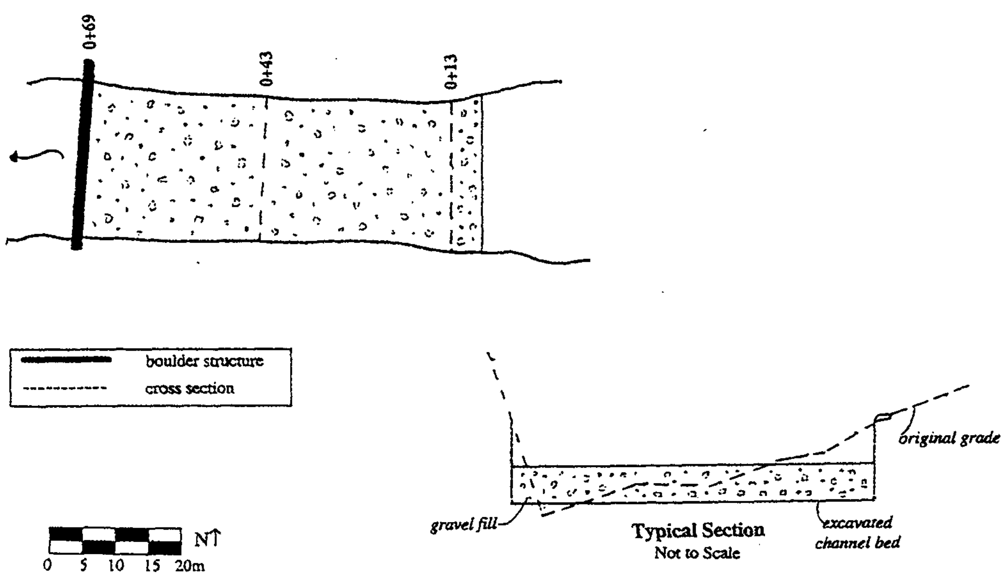

Figure 21. Site plan for riffle rehabilitation project at RM 50.4 on the Stanislaus River, with locations of our surveyed cross sections superimposed. See text for description.

METHODS

We documented physical changes at the Tuolumne River Riffle 1B and Stanislaus River Riffle RM 50.4 project sites since their completion in 1994 by conducting channel surveys at both sites in November 1995 and comparing these results with the project construction plans. Because changes in bed configuration implied movement of the imported gravel, we calculated the particle sizes that would be mobile under flow conditions surveyed at the sites after project completion.

Channel Surveys

At the Tuolumne River Riffle 1B Site, we surveyed two cross sections and a longitudinal profile (along the thalweg) of the channel bed in November 1995 (figure 20). At the Stanislaus River Riffle RM 50.4 Site, we surveyed three cross sections and two longitudinal profiles (one center line and one thalweg) of the channel bed in November 1995 (figure 21). The surveys were conducted using the methods described in Chapter Six. However, we were unable to recover the CDWR's vertical control points at the sites. It is likely that the points were destroyed or buried by high flows. We, therefore, used the average surveyed elevation of the downstream boulder control structure at each site to establish approximate vertical control, setting these average elevations equal to the structures' constructed elevations as indicated in the design plan drawings. Because this method provides only approximate vertical control, it limits our ability to document channel erosion or aggradation within the project sites.

We plotted the November 1995 surveys against the as-built project configurations as depicted in the design drawings to document changes in channel form since project construction. This approach assumes the projects were built as specified in the drawings since no survey of the site was conducted immediately after project construction.

Flow Conditions

Mean daily flow records were obtained from the USGS gauges on the Tuolumne River below La Grange Dam, approximately 2.4 river km (1.5 river miles) upstream of the Riffle 1B Site, and the Stanislaus River below Goodwin Dam, 14.3 river km (8.9 river miles) upstream of the RM 50.4 Site. Using these daily flow values, we plotted the discharge hydrographs for each river to identify periods of high flow since project construction (figures 22 and 23).

We also used these records to determine discharge at the sites during the channel surveys. USGS flow data were not available for the May 9, 1996 survey on the Stanislaus River. The average daily discharge at the site that day was assumed to equal the flow release from Goodwin Dam, obtained from the Tri-Dam Project Office (Manteca, Ca.). To put these flows in a long-term context, we conducted flood frequency analyses for post-New Melones reservoir conditions

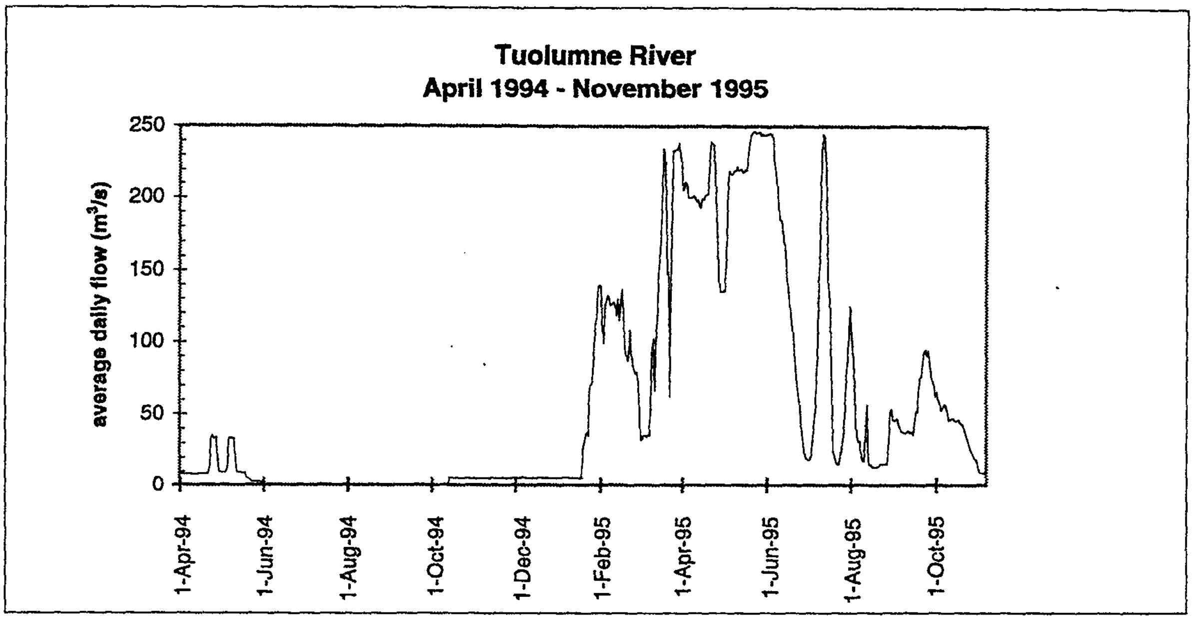

Figure 22. Hydrograph for the Tuolumne River below La Grange Dam for water years 1994 - 1996. (Water years begin October 1.) Solid line shows mean daily flows, dashed line reflects preliminary mean daily flow data. (source: USGS, Sacramento, California)

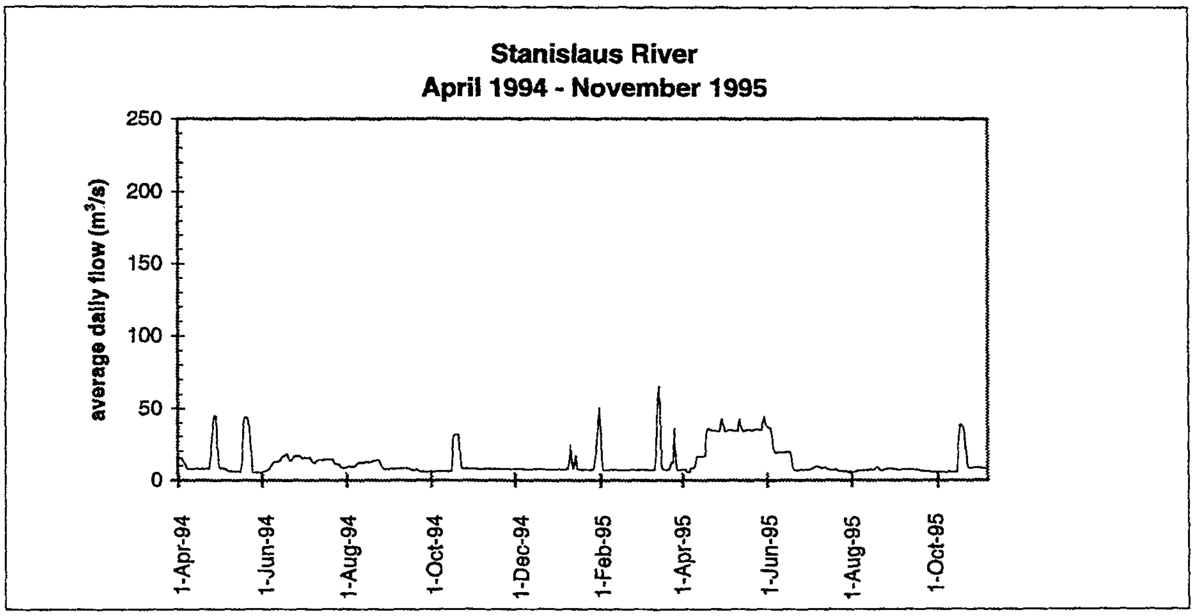

Figure 23. Hydrograph for the Stanislaus River below Goodwin Dam for water years 1994 - 1996. (Water years begin October 1.) Solid line shows mean daily flows, dashed line reflects preliminary mean daily flow data. (source: USGS, Sacramento, California)

(since 1979) on the Stanislaus River and the post-New Don Pedro reservoir conditions (since 1971) on the Tuolumne River using the annual maxima series.

In the course of surveying the channels in November 1995, we also measured flow depth, water surface elevation, and water surface gradient at 8.7 m^3/s (308 cfs) on the Tuolumne River and 8.4 m^3/s (296 cfs) on the Stanislaus River. In June 1995, we surveyed water surface elevation and gradient at the Tuolumne River Site during a discharge of 208 m^3/s (7,330 cfs), comparable to but less than the maximum mean daily flow of 245 m^3/s (8,670 cfs) between project construction in 1994 and our survey in 1995 (figure 22). In May 1996, we surveyed water surface elevation and gradient at the Stanislaus River Site during a discharge of 42 m^3/s (1,500 cfs), comparable to but less than the maximum daily discharge of 65 m^3/s (2,300 cfs) between project construction in 1994 and our survey in 1995 (figure 23). Thus, we obtained direct measurement of water depth and water surface gradient, variables needed to calculate shear stress on the bed, at flows representing conditions experienced at the sites after project construction.

Bed Material Size

We conducted one pebble count at each of the two project sites in November 1995. These counts documented the size of the imported bed material remaining in place at the site since project construction. We used these data to plot the cumulative size distribution of gravel remaining on the site. These plots were used to estimate the d_{50} (the median grain diameter, or the size at which 50% of the sample is finer) of the bed material remaining on the site since project construction. The pre-project bed material size at the sites was not documented.

We obtained the range of bed material sizes placed at the Riffle 1B and Riffle RM 50.4 Sites from CDFG project descriptions (CDFG 1993, 1994). These documents did not specify the particle size gradation or state the desired gravel mixture. We, therefore, assumed that the spawning mixture used at the Tuolumne and Stanislaus Sites was the same as that used at the Merced River Riffle 1B Site (Chapter Six).

Calculation of Shear Stress Exerted on the Bed

Using our direct measurements of flow depth and slope, we calculated basal shear stress (Chapter Six, equation one) and applied the Shields equation (Chapter Six, equation four) to determine the particle sizes that would be at incipient motion at the two sites during the flows for which data were collected. Using these equations, we determined the particle sizes at incipient motion for the 8.7 and 208 m^3/s (310 and 7,300 cfs) discharges on the Tuolumne River and the 8.4 and 42 m^3/s (300 and 1,500 cfs) discharges on the Stanislaus River.

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RESULTS

Bed Material Transport Calculations

Gravel imported to the project sites was reported to range in size from 13 to 102 mm, but grain size distributions of this material was not reported (CDFG 1993 and 1994). Surficial bed material sampled in November 1995 at the Tuolumne River Site ranged in size from <8 to 64 mm and had a d_{50} of 24 mm (figure 24). At the Stanislaus River Site, surficial material ranged from 8 to 64 mm and had a d_{50} of 23 mm (figure 24). The d_{50} of the material sampled at the two sites was similar to the d_{50} of the imported mixture at the Merced River Riffle 1B Site (Chapter Six), implying that similar gravel mixtures were used in these projects. The project documents did not include data describing bed material at the sites prior to project construction.

At the Tuolumne River Riffle 1B Site, calculated bed shear stress at the low spawning season flow during our field survey in November 1995 of 8.7 m^3/s (310 cfs, return interval < one year) ranged from 1.1 to 1.6 N/m^2 over the two cross sections surveyed (table 12). Particles expected to be mobilized at this discharge are $<d_1$ of the bed material sampled at the site, i.e. the bed was expected to be stable at this flow; consistent with our observations. At the high snowmelt release of June 1995 of 208 m^3/s (7,300 cfs, return interval 6.3 years), calculated bed shear stress ranged from 112 to 129 N/m^2 (table 12), mobilizing all sizes of the bed material sampled at the site ($>d_{100}$).

At the Stanislaus River RM 50.4 Site, calculated bed shear stress at the low spawning season flow during our field survey in November 1995 of 8.4 m^3/s (300 cfs, return interval < one year) ranged from 2.2 to 20 N/m^2 over the three cross sections surveyed (table 12). Particles expected to be mobilized at this discharge are between the $<d_1$ and d_{60} of the bed material sampled at the site, although we did not observe grains in motion at the time. At the high snowmelt release of May 1996 of 42 m^3/s (1,500 cfs, return interval 1.1 years), calculated bed shear stress ranged from 24 to 38 N/m^2 (table 12), capable of mobilizing particles as large as the d_{75} to d_{95} of the bed material sampled at the site.

Based on the Shields analysis, the τ_{ci} to mobilize the d_{50} of gravel sampled at the site, and a surrogate for the mobility of the bed, was exceeded at the Tuolumne River Site during the 6.3-year discharge and at the Stanislaus River Site during the 1.1-year discharge. The τ_{ci} for the d_{50} of gravel sampled at either site was not exceeded during the November 1995 spawning flows. Thus, the gravels in these projects can be expected to be stable during the controlled spawning season releases but not at higher flows experienced over the year.

