Factors That Potentially Limit the Populations of Fall-Run Chinook Salmon in the San Joaquin River Tributaries

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Abstract

Correlations were tested between recruitment, flow related variables, ocean conditions, and harvest between 1939 and 1995 to identify likely environmental factors that limit fall-run chinook salmon (*Oncorhynchus tshawytscha*) in the Stanislaus and Tuolumne rivers, which are tributaries to the San Joaquin River, California. To test correlations, recruitment was estimated by first segregating escapement estimates into cohorts and then expanding cohort abundance to include harvested fish. The segregation of fish into cohorts included length-frequency analysis to determine the percentage of two-year-old fish and the estimation of the percentage of three-, four- and five- year-old fish using age composition data from the 1947-49 and 1951 gill-net catches in the Sacramento-San Joaquin Estuary, marked fish returning to Tehama-Colusa Fish Facility from 1973-1977, and coded-wire tag returns to the San Joaquin Basin from 1988 to 1996.

Recruitment to the Stanislaus River population from 1945 to 1995 and the Tuolumne River population from 1939 to 1995 were strongly correlated with springtime flows in the mainstem San Joaquin River and the tributaries, the ratio of Delta exports at the State Water Project and federal Central Valley Project to Vernalis flows and to a lesser degree, the abundance of spawners (stock), ocean harvest, and anchovy landings. Correlations with herring landings, November flows during spawning, water temperature at Vernalis, and ocean climate conditions, which include the Pacific Interdecadal Climate Oscillation, North Pacific Index, and Pacific Fisheries Environmental Laboratory Upwelling Index were nonsignicant.

The influence of flow and Delta exports is greatest in the Delta near Stockton as demonstrated by U.S. Fish and Wildlife Service (USFWS) smolt survival studies that used coded-wire-tagged juveniles reared in hatcheries. These studies indicated that the survival of smolts migrating in the Delta downstream from Dos Reis to Jersey Point is strongly correlated with flow and to a lesser degree water temperature and Delta exports. However, even when Vernalis flows exceeded 20,000 cfs and Delta exports were low at about 1,800 cfs, smolt survival near Stockton did not exceed 33%. Juvenile salmon survival was

much higher in the tributaries, the mainstem San Joaquin River upstream of Dos Reis, and in the Delta downstream from the Mokelumne River. The source of mortality in the reach near Stockton, which is a dredged deepwater ship channel, is presumed to be predation or entrainment at unscreened diversions because most of the juvenile fish migrate through this reach in less than 5 days and other stressors probably could not act rapidly enough to result in mortality.

The USFWS smolt survival studies also suggest that the impacts of Delta exports primarily have an indirect effect as few tagged fish were collected at the screens at the pumping facilities. Presumably indirect effects of exports occur because flow and fish are diverted into the Old River and Clifton Court Forebay where predator densities are thought to be high and because exports reduce flows in the mainstem river near Stockton. However, these presumed impacts have been ameliorated since 1992 by installing a barrier at the head of the Old River.

Ocean harvest affected recruitment by reducing the abundance of four-year-old fish and population fecundity. Reduced population fecundity was a limiting factor for the Stanislaus and Tuolumne river populations during about 40% of the years after 1950. It is also likely that the large four-year-old fish help improve the permeability of riffle habitat by constructing very large redds.

The correlations between ocean conditions and recruitment to the Tuolumne and Stanislaus rivers were weak probably due to the overriding influence of streamflow. A decline in Tuolumne River recruitment during the mid 1940s was probably in response to the cessation of unusually high flows that persisted from 1935 to 1946; whereas a 30-year cool, productive cycle began off the California Coast in 1947. There were relatively small declines in mean recruitment to both the Tuolumne and Stanislaus rivers in response to a warm, nonproductive cycle that began in 1977.

Other potential limiting factors discussed include (1) instream gravel mining; (2) sedimentation from the construction of new housing which is rapidly increasing along the Stanislaus River corridor; (3) encroachment of riparian vegetation on floodplains as a result of flattened hydrographs; (4) increased Delta exports during the fall when adults are migrating through the Delta; (5) contaminants; and (6) disease.

Introduction

To identify environmental factors that limit fall-run chinook salmon (*Oncorhynchus tshawytscha*) populations in the Stanislaus and Tuolumne rivers, tributaries to the San Joaquin River, California (Figure 1), correlations were tested between escapement data, flow related habitat variables, ocean conditions, and harvest between 1939 and 1995. The results of these tests are presented here along with a review of habitat alterations, harvest, and fish survival studies in the Central Valley to evaluate potential causal mechanisms.