Channel Surveys

Transport of bed material within the project sites was evident in the 1995 channel surveys. Our cross sections and long profiles show that the bed eroded at both sites between

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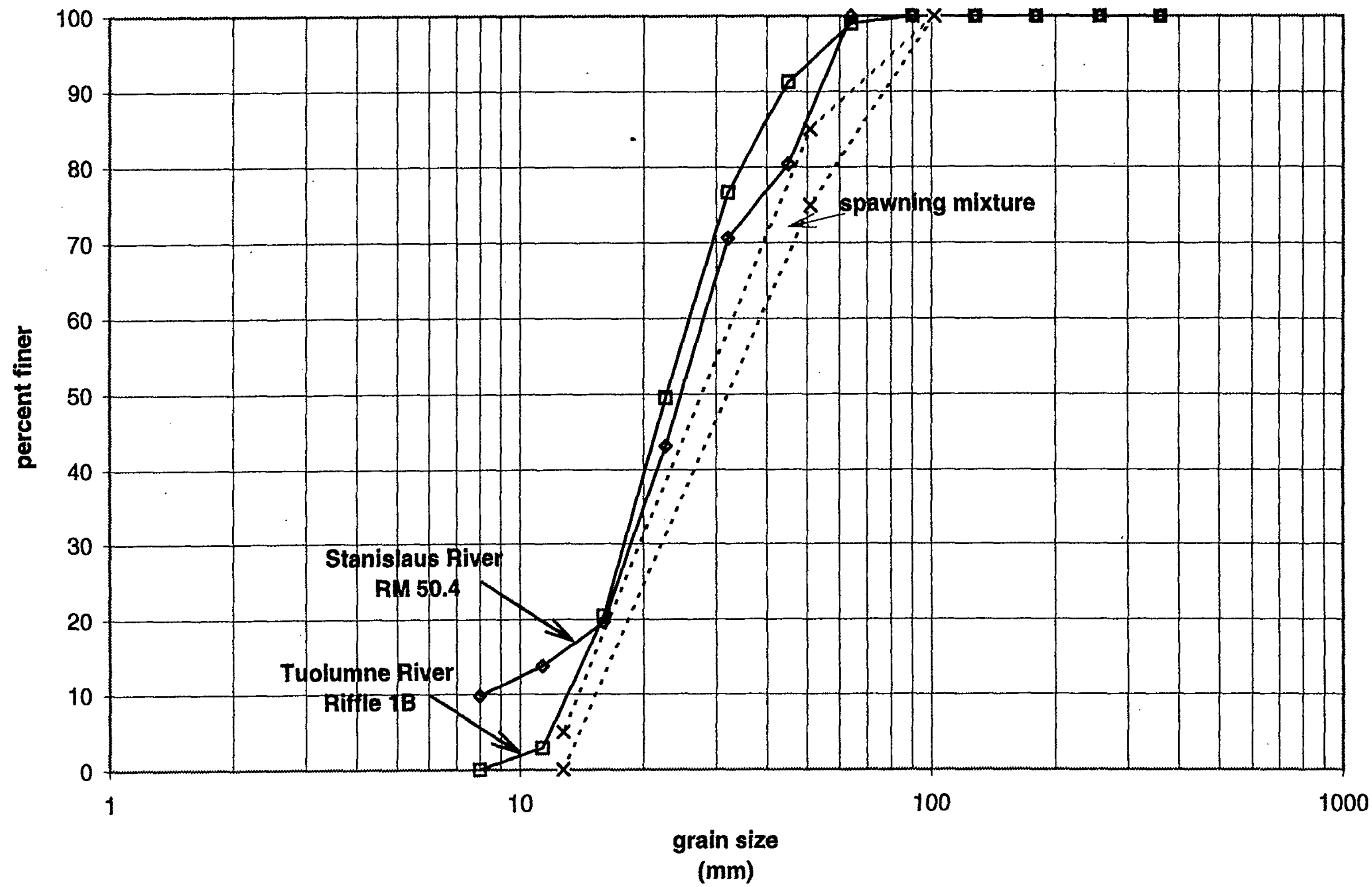

Figure 24. Cumulative size distributions for imported gravel remaining at the Riffle 1B and RM 50.4 rehabilitation sites (from field measurements November 1995).

Table 12
Calculated Basal Shear Stress and Particle Sizes Mobilized at the Tuolumne River Riffle 1B and Stanislaus River Riffle At Rm 50.4 Sites

Cross Section	Shear Stress (N/m^2)	Particle Size Mobilized (mm)	Percentile of Gravel Sampled at Site
TUOLUMNE RIVER			
November 1995			
$Q = 8.7\ m^3/s$			
0+57 m	1.1	1	$<d_1$
0+40 m	1.6	2	$<d_1$
June 1995			
$Q = 208\ m^3/s$			
0+57 m	110		$>d_{100}$
0+40 m	130	148	$>d_{100}$
STANISLAUS RIVER			
November 1995			
$Q = 8.4\ m^3/s$			
0+69 m	20	26	d_{60}
0+43 m	5.9	8	$<d_1$
0+13 m	2.2	3	$<d_1$
May 1996			
$Q = 42\ m^3/s$			
0+69 m	24	32	d_{75}
0+43 m	25	33	d_{76}
0+13 m	38	51	d_{95}

project construction in 1994 and field surveys in 1995. At the Riffle 1B Site on the Tuolumne River, the channel thalweg eroded a maximum 0.8 m (2.6 ft), and the bed changed from the constructed flat profile to a concave profile (figure 25). At cross section 0+40, the channel bed eroded by up to 0.8 m (2.6 ft) (figure 26). These values are only approximates since the vertical control for the survey was based on the average elevation of the downstream control structure. Cross section 0+57 was located on the grade control structure and, therefore, is not indicative of changes in channel bed elevation.

At the Riffle RM 50.4 Site on the Stanislaus River, the channel thalweg eroded a maximum 0.8 m (2.6 ft), and the centerline eroded a maximum 0.4 m (1.3 ft). As at the Tuolumne River Site, the bed changed from its constructed flat profile to a concave profile (figure 27). The channel bed eroded by up to 0.4 m (1.3 ft) at cross section 0+43 and 0.3 m (1.0 ft) at cross section 0+13 (figure 28). These values are approximate only as the vertical control for the survey was based on the average elevation of the control structure. Cross section 0+69 was located on the grade control structure and, therefore, is not indicative of changes in channel bed elevation.

DISCUSSION AND CONCLUSIONS

Like the Merced River Riffle 1B project, the Tuolumne and Stanislaus River riffle reconstruction projects were intended to create hydraulic conditions (flow slope, depth, and velocity) and provide bed material suitable for spawning chinook salmon. However, the design of these sites considered hydraulic conditions only at controlled releases during the fall spawning season, ignoring the effects of higher flows which would be expected to occur almost annually in other seasons. Boulder structures were assumed to prevent the imported gravel from being washed downstream from the site during higher flows.

In the period between project construction in 1994 and the channel survey in November 1995, the Tuolumne River Riffle 1B Site experienced flows exceeding 240 m^3/s (figure 22). Application of the Shields equation indicates these flows are sufficient to mobilize the gravel imported to the site, a prediction borne out by the bed erosion of up to 0.8 m (2.6 ft) we observed at the site. Absent an upstream supply of gravel similar in size to the imported gravel, we expect that channel bed at the project site will continue to erode until it reaches an equilibrium with the available sediment supply and discharge conditions of the river. This equilibrium will likely resemble the pre-project channel configuration, although perhaps with net bed lowering due to the excavation for the project.

On the Stanislaus River, the Riffle RM 50.4 Site experienced flows exceeding 42 m^3/s four times in the period between project construction and the channel survey (figure 23). Application of the Shields equation indicates these flows are sufficient to mobilize the gravel

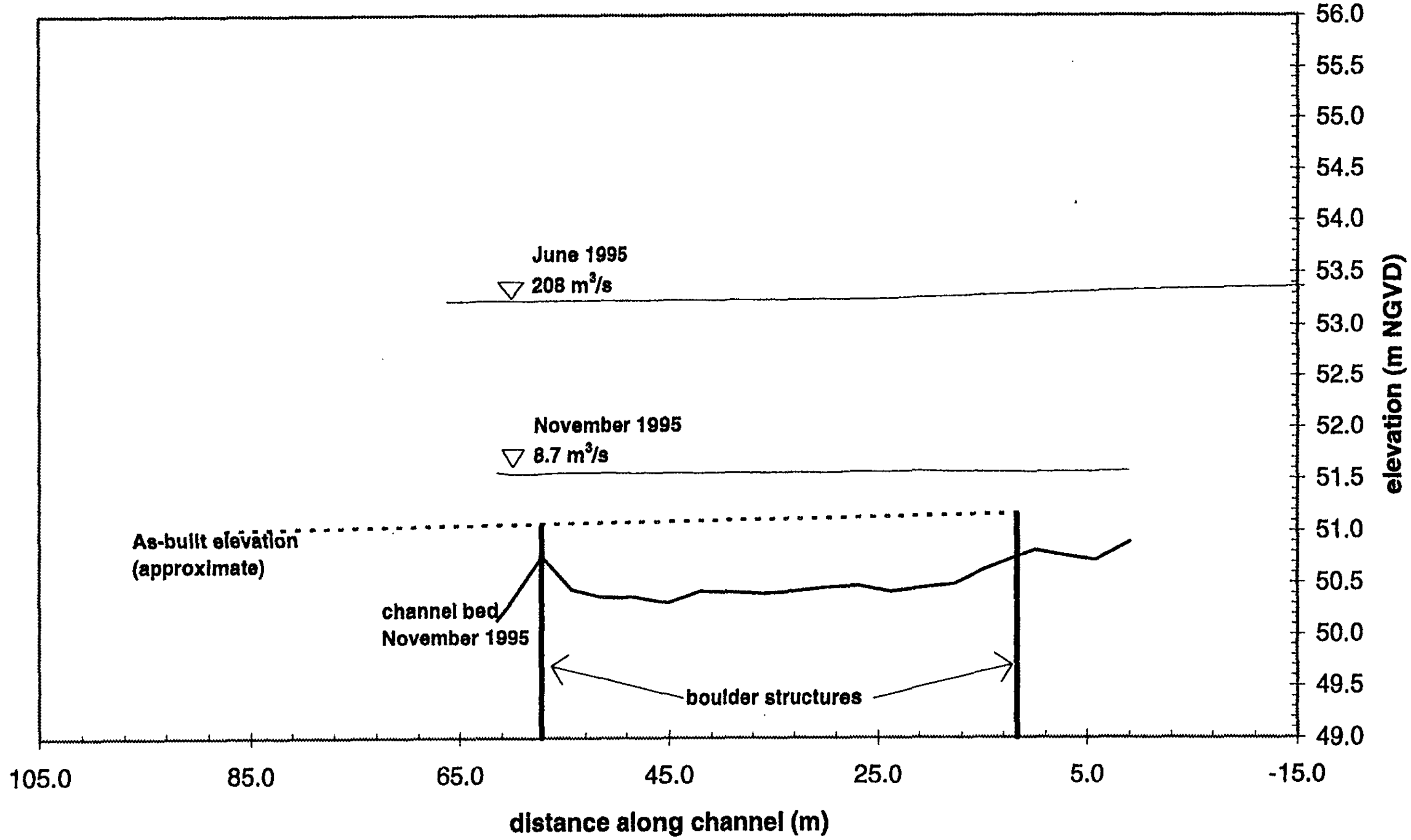

Figure 25. Surveyed water surface profiles and longitudinal bed profiles (from construction drawings and from field surveys November 1995) for the Tuolumne River Riffle 1B rehabilitation site.

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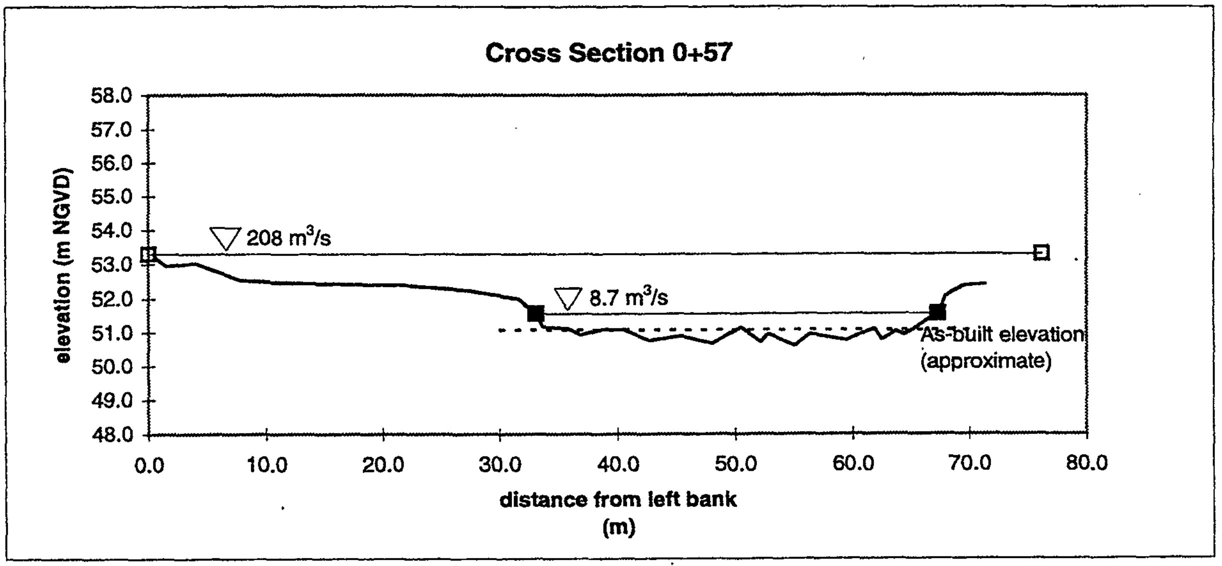

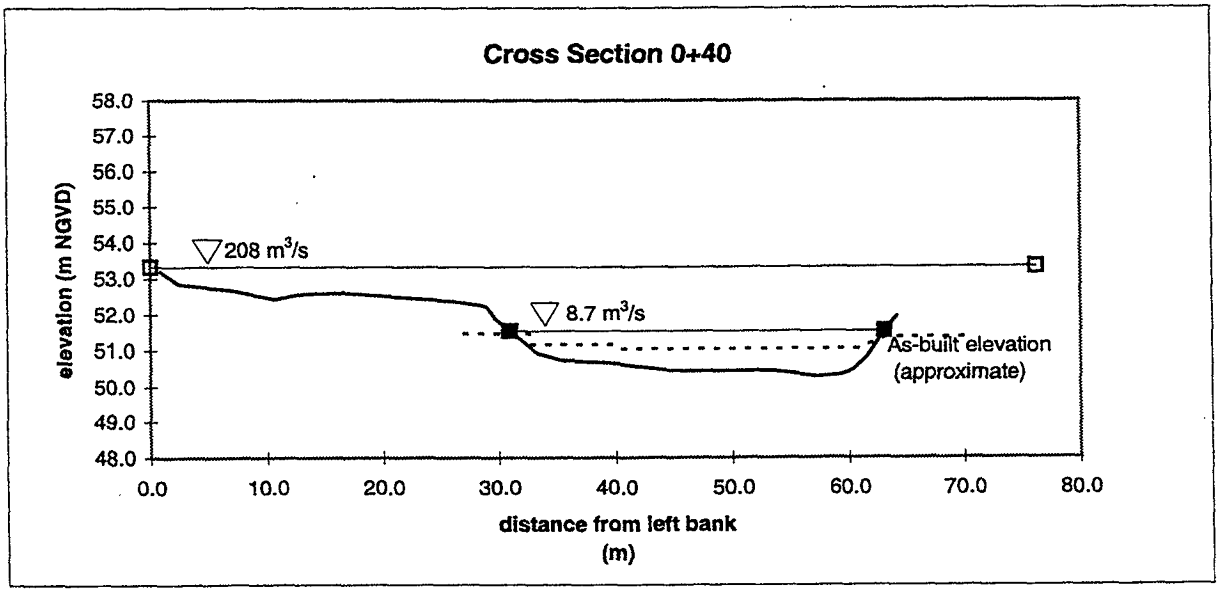

Figure 26. Channel cross sections of the Tuolumne River in the Riffle 1B rehabilitation site. Bed elevations from surveys November 1995 and from construction plans.

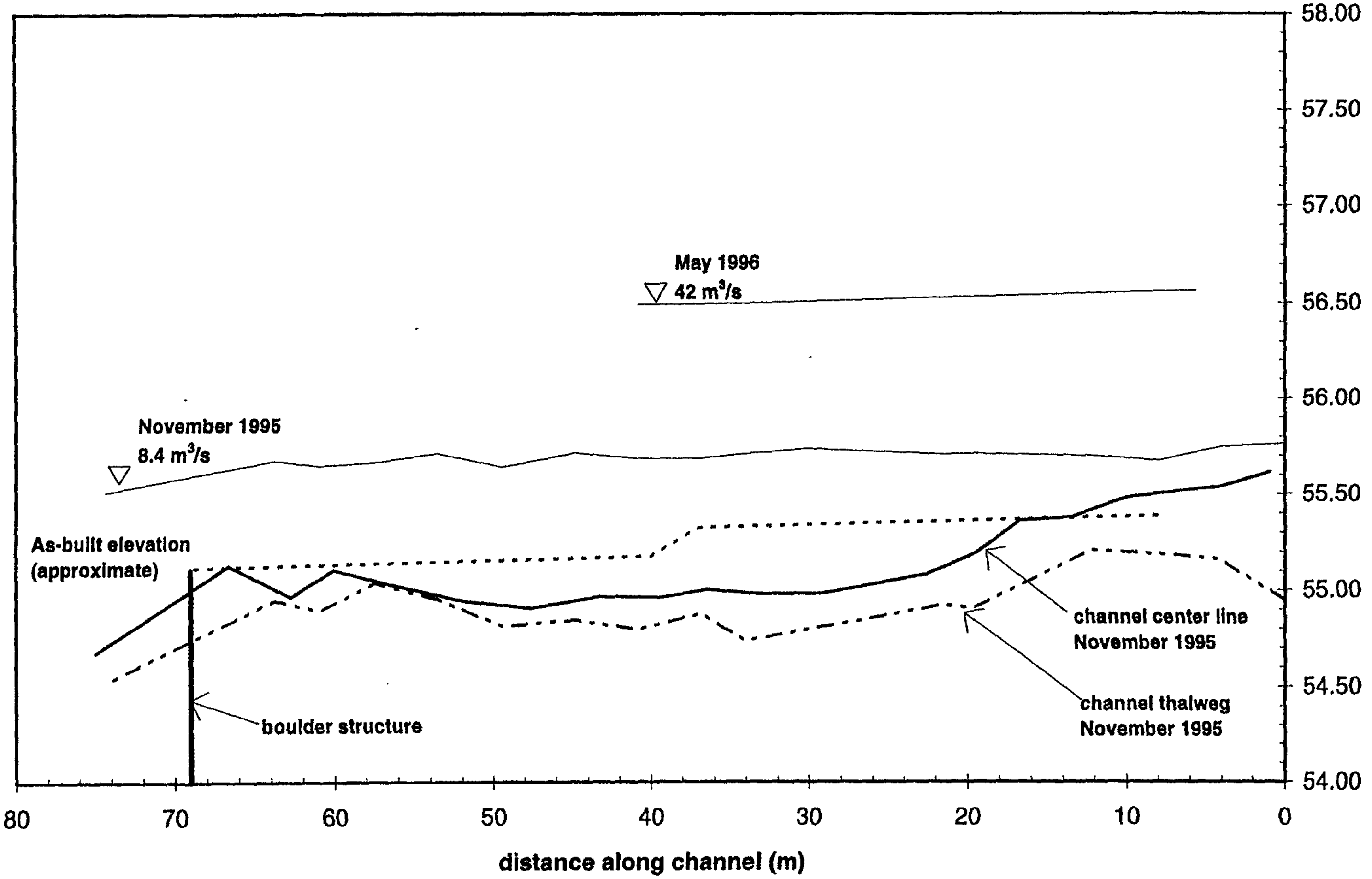

Figure 27. Surveyed water surface profiles and longitudinal bed profiles (from construction drawings and from field surveys November 1995) for the Stanislaus River Riffle RM 50.4 rehabilitation site.

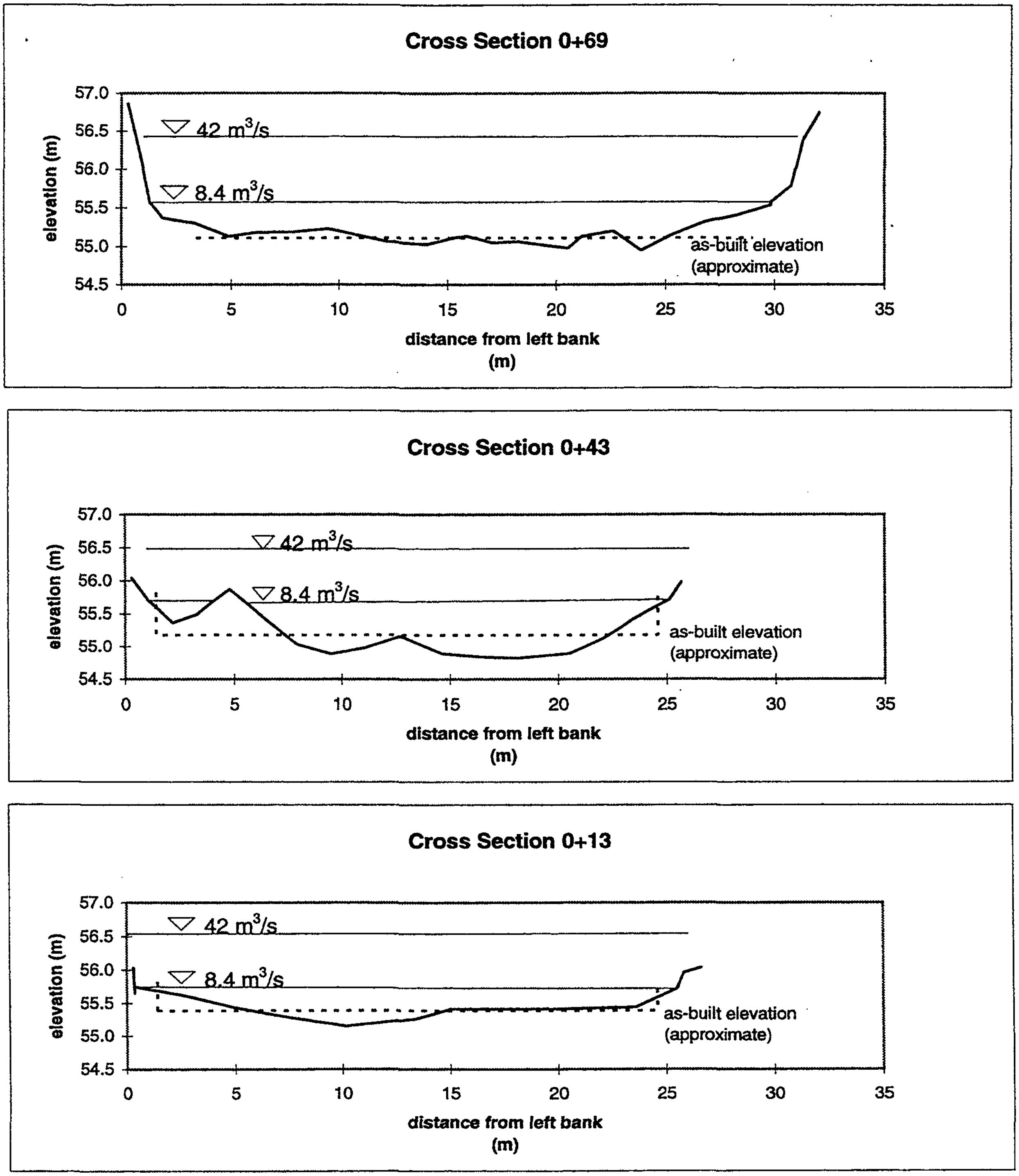

Figure 28. Channel cross sections of the Stanislaus River in the Riffle 50.4 rehabilitation site. Bed elevations from surveys November 1995 and from construction plans.

imported to the project site, a prediction borne out by the bed erosion of 0.4 m (1.3 ft) we observed at the site. As at the Tuolumne River Riffle 1B Site, absent an upstream supply of gravel similar in size to the imported gravel, we expect that channel bed at the project site will continue to erode until it reaches an equilibrium with the available sediment supply and discharge conditions of the river. This equilibrium will likely resemble the pre-project channel configuration, although perhaps with net bed lowering due to the excavation for the project.

Similar to the Merced River Riffle 1B Site, the Tuolumne and Stanislaus River Sites are adjusting to the sediment supply and flow conditions of the rivers. One-and-a-half years after project completion, these sites exhibited channel degradation, as would be expected based on simple shear stress calculations and Shields analyses at the sites. Without periodic additions of more spawning gravel, it is likely that the sites will return to their pre-project condition (or a degraded bed level) before the end of the 15-year life span projected by the project designers.

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Chapter 8. Case Study - Historical and Geomorphic Framework for Salmonid Habitat Rehabilitation on the Merced River

Like many Central Valley rivers, the Merced River has been affected by water development and instream mining projects, which have altered its channel morphology (see Chapter Two). Flow in the river is regulated by four mainstem dams and four tributary dams, which control runoff from more than 82% of the basin. The largest dam, the New Exchequer Dam was originally constructed in 1926 and enlarged in 1967. This dam, with a capacity of 1,272 $10^6 m^3$ (1.03 million acre-feet), retains high flows generated by winter storms and spring snowmelt for release and diversion into the Merced Irrigation District's Main Canal during the summer. In addition, to damming and diversion of instream flows, the Merced River has been mined for both gold and aggregate. Between 1907 and 1952, the area in the vicinity of the Crocker-Huffman Dam was dredged to recover gold from the alluvial deposits. The dredger boats excavated the river's channel and floodplain and redeposited their cobble spoils on the banks and floodplain. Large-scale aggregate mining began in the Merced River in the 1940s and continues today. At these mines, operators excavate the river channel, floodplain, and terrace deposits leaving behind deep pits both in the active channel and the adjacent floodplain and terraces.

Many of the effects of damming and mining are evident on the Merced River as the channel has adjusted to reduced flows, reduced bed material supply, and excavation of stored bed material within the channel and floodplain. Within the Lower Merced River, the CDFG and the CDWR are working to restore habitat for native chinook salmon. However, the agencies' approach thus far has been limited to attempts to impose a desired channel form at specific locations within the channel, regardless of the geomorphic context of the project site. The geomorphic context of the Lower Merced River includes reduced flows, bed material starvation, and the presence of numerous nickpoints and sediment traps at the in-channel mining sites. A complete understanding of this context and the ongoing geomorphic processes at work in the river is fundamental to successful habitat rehabilitation in the Merced or any other river (NRC 1992).

Historical analysis of watershed and channel conditions is a useful tool for providing the geomorphological information needed for successful restoration planning and design. This analysis allows the planner to understand the underlying processes determining channel form, to establish realistic objectives, and to select appropriate strategies for meeting these objectives (Kondolf and Larson 1995). Kondolf and Larson (1995) identify four steps in conducting historic channel analysis: (1) analysis of the hydrologic regime, (2) identification of channel planform and floodplain characteristics through analysis of historic maps and photographs, (3) identification of channel cross section geometry and slope through analysis of historic surveys, and (4) review of historical narrative accounts.

This chapter illustrates the application of historical analysis to assess the geomorphic impacts of damming and in-channel mining in the Lower Merced River (defined as the mainstem channel between the Crocker-Huffman Dam and the confluence with the San Joaquin River) and to define the geomorphic context of restoration activities in the Merced River system. Specifically, the study (Vick 1995) presents a description of dam and diversion-induced changes in river hydrology, identification of historical and on-going in-channel mining, quantification of bed material intercepted by dams or removed from the channel downstream of the dams, and description of the channel's planform and cross-sectional response to damming and mining.

STUDY AREA

The Merced River drains 3,305-km^2 (1,276 mi^2) on the western slope of the Sierra Nevada Range, joining the San Joaquin River in California's Central Valley (figure 29). Elevations in the basin range from 3,962 m (13,000 ft) NGVD at its crest in Yosemite National Park to 15 m (49 ft) at its confluence with the San Joaquin River. The basin experiences a Mediterranean climate, having wet winters and dry summers, with rain at the lower and snow at the higher elevations. Nearly ninety percent of the annual precipitation falls from November to April (USCOE 1967).

The Merced River's hydrology has been greatly altered by damming and flow diversion. As early as the 1870s, large diversions provided irrigation for the extensive agricultural lands of the lower river valley. The largest and oldest of these diversions, the Merced Irrigation District's (MID's) Crocker-Huffman Dam and Main Canal, is still in place and provides irrigation to 625 km^2 (241 mi^2) of agricultural land. In addition to the Main Canal diversion, the California Department of Fish and Game has identified 68 riparian diversions in the 84-km (52-mi) reach between the Crocker-Huffman Dam and the San Joaquin confluence (Reynolds et al. 1993).

Prior to 1926, Yosemite Lake, a shallow off-channel reservoir fed by the Main Canal, was the only storage in the MID irrigation infrastructure. In 1926, the MID built the Exchequer Dam, a 346,608 10^3m^3 (281,000 acre-foot) mainstem reservoir, to augment storage. This reservoir stored high flows generated by winter rains at lower elevations and spring snowmelt from higher elevations, which were released during the summer irrigation season. The released flows were diverted into the MID Main Canal at the Crocker-Huffman Dam, located 17 river km (10.5 river mi) downstream. While the Exchequer Dam provided some reduction in flood peaks downstream, it was operated primarily for irrigation storage and hydropower generation and did not include a specific flood control component.

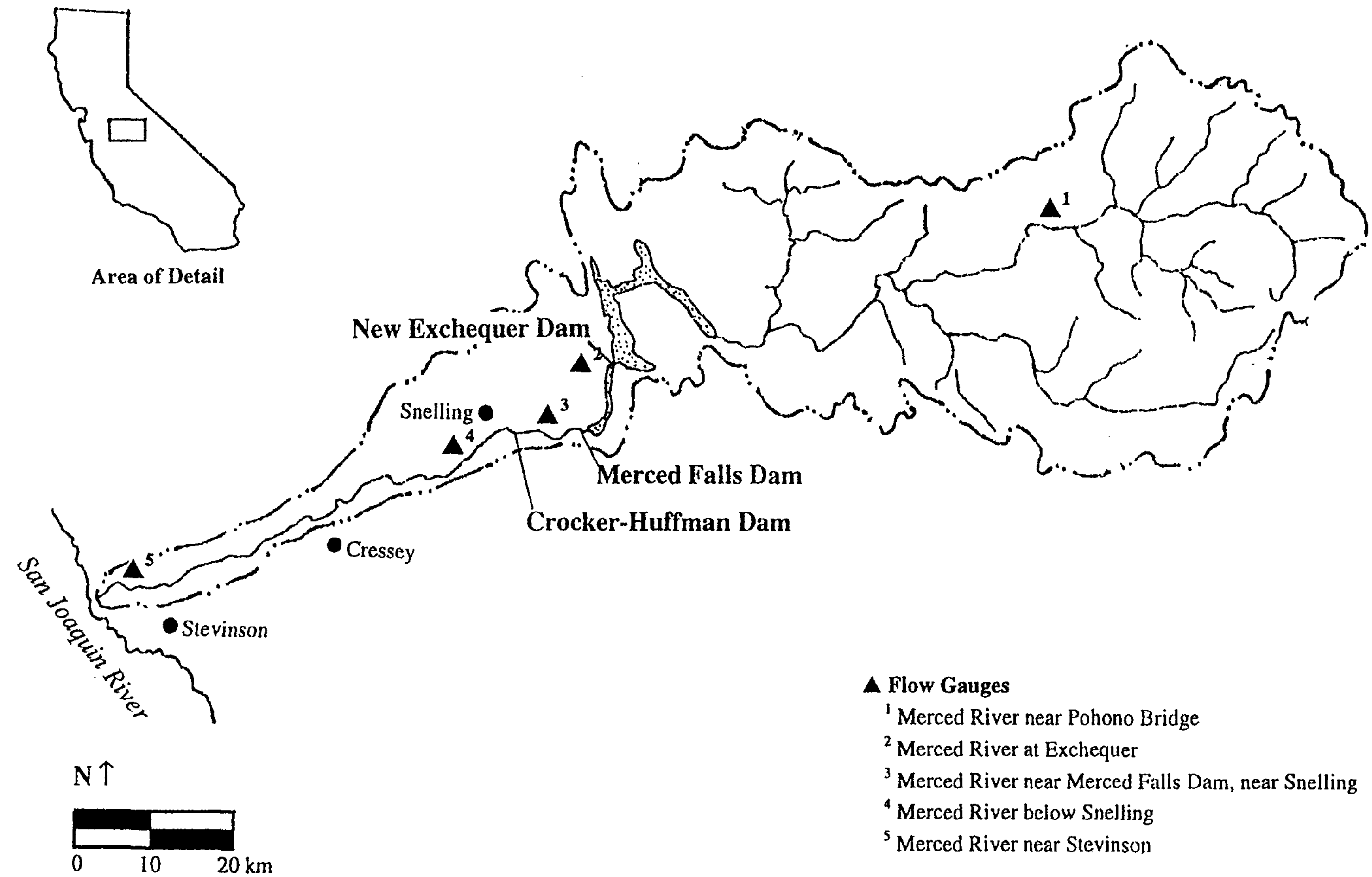

Figure 29. Merced River Watershed

In 1967, in response to local flood control demands, the MID and the U.S. Army Corps of Engineers constructed the New Exchequer Dam (located at the site of the original Exchequer Dam) and the McSwain Dam, which serves as the New Exchequer Dam's afterbay. The New Exchequer Dam has a storage capacity of 1,272,970 10^3m^3 (1,032,000 acre-feet), approximately 105% of the average annual runoff from the basin (as measured at the U.S. Geological Survey gauge Merced River below Merced Falls Dam, near Snelling) (USGS 1989).

In addition to this large-scale irrigation infrastructure, five additional dams are located in the watershed - one on the mainstem upstream of the Crocker-Huffman Dam, two on the North Fork and two on tributaries (table 13). The combined capacity of these dams is 3,028 10^3m^3 (2,455 acre-feet). One of the tributary dams is located on Dry Creek, the only major tributary to the Merced River downstream of the New Exchequer Dam.

The Lower Merced River (downstream of the Crocker-Huffman Dam), has been mined extensively for gold and aggregate. Placer (gold) mining, which began in the valley in 1907 and was discontinued in 1952, was accomplished by continuous bucket dredges. The dredges excavated the channel and floodplain deposits usually to the depth of bedrock, recovered the gold, and redeposited the tailings in long rows on the floodplain. The tailings consist of fine sand and gravel overlain by cobbles and boulders (Goldman 1964), and are a dominant feature of the floodplain in the vicinity of Snelling (figure 30).

Large-scale aggregate mining began in the valley in the 1940s and continues today. The older mines excavated aggregate directly from the active channel, leaving behind large in-channel pits. More recent mines were located on the floodplain and terraces, and resulted in deep excavated pits adjacent to the active channel. These pits, which extended to the bottom of the alluvial deposit (typically 8 m in depth), were separated from the river by a narrow strip of land left in place during the excavation. These narrow separators, themselves alluvial deposits, have been breached by the river in many cases, resulting in capture of the active channel. A few mines, none of which were breached, were located on river terraces more than 75 m (245 ft) from the active channel.

METHODS

Hydrologic Analysis

Geomorphically and ecologically, reduction in peak flow magnitude and the seasonal distribution of flows are among the most critical hydrologic impacts of dams and flow diversions. To determine the reduction in peak flow magnitude, Vick conducted flood frequency analyses using a Gumbel Type I distribution and calculated the mean annual flood (Q_{maf}) at five flow gauges during three study periods (Dunne and Leopold 1978) (table 14). To describe the

Table 13
Dams Regulated by the Division of the Safety of Dams in the Merced River Basin

Dam	Stream	Year Closed	Capacity ($10^6 m^3$)	Drainage Area (km^2)	Percent of Watershed Regulated
Mainstem					
New Exchequer	Merced River	1967	1,272	2,686	81
McSwain	Merced River	1966	12	2,686	81
Merced Falls	Merced River	1901	0.76	2,694	82
Crocker-Huffman	Merced River	1910	0.37	2,707	82
Tributaries to Mainstem					
McMahon*	Maxwell Creek	1957	0.64	47	1
Kelsey	Dry Creek	1929	1.2	3.0	<1
North Fork					
Green Valley*	Smith Creek	1957	0.30	1.6	<1
Metzger*	Dutch Creek	1956	0.09	2.6	<1
Total:			1,287		

sources: CDWR 1984, Kondolf and Matthews 1993, USGS 1989
*Dam is located upstream of the New Exchequer Dam

Table 14
Stream Flow Gauges Used in Hydrologic Analysis

Gauge Name	Agency	Period of Record Analyzed	Drainage Area (km^2)	Location Relative to Dams
Merced River near Pohono Bridge	USGS[1]	1917-1993	831	upstream of New Exchequer
Merced River at Exchequer	USGS[1]	1901-1964	2,686	between New Exchequer and Crocker-Huffman
Merced River below Merced Falls Dam, near Snelling	USGS[1]	1964-1993	2,748	between New Exchequer and Crocker-Huffman
Merced River below Snelling	CDWR[2]	1961-1993	2,839	downstream of Crocker-Huffman
Merced River near Stevinson	USGS[1]	1941-1993	3,297	downstream of Crocker-Huffman

Figure 30. Tailings left behind by gold dredgers on the Merced River floodplain. The town of Snelling is located in the upper, right-hand quadrant. (photo: Agricultural Stabilization and Conservation Service)

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modification of seasonal flow patterns, Vick generated annual hydrographs based on average daily flows at each gauge averaged over each study period, or the portion of the study period for which data were available. Study periods were defined as follows: pre-dam (1901-1925), post-Exchequer (1926-1966), and post-New Exchequer (1967-1993).

The five gauges were chosen based on their location relative to dams and diversions (figure 29). The Pohono Bridge gauge was located upstream of the reservoir created by the New Exchequer Dam. Because flows at this gauge were not affected by the dams or diversions, these data were used as a benchmark for comparing data collected downstream of the dams and diversions. The Exchequer gauge and Merced Falls gauge (which replaced the Exchequer gauge in 1964) were located between the New Exchequer Dam and the Main Canal diversion at the Crocker-Huffman Dam. These data were used to analyze the hydrologic impacts of the Exchequer dams upstream of the Crocker-Huffman diversion. The Snelling gauge was located 8.9 river km (5.5 river mi) downstream of the Crocker-Huffman diversion and was used to determine the hydrologic impact of the Crocker-Huffman diversion in the post-New Exchequer period. The Stevinson gauge was located near the confluence with the San Joaquin River. These data were used to analyze hydrologic conditions in the extreme downstream reaches of the river.

Analysis of Aerial Photographs and Historic Maps

To document channel alignment, channel width, aggregate mining excavation, and placement of gold mine tailings, Vick relied on aerial photographs taken in 1937, 1950, 1967, 1979, and 1993, as well as U.S. Geological Survey topographic maps surveyed between 1914 and 1916 (table 15). For each photograph or map year, specific channel features were digitized using Microstation 5.0, a computer-aided design package capable of accurately geopositioning data onto a digital mapping plane. By identifying known landmarks (e.g. road or canal intersections) in the aerial photographs and relating them to known monument points in the digital map projection (coordinates entered by hand or digitized from topographic maps), all photographs and maps were converted to a uniform scale and photographic distortion was reduced or eliminated within the error of the landmark identification. Approximately 50 points were used to register each year of photographs. To the extent possible, the same points were used for each year. Because the 1993 photographs were at a much larger scale, the narrower field of view prevented use of the control points applied to the 1937, 1950, 1967 and 1979 photographs. A new series of points was developed for these photographs.

Specific channel features digitized included the mainstem active channel boundary, distributary sloughs center-lines, aggregate mine pit boundaries, and tailings deposit boundaries. The channel features for each year were entered into individual layers in Microstation which

Table 15
Maps and Aerial Photographs Used in the Identification of Mines and Geomorphic Analysis

Year	Date	Format	Scale	Coverage	Comment
1922[1]		topographic map	1:31,680	Merced Falls	USGS[2]
		topographic map	1:31,680	Snelling	USGS[2]
1916[1]		topographic map	1:31,680	Yosemite Lake	USGS[2]
1916[1]		topographic map	1:31,680	Turlock Lake	USGS[2]
1917[1]		topographic map	1:31,680	Winton	USGS[2]
		topographic map	1:31,680	Cressey	USGS[2]
1918[1]		topographic map	1:31,680	Stevinson	USGS[2]
1917[1]		topographic map	1:31,680	Turlock	USGS[2]
1918[1]		topographic map	1:31,680	Gustine	USGS[2]
1937	July 31	aerial photograph	1:21,000	Crocker-Huffman Dam to Stevinson	ASCS[3] $Q = 51.3\ m^3/s$ [5]
1950	March 10	aerial photograph	1:20,000	Crocker-Huffman Dam to San Joaquin River	ASCS[3] $Q = 10\ m^3/s$ [6]
1967	May 1	aerial photograph	1:20,000	Crocker-Huffman Dam to San Joaquin River	ASCS[3] $Q = 97.4\ m^3/s$ [6]
1979	??	aerial photograph	1:23,500	Crocker-Huffman Dam to San Joaquin River	ASCS[3]
1993	June 8	aerial photograph	1:6,000	New Exchequer Dam to San Joaquin River	BoR[4] $Q = 18.3\ m^3/s$ [6]

[1] Year of Map Edition
[2] U.S. Geological Survey
[3] Agricultural Conservation and Stabilization Service
[4] U.S. Bureau of Reclamation
[5] Discharge Measured at Exchequer/Merced Falls Gauge
[6] Discharge Measured at Stevinson Gauge

were overlain to detect changes in mainstem channel alignment, slough configuration, aggregate mining excavation, and tailings deposits. The active channel boundaries were identified based on the location of riparian vegetation, evidence of recent channel scour, and bank location. Scoured areas devoid of shrubs or trees were included within the boundary of the active channel. The active channel boundary was difficult to distinguish in the 1967 photographs because the photographs were taken during a discharge of 97.4 m^3/s (3,440 cfs), approximately 1.4 times the Q_2 for the 1967-1993 period.

To document change in the width of the mainstem active channel downstream of the Crocker-Huffman Dam, Vick measured 113 transects at 500-m (1,640-foot) intervals on the digital channel boundary map layers for 1937, 1967, and 1993. Transect locations were entered into an independent layer in Microstation, which was lain over the active channel boundary maps for each photograph year. This overlay method assured consistent placement of the transects among photograph years. The transects were divided into two groups - transects at mine sites and transects at unmined sites - and analyzed separately. Mined sites included in-channel, captured, and breached instream mines.

The surface area of aggregate mining pits and gold dredger tailings deposits was measured by converting the pit and tailings boundaries into polygons. The area of these polygons was measured using Microstation measurement tools. The timing, levee condition, and type of aggregate mine was also interpreted from the aerial photographs. Levees were characterized as *breached*, *captured*, or *intact* (as of the 1993 aerial photographs). *Breached* levees were broken at only one location and did not capture the active channel. At *captured* mines, the levee was broken in more than one place and the active channel flowed through the extraction pit. *Intact* levees were not broken. Mine type was designated as *in-channel*, *terrace*, and *off-channel*. *In-channel* mines were located within the active channel (as defined by the 1993 aerial photographs). No levees were evident at these mines in any aerial photograph series. *Terrace* mines were located within 75 m (245 ft) of the 1993 active channel and were presently or at one time separated from the channel by a levee. *Off-channel* mines were located more than 75 m (245 ft) from the 1993 active channel.

Channel Surveys

To document changes in channel cross section and slope since closure of the New Exchequer Dam, Vick reoccupied 16 cross sections originally surveyed in 1967 by the U.S. Geological Survey (USGS) between the Crocker-Huffman Dam and Cressey in the upstream 40.4 river km (25.1 river mi) of the 83.7-river km (52.0 river mi) study area (Blodgett and Bertoldi 1968). Four additional cross sections were surveyed between the Crocker-Huffman Dam and the first USGS cross section downstream of the Crocker-Huffman Dam (section 148).

The locations of the 1967 cross sections were identified using 1:24,000-scale base maps included in the original study report (Blodgett and Bertoldi 1968) and 1:6,000 color aerial photographs taken in 1993. Because the cross sections were not monumented, relocation was only approximate.

Vick surveyed cross sections using an automatic level and rod to measure elevation and a standard survey tape to measure horizontal distance. At cross section 127, Vick measured water surface elevation with a level and rod and measured water depth with a weighted survey tape deployed from a boat. For most sections, Vick established vertical control at USGS benchmarks (1929 datum). At cross sections 3 and 3A, Vick established vertical control from a benchmark established by the CDFG at the Merced River Fish Facility, a hatchery located immediately downstream of the Crocker-Huffman Dam. At cross sections 145 and 144, Vick used survey pins placed by the CDWR on the Snelling Road bridge, just upstream of the CDWR Merced River at Snelling gauge.

Document Review

To obtain additional information describing aggregate and gold mine operations, Vick reviewed historic mine records, land excavation and conditional use permits, and mine reclamation plans archived at the offices of the California Division of Mines and Geology in Sacramento and the Merced County Planning Department in Merced. Specific information drawn from these documents, where possible, included the following: period of operation; name of mine operator; and permitted volume, area, and depth of extraction. When this information was not available as was frequently the case, the period of operation was estimated using the dates of the aerial photographs in which the mine first appeared.

Bed Material Deficit in the Lower River

Vick quantified the volume of bed material trapped by the Exchequer and New Exchequer Dams based on reservoir sedimentation surveys conducted in 1926 and 1946 (Dendy and Champion 1978). Because these surveys measured bed and suspended load trapped by the dam, Vick used published estimates of bedload as a percentage of suspended load to estimate the volume of trapped sediment consisting of bedload.

Accurate calculation of the quantity of bed material removed from the active channel by aggregate mining downstream of the dams was not possible from the information available. Vick calculated an order of magnitude estimate based on the depth and area of each mine. Mine area was measured from the digitized aerial photographs. Mine depth was estimated by comparing pre- and post excavation channel surveys at or near mine pits (where available) and from review of mining records, permits, and reclamation plans.

RESULTS

Dam and Diversion-induced Changes in River Hydrology

As demonstrated by the flood history, the mean annual flood, and the flood recurrence intervals, flood peaks in the lower river have been reduced substantially since closure of the Exchequer Dam. Prior to dam closure, annual peak flows at the Exchequer/Merced Falls gauge exceeded 500 m^3/s (17,657 cfs) in 10 of the 22 years of record (figure 31). During the 41 years of the post-Exchequer period, flows exceeded 500 m^3/s only once, during the floods of December 1950. In the post New-Exchequer period, flows never exceeded 500 m^3/s. The largest flood recorded in this period was 283 m^3/s (9,980 cfs).

The mean annual flood at the Exchequer/Merced Falls gauge also reflects the reduction in peak flows imposed by the two dams (table 16). The Q_{maf} at the Exchequer/Merced Falls gauge was reduced by 56% after closure of the Exchequer Dam, and by additional 17% after closure of the New Exchequer Dam. Downstream of the Main Canal diversion at the Snelling gauge, Q_{maf} was 40% less than flows upstream of the diversion at the Exchequer/Merced Falls. Without the diversion, the Q_{maf} at these two gauges would be approximately equal.

Annual maximum discharges of a given return period were also reduced after dam closure. At the Exchequer/Merced Falls gauge, the Q_2 , Q_5 , and the Q_{10} discharges were reduced by 66, 64, and 66%, respectively from the pre-dam to the post-New Exchequer periods (table 17). Notably, the Q_2 discharge for the pre-dam period was only slightly less than Q_{50} discharge for the post-New Exchequer period. Flood peaks were further reduced downstream of the Main Canal diversion. The post-New Exchequer Q_2 discharge at the Snelling gauge was only 59% of the Q_2 discharge upstream of the diversion in the post-New Exchequer period and was only 20% of the Q_2 discharge at the Exchequer/ Merced Falls gauge prior to construction of the Exchequer Dam.

The seasonal distribution of flows was also altered by both the dams and the diversion. The dams altered flow patterns by eliminating the spiky, dynamic nature of the winter hydrograph and reducing spring snowmelt flows downstream of the dam (figure 32). Upstream of the Main Canal diversion, releases from the dam greatly augmented summer flows. These augmented flows were diverted into the Main Canal at the Crocker-Huffman Dam resulting in extremely low summer flows downstream (as measured at the Snelling and Stevinson gauges). Downstream of the diversion, annual flows are essentially uniform throughout the year in the post-Exchequer and post-New Exchequer periods.

Gold and Aggregate Mining

Seven gold dredging companies, operating ten dredges, mined the Merced River valley between 1907 and 1952 (table 18). Dredgers excavated the channel and floodplain deposits to

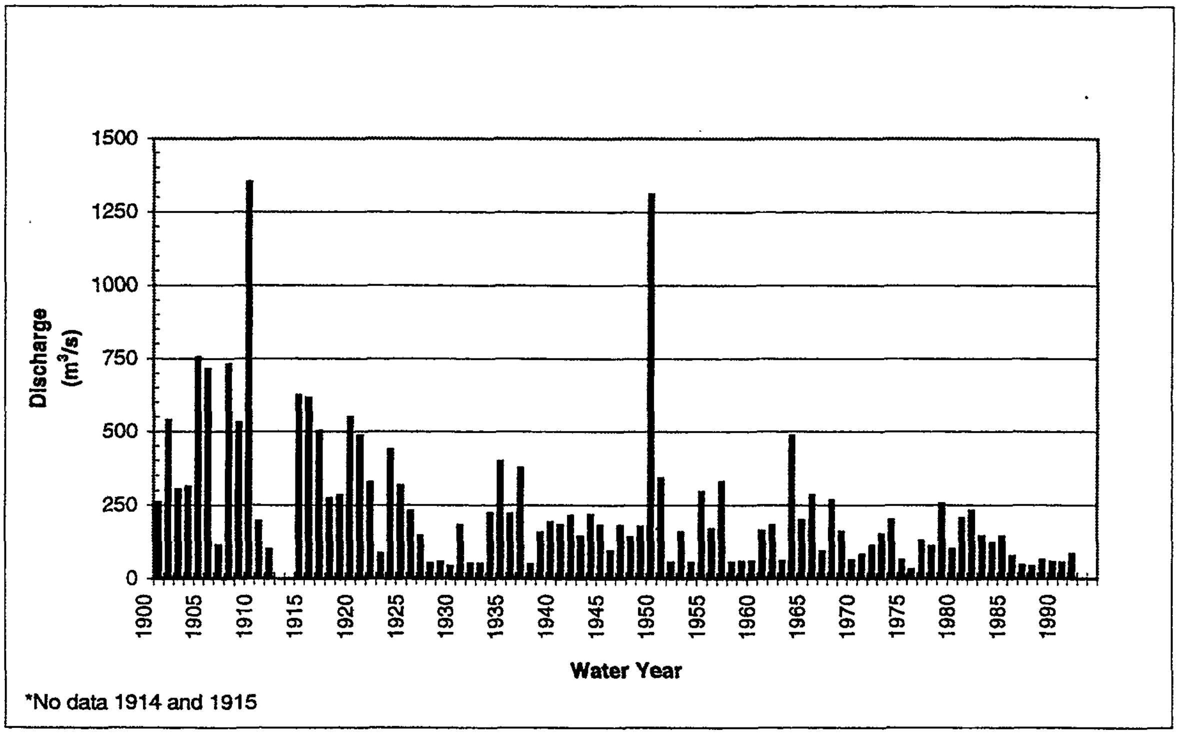

Figure 31. Merced River flood history. Annual peak discharges measured at the Exchequer and Merced Falls gauges.

Table 16
Mean Annual Flood (Q_{maf}) in the Lower Merced River

Gauge	Mean Annual Flood (m³/s) 1917-1925	1926-1966	1967-1993
Pohono Bridge	135.9	174.9	142.9
Exchequer/Merced Falls	457.7	199.9	123.7
Snelling	No Data	No Data	74.8
Stevinson	No Data	131.9	81.9

Table 17
Flood Frequencies in the Lower Merced River

Gauge	$Q_{1.5}$ (m³/s)	Q_2 (m³/s)	Q_5 (m³/s)	Q_{10} (m³/s)	Q_{50} (m³/s)
Pohono Bridge					
Pre-dam[1]	114.2	130.6	170.6	196.4	253.0
Post-Exchequer[1]	96.2	112.1	151.2	176.4	232.0
Post-New Exchequer[1]	98.0	129.3	209.4	260.9	374.6
Exchequer/Merced Falls					
Pre-Dam	233.8	321.9	548.3	649.1	1,015.6
Post-Exchequer	99.3	133.8	222.3	279.9	404.9
Post-New Exchequer	79.1	109.1	186.1	235.8	345.1
Snelling					
Pre-Dam	No Data	No Data	No Data	No Data	No Data
Post-Exchequer	No Data	No Data	No Data	No Data	No Data
Post-New Exchequer	40.2	64.3	126.7	167.0	255.6
Stevinson					
Pre-Dam	No Data	No Data	No Data	No Data	No Data
Post-Exchequer	57.5	82.7	147.9	189.9	282.4
Post-New Exchequer	71.1	71.1	135.1	176.6	267.1

[1]Pre-dam period is 1917-1925; Post-Exchequer is 1926-1966; and Post-New Exchequer is 1967-1993

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Table 18
Gold Dredging Operations in the Lower Merced River

Operator	Period of Operation	Earthmoving Capacity (m^3/yr)
Yosemite Mining and Dredging Company	1907 - 1919	unknown
San Joaquin Mining Company	1937 - 1942	unknown
Snelling Gold Dredging Company	1932 - 1942: 1946 - 1951 (boat 1) 1935 - 1942; 1947 - 1949 (boat 2)	2.59 million (boat one only)
Merced Dredging Company	1934 - 1942 (boat 1) 1945 - 1949 (boat 2)	2.50 million
Yuba Consolidated Gold Fields	1931 - 1941 (boat 1) 19.35 - 1939 (boat 2)	2.08 million 1.11 million
La Grange Gold Dredging Company	1917 - ?	unknown
Thurman and Wright	1941	unknown

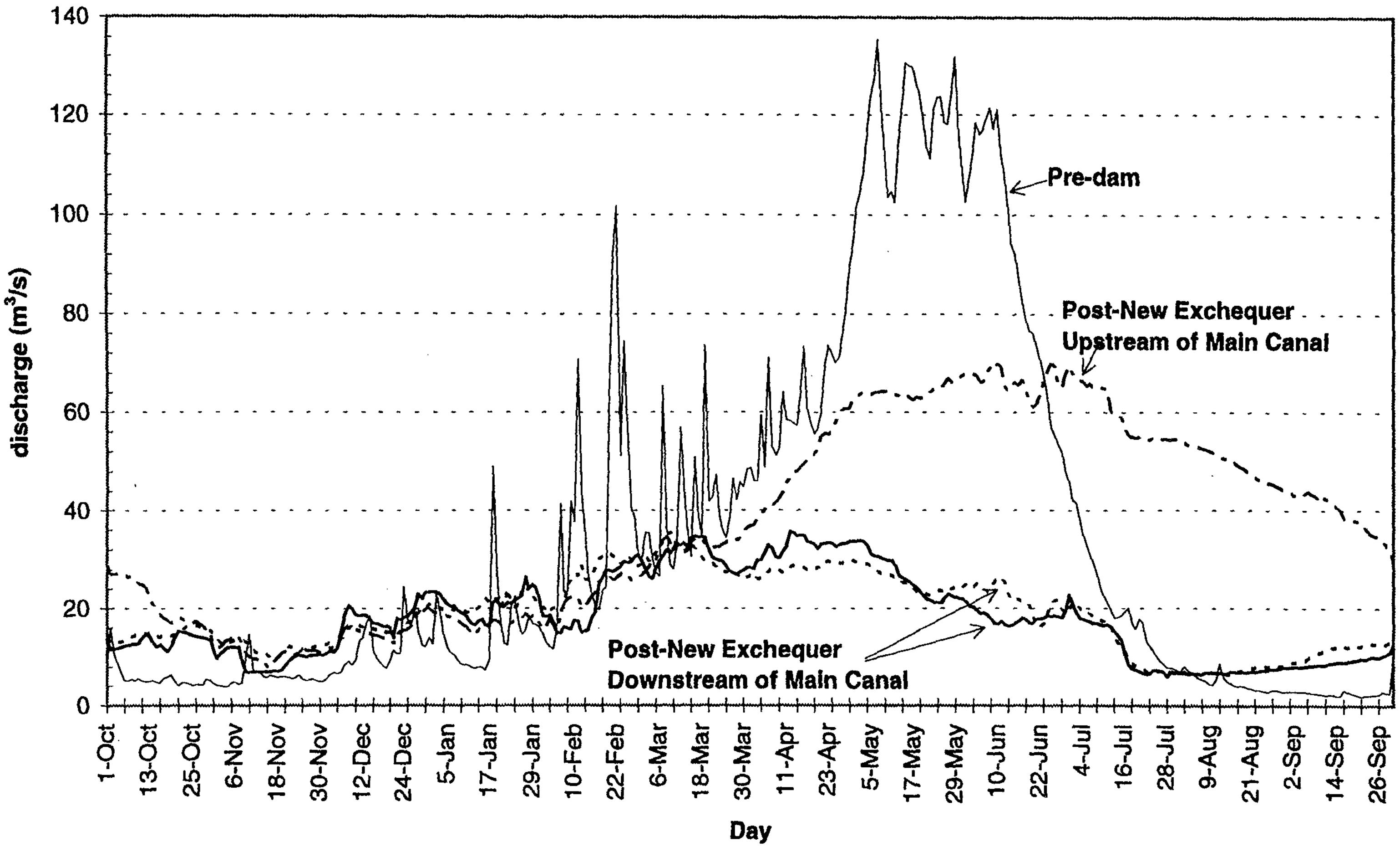

Figure 32. Merced River averaged annual hydrograph. Pre-dam flows are measured at the Exchequer gauge; post-New Exchequer upstream of the diversion at Merced Falls gauge; and post-New Exchequer downstream of the diversion at Snelling and Stevinson Merced Falls gauges.

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bedrock, usually at a depth of 6-11 m (20-36 ft) (Clark no date). The Snelling Gold Dredging Company reported mining depths averaging 5.5 m (18 ft) (Davis and Carlson 1952), and the Yosemite Mining and Dredging Company reported a gravel depth of 6.1 m (20 ft) plus 1-2 m (3-6 ft) of sandy loam overburden (Aubery 1910). The earthmoving capacity of each dredge ranged from 1.1-2.6 million m^3/yr (39-92 million ft^3/yr). The tailings left behind by these operations covered 19.7 km^2 (7.6 mi^2).

In addition to gold mining, a total of thirty-two aggregate extraction sites, including five off-channel, twenty-two terrace, and eight in-channel operations were identified from aerial photographs and mine records (figures 33 and 34, table 19). (The sum of the sites by mine type was greater than thirty-two because three sites included multiple mine types.) Two of these sites (a waste water treatment and a sewage disposal facility) were not mines. Although these facilities were not constructed exclusively for aggregate production, they are included in this study because their overall form and effect on the sediment budget of the Lower Merced River are the same as terrace and off-channel mining pits.

The in-channel and terrace mines were concentrated in the 27 river km (17 river mi) between Snelling and Cressey (figure 35). All eight of the in-channel mines and fourteen of the twenty-two terrace mines (including all of the breached and captured terrace mines) were located in this reach. In-channel, captured, and breached terrace mines occupied 9 km (5.6 mi), or 33% of the channel in this reach, forming large, lake-like areas in the active channel (figure 36).

It was not clear whether operators intended to maintain a separation between terrace pits and the channel over the long term. As late as 1972, the Merced County Planning Commission required operators to knock down the levees separating the pits from the channel once extraction was completed, evidently believing it beneficial to incorporate pits into the channel. The Merced County Planning Commission minutes of March 8, 1972 report on a discussion of the issue:

> Director Colwell stated that in some years to come it appears that we will have a very shallow river, and if the river can be improved by widening, it would be a good thing. We should improve our riverbed by making it a better channel. He suggested that the elimination of the berm be included upon completion of harvesting of these two [De Micheli] parcels...Director Colwell stated that was another reason for eliminating the berm, mosquitoes do not breed in moving water.

Despite the sentiment for breaching separation berms, operators of the pits being discussed (pits 22, 23, and 24 [table 19]) were specifically required to leave the berms in place.

Figure 33. Typical terrace aggregate mining pit. The pit in photograph is mine number 20 (table 19). (photo: U.S. Bureau of Reclamation)

Figure 34. Typical in-channel aggregate mining pit. The pit in photograph is number 26 (table 19). (photo: U.S. Bureau of Reclamation)

Table 19
Aggregate Mines in the Lower Merced River

Mine No.	River km	Mine Type[1]	Mine Status (as of Jan. 1994)	Levee Condition	Operator	Mine Name	Area (ha)	Excavation Depth (m)	Permitted Volume or Weight	Comments
1	N/A	Off-channel	Pending	N/A	Merced River Reclamation Company	Kelsey Ranch	14.3[3]	5.18 m below natural grade (to bedrock)[5]	1,465,817 tonnes	Permitted 1994
2	N/A	Off-channel	Active	N/A	J.S. Hardin & Sons J. Blasingame & Sons	Blasingame Pit	8.9[3]	to pre-dredging ground surface[5]	--	Permitted 1983
3	N/A	Off-channel Pit	Active	N/A	Western Stone	Snelling Pit (Triple C)	180.1[3]	7.62 - 9.14[5]	8.1 to 12.2 million tonnes	Permitted 1987
4	72.1	Off channel and Terrace Pits	Inactive Reclamation pending	Intact	Western Stone	Carson I Pit	16.2[3]	9.14[5]	--	Permitted 1984
5	71.1	Terrace skimming	Active	N/A	Western Stone	Carson II Pit	1.7[4]	5.49 (maximum)[5]	2.5 - 3 million tonnes	Permitted 1992
6	70.0	Terrace Pit	Inactive Reclamation pending	Intact	Western Stone	Robinson North	12.1[3]	2.44 below river bed[5]	--	Permitted 1975 Modified 1986 to increase depth
7	68.4	Terrace Pit	Inactive Reclamation pending	Breached	Western Stone	Robinson South	15.8[4]	--	--	Permitted 1984
8	66.8	In-channel and Terrace Pits	Abandoned	Channel Captured	River Rock	River Rock, No. 1	39.9[4]	9.14[7]	--	Began 1946 Abandoned by 1967
9	66.8	Terrace Pit	Abandoned	Intact[2]	Flintkote Co.	Silva Pit	21.7[4]	not deeper than 51.72 m NGVD[5]	--	Permitted 1972
10	66.8	Terrace Pits	Active	Intact	Western Stone	Silva Pit	3.1[4]	--	--	Permitted 1972
11	62.8	In-channel Pit	Abandoned	N/A			3.1[4]	--	--	No records First shown in 1967 photos

12	56.3	In-channel Pit	Abandoned	N/A			49[3]	--	--	No records First shown in 1967 photos
13	56.3	Terrace Pit	Abandoned	unknown	Flintkote Company	Bettencourt	4.1[4]	not deeper than 40.23 m NGVD[5]	---	Permitted 1972 Not evident in photographs
14	54.7	In-channel Pit	Abandoned	N/A			5.3[4]	--	--	No records First shown in 1967 photos
15	54.7	Terrace Pit	Abandoned	Intact	Flintkote Company	Bettencourt	2.1[4]	not deeper than 37.18 m NGVD[5]	35,562 tonnes	Permitted 1972
16	54.7	Terrace Pit	Active	Intact	M.J. Ruddy and Sons	Bettencourt Ranch	157[3] 2.5[4]	9.14 - 11.28[5]	9.6 million tonnes aggregate	Permitted 1989
17	53.1	Terrace Pit	Abandoned	Breached[2]			5.5[4]	--	--	No records First shown in 1942 photos
18	51.7	Terrace Pit	Abandoned	Channel Captured	River Rock	River Rock, No. 2	2.2[4]	9.14[7]	--	Began 1944
19	51.2	Terrace Pit	Abandoned	Channel Captured	River Rock	River Rock, No. 2	3.2[4]	--	--	No records First shown in 1950 photos Channel captured in 1967 photos
20	50.1	Terrace Pit	Active	Intact	Turlock Rock		10.4[4]	7.62 - 9.14[5]	382,277 m^3	Permitted 1987
21	48.6	In-channel Pit	Abandoned	N/A	Silva Gravel/Turlock Rock		10.7[4]	approx. 7.62[6]	--	Began 1950
22	48.0	Terrace Pit	Abandoned	Breached	Turlock Rock		2.8[4]	--	--	No records First shown in 1979 photos
23	47.1	Terrace Pit	Abandoned	Channel captured	Turlock Rock	Magneson Pit	4.5[4]	--	--	No records First shown in 1979 photos

24	46.3	Terrace Pit	Abandoned	Channel Captured	Turlock Rock	De Micheli Pit	1.3[4]	--	--	Approved 1972 First shown in 1979 photos
25	43.8	In-channel Pit	Abandoned	N/A	Cressey Sand and Gravel		3.6[4]	9.14[7]	--	Approved 1972 First shown in 1950 photos
26	43.3	In-channel Pit	Abandoned	N/A	Turlock Rock	Cressey Pit	8.5[4]	9.14[7]	--	Began 1948
27		Terrace Pit	Abandoned	Intact			0.2[4]			No records First shown in 1993 photos
28	~42	In-channel Pit	Abandoned	N/A	Slov and Wychophan			9.14[7]	--	Began 1951 Reported by Davis and Carlson (1952); Not discernible in aerial photos.
29	37.0	Terrace Pit	Abandoned	see comment			5.8[4]			No records First shown in 1967 photos Reclaimed to agriculture by 1979
30	33.8	Off-channel and Terrace Pits	Wastewater Treatment	Intact	Foster Farms		21.6[4]			No records First shown in 1967 photos
31	31.1	Terrace Pits	Sewage Disposal	Intact			10.2[4]			
32	24.1	Terrace Pit	Abandoned	Intact			1.1[4]			No records First shown in 1993 photos

[1] See text for definition.
[2] Pit filled with sediment.
[3] Area stated in County Use and/or Land Excavation Permits
[4] Area measured from digital map file
[5] Excavation depth stated in County Use and/or Land Excavation Permits
[6] Excavation depth estimated from channel cross sections surveyed in 1967 and/or 1994
[7] Excavation depth from Davis and Carlson (1952)

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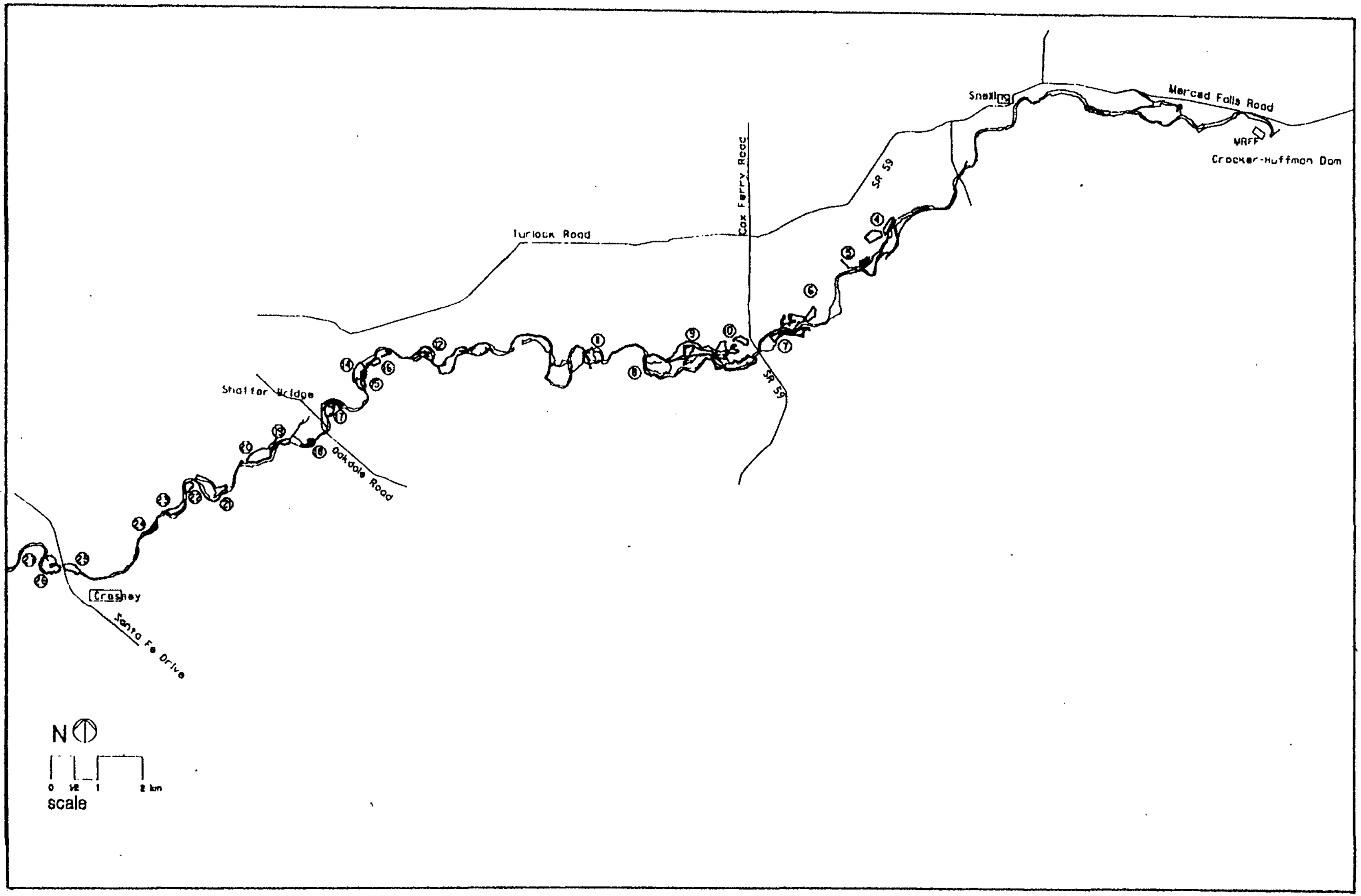
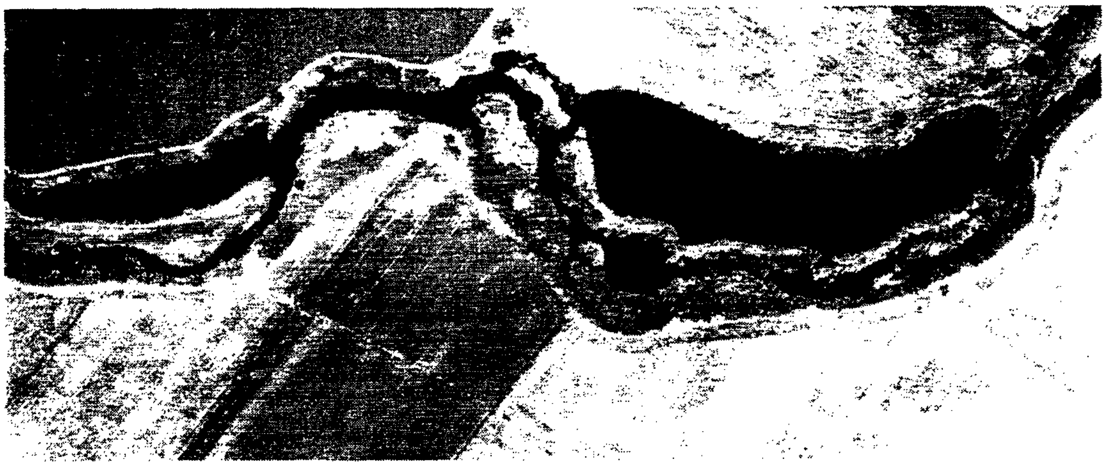


Figure 35. Aggregate mines located between Snelling and Cressey. Eight in-channel and fourteen terrace mines are located in this 27 km reach.



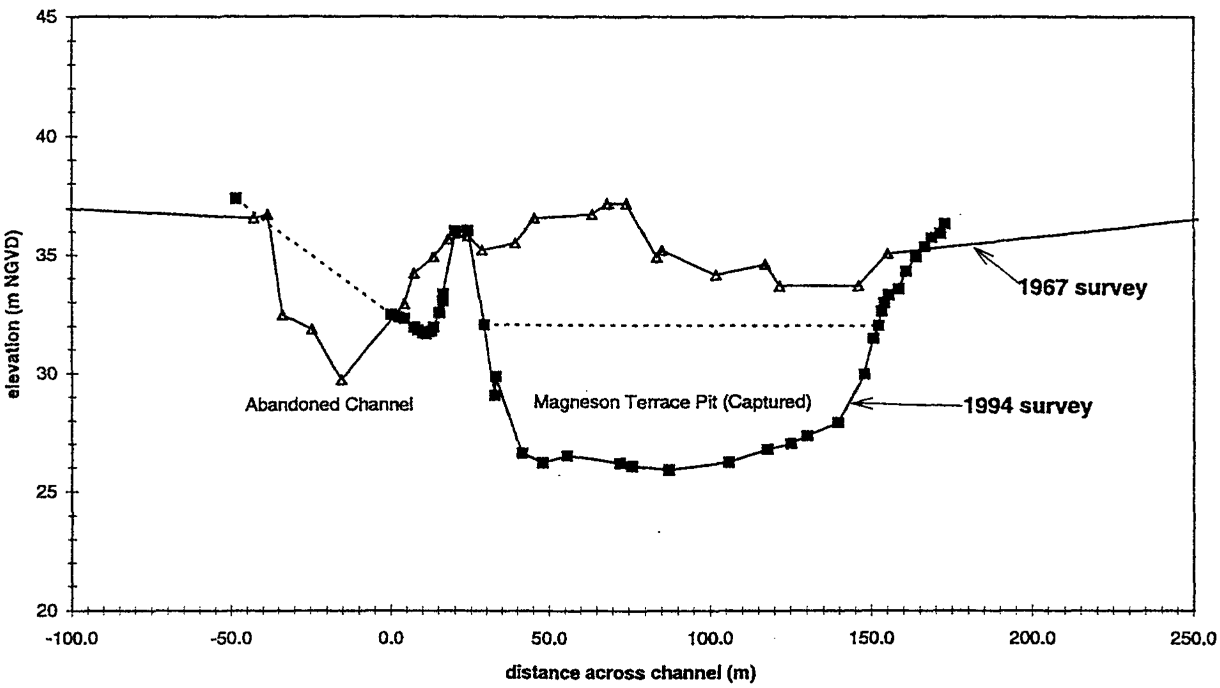


Figure 36. Aerial view and cross section of a captured terrace pit (table 19, mine number 23). Note the 3.5-m increase in depth and three-fold increase in channel width caused by the pit capture. (photo: U.S. Bureau of Reclamation)

Bed Material Deficit in the Lower River

Reservoir sedimentation surveys indicated that the Exchequer Dam reservoir lost 456 $10^3 m^3$ (369 acre-feet) of capacity due to infilling by suspended load and bedload between 1924 and 1946, for an average annual sediment yield of 89 tonnes/km^2 (254 tons/mi^2) for the 2,650 km^2 (1,023 mi^2) basin above the dam (Dendy and Champion 1978).

Assuming a bedload density of 2.0 tonnes/m^3 (1.5 tons/yd^3) and that bedload is between 5% and 10% of the suspended load (Chapter Two), the volume of bedload trapped by the Exchequer Dam that would have been transported through the lower river was between 45,600 and 91,200 tonnes (44,880 and 89,760 tons) over the 20-year survey period, or 2,245-4,490 tonnes/yr (2,210-4,420 tons/yr). Extrapolating this rate over the 68-year period since closure of the Exchequer Dam (1926-1993), the cumulative bedload deficit resulting from the dams' entrapment of bedload would be 152,660 to 305,320 tonnes (150,250 and 300,500 tons).

Available data describing mine depth were extremely poor. Many of the recorded mine depths did not include the datum to which the depth was measured, and survey data were available at only four pits (table 20). However, these data support a rough estimate of mine depth ranging from 3.0 to 6.1 m (10 to 20 ft). Total surface area of all captured, breached and in-channel mines measured from the digitized photographs was 1.11 million m^2 (11.9 million ft^2). Based on the depth and area information, the volume of bed material removed from in-channel, captured, and breached pits between 1942 and 1993 was estimated to be between 3.4 and 6.8 million m^3 (120 and 240 million ft^3), or between 6.8 and 14 million tonnes (6.7 and 13.8 million tons). The reader is cautioned that this calculation is very rough, relying on poorly documented estimates of mine depth and including no adjustments for channel aggradation or degradation.

Channel Response to Changes in Hydrology and Bed Material Supply and Storage

Changes in planform morphology documented by the aerial photograph analysis included reduction of lateral migration, elimination of slough complexes, and reduction of active channel width. Between 1915 and 1993, the channel alignment downstream of the Crocker-Huffman Dam remained remarkably constant, with the only notable changes being the cutting-off of one meander and the capture of five terrace pits. However, the 1937 photographs showed extensive meander scars, oxbow lakes, and backwaters, providing evidence of past channel migration. In the later photographs, this evidence was successively eliminated by agricultural development in the floodplain which was made possible by the flood control function of the Exchequer Dams (figures 37 and 38).

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Table 20
Estimated Depth of Extraction at Sand and Gravel Mines

Mine Number[1]	Depth (m)	Datum	Source
Records			
7	1.21	below 1989 riverbed	Laird et al. 1989
8	9.14	no datum	Davis and Carlson 1952
13	to 12.3 m elevation	NGVD (no surveys available)	MCPD 1972
18	9.14	no datum	Davis and Carlson 1952
25	9.14	no datum	Davis and Carlson 1952
26	15.24	no datum	Davis and Carlson 1952
27	9.14	no datum	Davis and Carlson 1952
Surveys			
21	5.79	below 1967 riverbed	Blodgett and Bertoldi 1968
22	5.49	below 1967 riverbed	Blodgett and Bertoldi 1968; 1994 surveys
23	3.66	below 1967 riverbed	Blodgett and Bertoldi 1968; 1994 surveys
26	4.88	below 1967 riverbed	Blodgett and Bertoldi 1968

[1] refer to table 7

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Figure 37. Merced River floodplain upstream of Shaffer Bridge in 1937 (photo: Agricultural Stabilization and Conservation Service)

Figure 38. Merced River floodplain upstream of Shaffer Bridge in 1993. Note the elimination of meander scars and oxbows and the appearance of several aggregate mines in the 1993 photograph. (photo: U.S. Bureau of Reclamation)

In addition to elimination of channel migration and floodplain complexity created by past migration, distributary sloughs were eliminated or channelized. Much of this elimination resulted from agricultural development of the floodplain (made possible by the flood control function of the New Exchequer Dam) which filled and leveled many sloughs and converted others to irrigation supply and drainage ditches. In the 1937 photographs, a complex of distributary sloughs was found on the north side of the active channel between river km 80 and 55 (river mi 50 and 34). These sloughs departed from the main channel between river km 80 and 72 (river mi 50 and 45), converged into Ingalsbe Slough, and rejoined the Merced River at river km 55 (river mi 34) (figure 39). In the later photographs, the sloughs were progressively reduced. Only disconnected fragments remained by 1979 (figure 40). (The sloughs were not included in the 1993 photographs' field of view.)

At the unmined transects, channel width was significantly reduced between 1937 and 1993. Reduction in channel width averaged 26 $\pm$ 35 m (mean $\pm$ standard deviation), or 33% of the average 1937 channel width (table 21). At the mined transects, no significant change was detected, implying that mined sites were excavated to the 1937 active channel width and, because the pits were too deep to allow establishment of riparian vegetation, did not experience subsequent channel narrowing. In 1937, transects at locations that were later mined averaged 35 m (116 ft), or 45%, wider than the transects at locations that were not later mined. In 1993, the same mined transects averaged 73 m (240 ft), or 137%, wider than the unmined transects (table 22). No significant change was detected for the period between 1937 and 1967, probably due to overestimation of the 1967 channel width caused by the high water conditions at the time of the aerial photographs.

Of the sixteen cross sections reoccupied by this study, fourteen exhibited thalweg degradation, ranging from -0.15 m (0.49 ft) to -6.3 m (20.7 ft), and two exhibited aggradation (table 23). Because reoccupation of the surveys was based on 1:24,000-scale base maps and, therefore, only approximate, changes in bed elevation of less than 0.3 m (1 ft) were considered to be within the margin of error for the survey. Discarding values less than 0.3 m, ten cross sections exhibited degradation and one exhibited aggradation.

In the reach between the Crocker-Huffman Dam and Snelling, upstream of the concentration of aggregate mining, two cross sections exhibited degradation and three cross sections exhibited no change. Within the mined reach between Snelling and Cressey, eight cross sections exhibited degradation. The channel at three of these sections was directly modified by aggregate mining since the original survey in 1967. At sections 137 and 135, the channel was narrowed and restricted by a levee constructed to isolate the Turlock Rock aggregate mine (table 19, mine number 20), and section 127 was located in a terrace mine (table 19, mine number 23) that was captured the channel since the 1967 survey. The remaining five cross sections (143,

Figure 39. Distributary slough system located between Snelling and the Shaffer Bridge in 1937. The southernmost channel in the photograph is the current Merced River mainstem channel. (photo: Agricultural Stabilization and Conservation Service)

Figure 40. Distributary slough system located between Snelling and the Shaffer Bridge in 1979 showing the elimination of sloughs and agricultural encroachment. The southernmost channel in the photograph is the current Merced River mainstem channel. (photo: Agricultural Stabilization and Conservation Service)

Table 21
Change in Transect Widths over Study Period

	Change in Channel Width (m)		
	1937/67	**1967/93**	**1937/93**
Unmined			
n	65	95	65
mean	4.15	-33.13	-26.10
standard deviation	47.99	38.43	35.48
minimum	-0.83	0.21	0.39
maximum	245.02	-260.73	147.62
p	0.20<p<0.50	<0.05	<0.05
Mined			
n	15	15	15
mean	29.12	-17.89	11.23
standard deviation	96.76	52.77	97.50
minimum	2.19	3.03	16.34
maximum	200.20	-131.50	179.17
p	0.20<p<0.50	0.20<p<0.50	>0.50

Table 22
1937 and 1993 Transect Widths

	Transect Width (m)	
	1937	**1993**
Unmined		
n	65	65
mean	79.00	52.91
standard deviation	29.75	28.34
Mined		
n	15	15
mean	114.31	125.54
standard deviation	57.34	85.6

Table 23
Results of Channel Surveys in the Merced River between the Crocker-Huffman Dam and Cressey

Cross Section	Location	Surficial Sediment d_{50} (mm)[1]	Change in Thalweg Elevation Since 1967 (m)	Comment
3	Crocker-Huffman Dam	130	No 1967 Survey	
3a	Merced River Hatchery	108	No 1967 Survey	
4	Calaveras Trout Farm	65	No 1967 Survey	CDWR gravel restoration site Gravel layer one grain thick over bedrock
5	Cuneo Fish Access	71	No 1967 Survey	
148	Henderson Park East	No Data[2]	-3.84	Apparent degradation may be due to poor relocation of channel cross section.
147	Henderson Park West	No Data[2]	-0.88	Cross section in backwater formed by diversion sill at east end of Henderson Park
146	Snelling	105	-0.27	
145	Snelling Road Bridge	75	+0.03	
144	CDWR Snelling Gauge	75	-0.06	
143	State Route 59 Bridge	89	-0.15	
141	Shaffer Bridge	No Data[3]	-1.95	
140		48	-0.21	
138	Hillardes	No Data[2]	-2.34	Located in mine number 19
137	Turlock Rock East	64	-0.42	Adjacent to Turlock Rock terrace pit (mine no. 20). Channel restricted by levee and mined after 1967.
135	Pump 8	27	-1.04	Adjacent to Turlock Rock terrace pit (mine no. 20). Channel restricted by levee and mined after 1967.
133		22	-0.30	
132	Turlock Rock Pit	No Data[2]	+1.68	Located in Turlock Rock in-stream gravel pit (mine no. 21).
129	South Pit	No Data[2]	- 6.31	Adjacent to breached terrace pit (mine no. 22) and downstream of large in-channel pit (mine no. 21)
127	Magneson Pit	No Data[2]	-3.69	Channel captured by former terrace pit (mine no. 23). Original channel abandoned.
126	Downstream of Magneson Pit	36	-2.74	Downstream of captured pit (mine no. 23).

[1] Surface sediment sampled by Wolman pebble count method (Wolman 1954)
[2] Water too deep to sample bed sediment
[3] Bed covered with rock revetment

138, 133, 129 and 126) were not directly modified. Cross section 132 was the only section in the study area that experienced aggradation exceeding 0.3 m (1 foot). This section was located in a large, in-channel mine (table 19, mine number 21) that was excavated in the 1950s.

Upstream of the Route 59 bridge, no change in bed profile since 1967 was detected. Downstream of the bridge, localized increases in slope resulting from bed excavation, scour or nickpoint migration were documented (figure 41). However, survey points were of an insufficient number and distribution to assess changes in average bed slope in any reach.

DISCUSSION

Channel form is the result of complex interactions between discharge and sediment supply. Alteration of the discharge or sediment delivery of the watershed disrupts the equilibrium state of the channel and induces channel adjustment to the new supply and discharge conditions. With time, the channel adjusts to a new equilibrium, in balance with the available energy and sediment supply in the watershed (Williams and Wolman 1984).

Water development and instream mining have altered the discharge and sediment supply characteristics of the Lower Merced River. Construction and operation of large dams have eliminated large floods below the New Exchequer Dam. Floods commonly exceeded 500 m^3/s (17,660 cfs) in the Lower Merced River before closure of the Exchequer Dam (recurrence interval approximately 4 years), but since closure of the New Exchequer Dam flows have not exceeded 201 m^3/s (7,100 cfs), approximately the pre-dam $Q_{1.4}$. Reduction in the magnitude of peak flows has greatly reduced inundation of the former floodplain, resulting in the direct loss of floodplain complexity. It has also encouraged development of row-crop agriculture, orchards, and irrigated pasture on the former floodplain, which involved the elimination of distributary sloughs between Snelling and the Shaffer Bridge as well as other side channels, backwaters, and seasonal wetlands.

In addition, channel forming (or "bankfull") flows were reduced, resulting in vegetative encroachment into the channel and significant channel narrowing. In many systems, the bankfull discharge (the flow that just exceeds the capacity of the channel banks) corresponds to the $Q_{1.5}$ or Q_2 (Leopold et al. 1964). Prior to dam closure, the $Q_{1.5}$ in the lower river was 234 m^3/s (8,360 cfs). Since the closure of the New Exchequer Dam, 234 m^3/s corresponded to the Q_{35}, and the $Q_{1.5}$ fell to 40.2 m^3/s (1,440 cfs), an 83% reduction from the pre-dam condition. In response to the reduction in channel forming flows, the channel narrowed an average of 26.1 m (85.6 ft), or 33% of the 1937 channel width. At the time of the 1937 photographs, the Exchequer Dam had been closed for 11 years. This study, therefore, does not document channel response in the first 11 years after dam closure and likely *underestimates* the reduction in channel width caused by the dam.

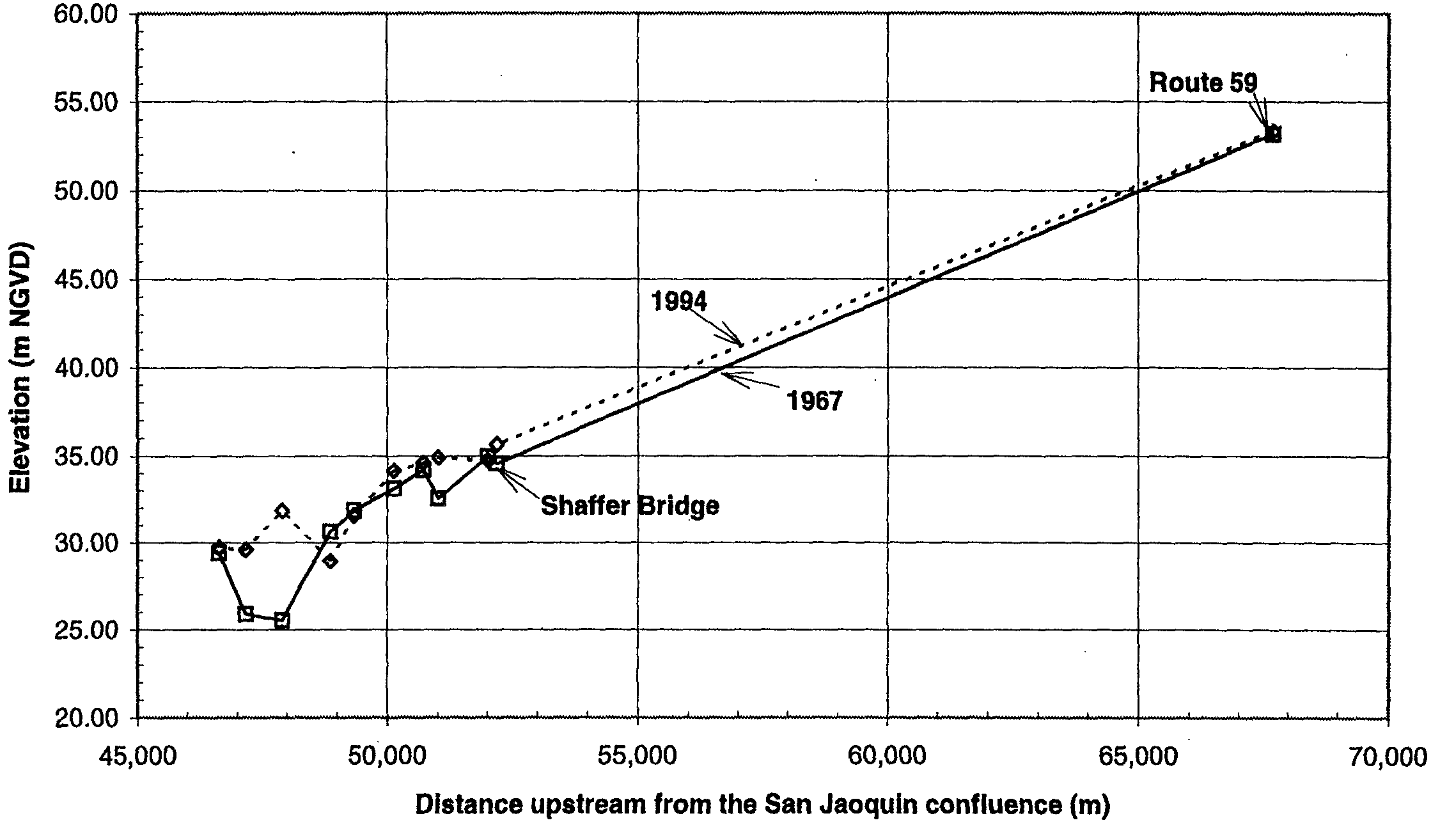

Figure 41. Channel profile between the Route 59 Bridge and the end of the survey. No detailed profile was surveyed. Points were taken from surveyed cross sections. Despite the paucity of survey points, the profile demonstrates the extreme increases in local channel slope caused by instream mining downstream of the Shaffer Bridge.

The dams also trapped bed material transported from the upper watershed, eliminating the bed material supply to the lower river. An estimated 152,660 to 305,320 tonnes (150,250 to 300,500 tons) of bed material was trapped behind the Exchequer Dams since 1926. Downstream of the dams, an estimated 6.8 to 14 million tonnes (6.7 to 13.8 million tons) of bed material was removed from the active channel at in-channel and beached or captured terrace mines. The excavated volume exceeds the amount of bed material that would have been supplied to the lower river (in the absence of the dams) by a factor of between 22 and 92. With the dams in place, the channel has no means to recapture this loss of stored bed material, even over the long term, implying that the pits now occupying 9 km (5.6 mi) of the active channel will not be reclaimed by natural processes.

Even with the greatly reduced discharges in the lower river, the channel has responded (and may continue to respond) to the bed material deficit and changes in channel profile caused by damming and mining. Due to the lack of channel surveys prior to 1967, this study can not assess changes in channel slope, bed elevation, or sediment character that occurred in response to closure of the first Exchequer Dam or early instream mining. However, based on comparison of surveys conducted in 1967 and 1994, recent channel adjustments can be identified. From these surveys, it is evident that much of the length of the channel between the Shaffer Bridge and Cressey has incised. The channel may continue to incise and adjust its slope, driven by local increases in channel slope at the in-channel and captured pits and lack of bed material supply, or channel incision and slope adjustments may be limited by the formation of an armor layer, a layer of coarse sediment that is not mobilized under current hydrologic conditions (Hammad 1972, Simons 1979). Channel incision may also be limited by the lack of flows adequate to mobilize the bed (Parker 1980).

The in-channel and breached and captured terrace pits should be the primary target of a large-scale attempt to rehabilitate the Lower Merced River. These pits, which occupy 9 km (5.6 mi) of the Lower Merced River channel, affect the channel both biologically and geomorphically. Biologically, they provide habitat for large-mouth and small-mouth bass, introduced species that prey on juvenile salmonids. In addition, the low flow velocity through these pits may result in disorientation of in-migrating adult and out-migrating juvenile salmonids. Geomorphically, these pits act as bedload sediment traps, and their upstream margins form nickpoints in the channel bed. The pits, therefore, may induce channel incision upstream and downstream of the mined sites (Chapter Two).

Isolation of the pits from the active channel would probably require the construction of levees or the development of new techniques. The development of a strategy to isolate these pits should prioritize the sites, identify potential restoration techniques and funding sources, and include demonstration projects to identify the best method(s) of pit isolation.

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CONCLUSIONS

The opportunities for restoration of the Lower Merced River are highly constrained by existing hydrologic and sediment supply conditions that require the channel to adjust to a new equilibrium state. In addition, the river is now dotted with instream mining pits which natural processes can not restore in a time frame of less than centuries.

Attempts to restore the channel and aquatic habitat to some target condition must consider the constraints under which the channel functions. For example, measures to restore historical hydrologic conditions must consider the lack of sediment supply to replenish bed scour and the potential for mobilization of the armor layer which may further destabilize the bed. In short, the restoration effort must consider the *interactions* between the sediment and the water, not merely sediment and water in and of themselves.

Regardless of the measures taken to restore or rehabilitate the Lower Merced River, the responsible agency should systematically and quantitatively monitor the performance of the restoration project. Monitoring project performance in achieving the desired physical form could provide valuable insights to inform future restoration efforts.

Chapter 9. Conclusions and Recommendations

The projects funded by the Four Pumps Agreement reflect a piecemeal approach to habitat restoration, focusing on an individual habitat component (i.e., spawning riffles) for a single species (i.e., chinook salmon). This approach can be partially attributed to Guideline Six of the Agreement which requires that the average amount paid for replacing fish under the Annual Account not exceed the cost of producing hatchery-reared yearling fish (Chapter Three). This requirement forces the agencies to produce largely unsupported estimates of fish production at each restoration site in order to guarantee a per fish cost of not more than $1.60 per yearling salmon. The piecemeal approach indoctrinated by this accounting system inherently hinders successful habitat restoration because it ignores important components of ecosystem structure (e.g., habitat connectivity) and ecosystem function (e.g., materials and nutrient transport). A process-based ecosystem restoration strategy for the San Joaquin River Basin should be developed to guide planners, biologists, and engineers in the implementation of effective and well-integrated habitat rehabilitation projects.

The Four Pumps Agreement requires the CDWR, in cooperation with the CDFG, to take action to improve steelhead and chinook salmon stocks in the Central Valley. In the San Joaquin River Basin, funds have been allocated primarily for projects to (1) prevent the stranding of adult salmon in the San Joaquin River upstream of its confluence with the Merced River ($1.0 million), (2) improve and construct hatcheries ($5.5 million), (3) isolate predator habitat from the mainstem channel ($1.4 million), and (4) rehabilitate physical habitat ($1.2 million). From the $1.2 million allocated for rehabilitating physical habitat, $1 million was allocated for projects that have been completed and $0.2 million for a project currently in the design phase (the Reed Site on the Tuolumne River). Of the completed projects, four involved reconstruction of nine individual riffles on the Merced, Tuolumne, and Stanislaus Rivers, and the fifth was a large-scale channel reconstruction to improve spawning and rearing habitat on the Tuolumne River (the Ruddy Site).

Although the primary purpose of the physical habitat rehabilitation projects was to increase spawning habitat, but the CDWR and the CDFG did not present evidence in the planning documents to demonstrate that spawning habitat is limiting the chinook salmon populations in the Merced, Tuolumne, or Stanislaus Rivers. In fact, in a study of the San Joaquin River Basin chinook salmon runs, the CDFG concluded that spawning habitat was *not* limiting these salmon populations. The CDFG report states that "[r]edd (or nest) overlap problems ... were not documented ... [t]he spawning adults were dispersed throughout the available spawning habitats ... spawning area capacity does not appear to be the most important factor limiting recovery of escapements to near historic levels" (CDFG 1987:12). This conclusion was subsequently supported by a field study conducted by the CDWR which concluded that gravel in Merced, Tuolumne, and Stanislaus Rivers were generally of good quality for spawning by chinook salmon (CDWR 1994b). Similarly, in its draft project proposal for the Ruddy Site, the CDWR states that "[i]t is widely accepted by fishery managers that the single most important factor in benefiting the chinook salmon resource in the Tuolumne River is the maintenance of adequate stream flows for adult migration in the fall and juvenile outmigration in the spring" (CDWR 1991: 37). The CDFG has identified other factors, such as low streamflows, unscreened diversions, and predation, that limit this salmon population (CDFG 1987; Reynolds et al. 1993; and SJRMPAC 1993).

At the nine riffle reconstruction sites, project designs were limited to an attempt to create specified hydraulic conditions during spawning flows. The designs did not account for erosion and transport of imported bed material from the sites or supply of new material to the sites under the full range of flows expected to occur at the sites. At the Ruddy Site, an attempt was made to restore channel function rather than merely channel form. A process-based approach focused on function will likely yield a more stable and lasting improvement, benefiting, salmon and other species that utilize the river and riparian corridor. For reasons that are unclear, however, the Ruddy Site project involved realignment of the river channel. The realignment has proven to be unstable as evidenced by the river having recaptures its old channel twice in the three years since project construction.

The designs for the nine riffle rehabilitation sites ignored fundamental geomorphic factors -- such as discharge, sediment supply, and sediment transport -- that determine the long-term stability of the site. At a minimum, project design should include an analysis of sediment transport at the site under pre-project and post-project conditions for *all* flows expected to occur at the site. Failure to address sediment transport during high flows ignores the most critical episodes during which the project may fail. With an adequate sediment transport analysis, a project can be designed to be stable (or in quasi-equilibrium) over the long-term, or the periodic addition of spawning gravel can be incorporated into the project design and budget.

Our surveys of three spawning riffles constructed by the CDWR and the CDFG showed that all three failed to perform as anticipated. (We did not evaluate performance for the Ruddy Site.) First, spawning usage of the reconstructed riffles has been less than 10% of that predicted. The CDFG and the CDWR predicted a total of 777 redds would be constructed annually at the nine riffles and the Ruddy Site. Actual counts of redds at the sites totaled only 77 redds per year. More fundamentally, however, redd counts by themselves are a poor indicator of a project's performance in creating the targeted physical habitat features, because spawning use may be influenced by factors not affected by the rehabilitation project, such as ocean fishing and flow conditions.

Measurement of the physical habitat features targeted by a project provides a better evaluation of project performance than do indirect biological indicators. Evaluations of three riffle reconstruction sites on the Merced, Tuolumne, and Stanislaus Rivers indicate that each of these projects fail to provide the targeted physical habitat features in the long term. At all sites, our channel surveys document erosion and transport of imported spawning gravel from the sites at relatively frequent flows. Shields analyses predicting bed mobility at these sites during flows experienced since project construction corroborates our field observations. Absent a supply of similar-sized gravel from upstream of the site or periodic maintenance to add gravel to the site, we expect the sites to continue to adjust to the discharge and sediment supply conditions of the rivers. In the near future, the project sites will likely return to their pre-project channel configuration and bed material condition in the near future or incised further due to initial excavation of the projects.

No funding, constructing, or permitting agency required or conducted monitoring of basic geomorphic parameters at any of the five project sites despite the explicit requirement in the Four Pumps Agreement that the performance of projects be reviewed and reported annually, and despite the Agreement's guideline which requires implemented projects to be amenable to cost and performance evaluation. To date, the monitoring conducted by the CDFG has been limited to (1) annual redd counts, and (2) monitoring of riparian vegetation planted at the Ruddy site. The redd count monitoring is useful but insufficient in evaluating project performance because it does not compare pre-construction to post-construction spawning at the project site or link changes in spawning usage at the site to the availability of physical habitat constructed by the projects. Moreover, changes in spawning usage and salmon populations at the sites may be affected by a host of factors other than availability of physical spawning habitat the factor that is addressed by the project. Thus, the monitoring program may document increased spawning and fish populations at the project site, but these changes may be unrelated to or in spite of the effects of the project. Likewise, lack of change in spawning usage need not imply that the project failed to create adequate spawning habitat but may simply reflect overall population decline or lack of saturation of spawning habitat already available. This is especially true of anadromous fishes, where populations are affected not only by spawning habitat but also by fishing pressure, impediments to passage, availability and quality of downstream rearing habitat, predation, and conditions in the marine environment (Kondolf and Micheli 1995).

While the redd counts should continue as part of a project monitoring program, the preferred monitoring approach would document the short-term and long-term development of the physical habitat parameters targeted by the project. For instance, for projects that seek to develop a specific channel planform, cross section, slope, and substrate character, the monitoring program should systematically evaluate the short-term and long-term development of the channel planform, cross section, slope, and substrate character. Specific components that should be incorporated into the monitoring program for spawning riffle reconstruction projects include channel cross section surveys, channel profile surveys, and pebble counts.

RECOMMENDATIONS

Identify Factors Limiting Chinook Salmon Populations

The CDWR and the CDFG should specifically identify the factors that currently limit the chinook salmon populations in the San Joaquin River Basin. From previous studies, it appears that low instream flows and losses at the pumping plants constitute the primary factor limiting salmon production, followed by predation by alien species and entrainment in unscreened diversions. It follows that funds provided for salmon recovery should address the primary issues factors.

Process-based Restoration on an Ecosystem Scale

The projects funded by the Four Pumps Agreement exhibit a piecemeal approach to habitat restoration. A process-based ecosystem restoration strategy for the San Joaquin River Basin should be developed to guide planners, biologists, and engineers in implementation habitat rehabilitation projects.

Design of Physical Habitat Rehabilitation Projects

Project design should be based on an understanding of the geomorphic evolution of the site and of the river as a whole, and should include quantitative evaluation of channel hydraulics and sediment transport at the project site under the river's existing discharge and sediment supply conditions. The sediment transport evaluation should be based on application of empirical tractive force methods such as the Shields analysis or a geomorphically informed application of a computerized model such as HEC-6 for *all* flow conditions expected to occur at the site. From this information, the site should be designed to be stable (or in quasi-equilibrium) over the long-term, or periodic maintenance, such as addition of spawning gravel, should be incorporated into the project design and budget.

Use of Historical Analysis in Project Planning and Design

Planning and design of individual projects should be undertaken with a recognition of the larger geomorphic context, which requires a historical geomorphic study. In the Merced, Tuolumne, and Stanislaus Rivers, the geomorphic context includes sediment starvation from upstream dam construction and instream gravel mining, reduced flood flows, and massive alterations of the channel and floodplain from gravel extraction and agriculture.

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Field surveys and sampling provide useful information about existing conditions and can establish a baseline against which future change can be measured. However, to adequately understand channel behavior requires that the period of observation be extended into the past to identify long-term trends and cyclical behavioral patterns. A historical channel study is essential to adequate project planning and design. The historical analysis can reveal the underlying causes of channel change and document prior habitat conditions, help establish realistic habitat restoration objectives, and provide a context within which changes observed at the project site can be interpreted (Kondolf and Larson 1995)

Project Monitoring

All projects should include systematic, objective evaluation of individual project performance. This evaluation is critically important to the long-term success of the overall restoration program. Effective project evaluation requires clearly stated goals, adequate baseline data, good study design, commitment to the long term (a decade or more), and willingness to acknowledge and learn from failures (Kondolf 1995). Results of evaluations should be used to inform the selection of future actions. Project evaluation should be based primarily on documented changes in physical habitat (which is directly modified by the project), rather than changes in biological populations (which are affected by a variety of other factors besides physical habitat). For example, for projects that attempt to modify channel slope, cross section, and bed material character, the monitoring program should quantitatively assess channel slope, cross section, and bed material character.

To assess channel cross section, surveys should be conducted at permanent, monumented locations within the project sites as well as upstream and downstream of the project sites. Annual cross section surveys should meet the following specifications (Jager et al. 1992):

1. cross sections should extend completely across the river channel and should indicate bankfull elevation;
2. cross sections should be adjusted to a permanent vertical datum (e.g., NGVD) which should be indicated for all cross sections;
3. cross sections should include the river bottom, including the thalweg location, as well as the water surface elevation;
4. endpoints and tie points should be permanently monumented in the field and accurately labeled on current aerial photographs or site maps;
5. measurement points between the endpoints should reflect geomorphic conditions at the site (e.g., slope breaks and water surface elevations) and should be indicated on the cross-sectional survey map for each monitoring episode;

6. cross sections should be resurveyed from the same endpoints during each monitoring event;
7. cross sections should be oriented perpendicular to the channel at bankfull flow;
8. cross sections should be presented consistently so that the right bank of the river as one faces downstream is at the right side of the drafted cross section; and
9. additional cross sections may be added to the original cross sections as channel geometry changes or additional data become necessary.

To document channel slope, a longitudinal profile extending from upstream to downstream of the project site should be surveyed annually. In this profile, elevations should be measured in the thalweg of the channel, while horizontal distances should be measured along the center of the bankfull channel (not the thalweg).

To document bed material character, pebble counts (Wolman 1954) should be used to document bed material size at the project site. A series of counts sufficient to describe bed material character throughout the site should be conducted each year at the same time as the channel surveys. Pebble counts provide a replicable, quantitative assessment of mean substrate diameter of the surficial bed material. Counts upstream of the project site may also be included to address interannual variation or fluctuations independent of the mitigation project (e.g. upstream watershed modification).

Determination of Project Benefits

The cost-benefit analysis methods used in project planning for rehabilitation projects unreasonably constrain project design and selection by limiting the definition of benefit to the number of smolts potentially produced at the sites. As demonstrated in this report, smolt equivalent estimates are flawed and serve as a poor tool for estimating smolt production. It would be preferable to define project benefits based on restoration of channel function, including sediment transport and sediment supply. These physical parameters are the ones the projects are intended to modify and can be quantified easily in the field. More importantly, the interpretation of the physical parameters is not complicated by confounding variables (such as ocean fishing) which give rise to uncertainties in the interpretation of redd counts.

NEPA and CEQA Evaluation

Agencies that provide funds or issue permits to construct habitat rehabilitation projects are responsible for assessing the potential environmental impacts of these projects. To adequately assess the potential impacts of any project that proposes to alter channel morphology (including channel alignment, width, slope, or substrate character), the funding, constructing, and permitting agencies must evaluate the channel's short-term and long-term geomorphic response to channel and substrate modifications proposed by the project. Based on the results of this assessment, the agencies can project realistically whether adverse environmental impacts or the beneficial impacts targeted by the project are likely to occur. A geomorphic assessment should include both a historical analysis (Chapter Eight) and application of tractive force methods such as a Shields analysis (Chapters Six and Seven) or a geomorphically informed application of available computer models such as HEC-6. Although the channel response to the proposed project can be predicted in a general sense, the predictive ability of the geomorphic assessment and hydraulic modeling are limited and considerable uncertainty will inevitably accompany any specific prediction. Thus, planning and permitting for any project that alters channel morphology should include a program to monitor geomorphic parameters.

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