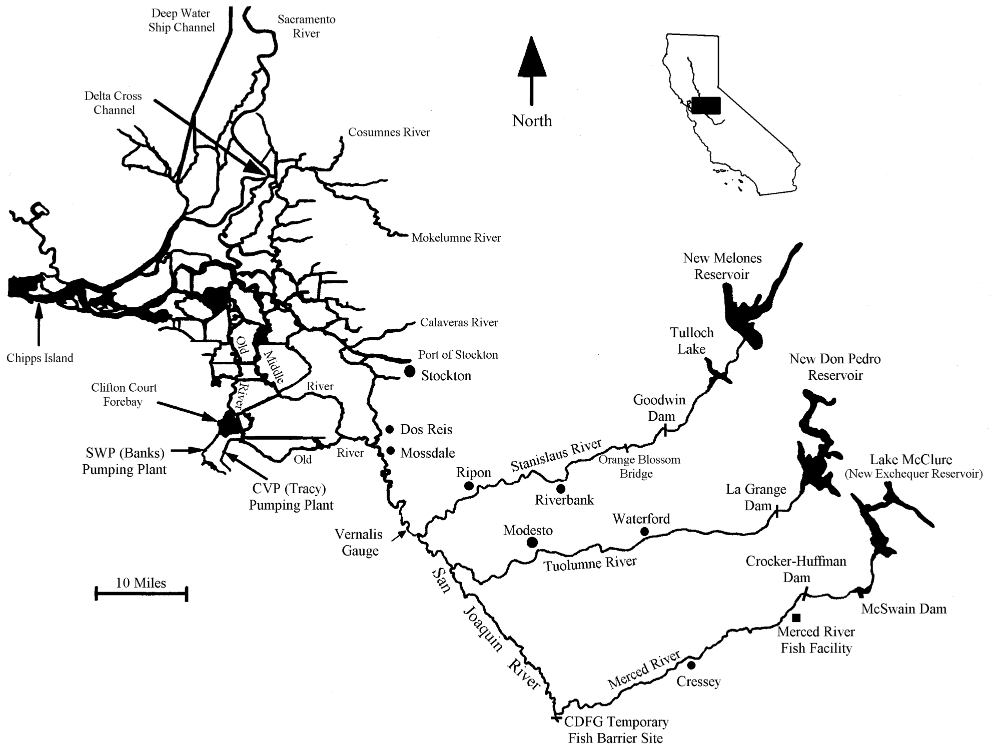

Figure 1 Map of the Stanislaus, Tuolumne, Merced, and San Joaquin rivers and Sacramento-San Joaquin Delta

Trends in Escapement

Escapement is the number of grilse (two-year-olds) and adults (a mixture of three-, four-, and five-year-old fish) that returned to the rivers to spawn after spending at least one and a half years in the ocean. It has been estimated in the San Joaquin tributaries since 1940 (Fry 1961; Department of Fish and Game, Anadromous Fisheries Branch, Sacramento). Until 1973, estimates were made using a combination of techniques that included (1) visual counts in the Tuolumne River at the Modesto Dam fish ladder in 1940, 1941, 1942, and 1944; (2) marking live fish and recovering carcasses the Stanislaus River in 1947 and 1948; and (3) extrapolation of the counts of spawning salmon and carcasses on the spawning areas based on the expertise of the Department of Fish and Game biologists (Fry 1961). Fry (1961) believed that the estimates extrapolated from the spawning bed surveys, the primary method used in the San Joaquin tributaries until 1973, were conservative and usually underestimated the actual run size. Beginning in 1973, carcass tag-and-recovery sampling was initiated to improve the accuracy of the estimates (EA Engineering, Science, and Technology 1992).

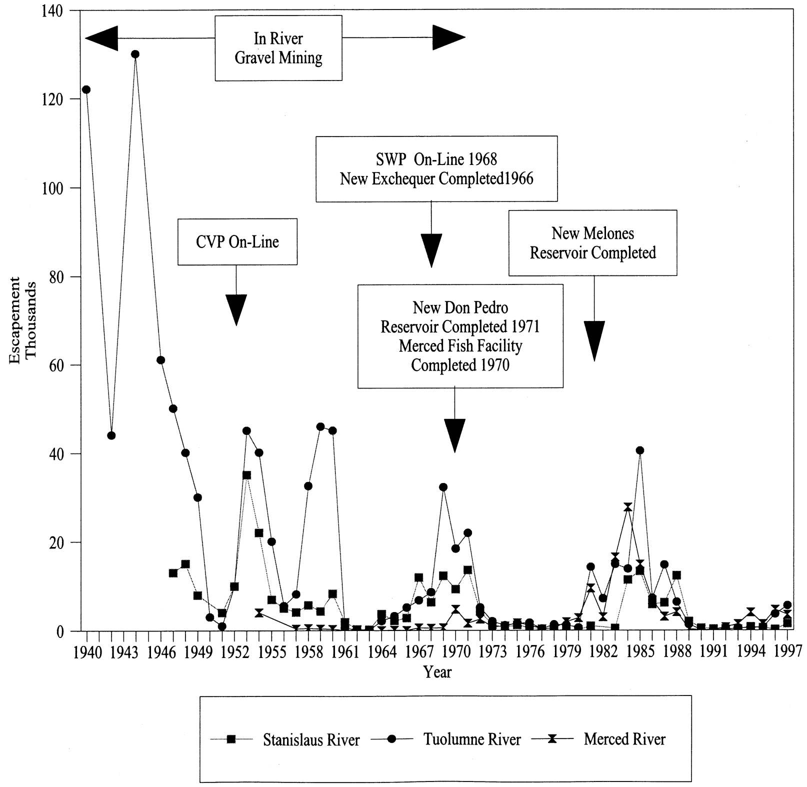

Figure 2 Annual escapements of fall-run chinook salmon in the Stanislaus, Tuolumne, and Merced rivers from 1940 to 1997

The trend in escapement from 1940 to 1997 for the San Joaquin tributaries (Figure 2) suggests while the salmon runs in the Stanislaus and Tuolumne rivers fluctuated greatly between years, they declined substantially between 1940 and 1958. It is likely that these trends were real and not an artifact of the different survey methods, because some of the highest pre-1960 estimates were made using the most accurate methods. The two highest counts on the Tuolumne River, 122,000 and 130,000 salmon, were made at the fish ladder at Modesto Dam. Two moderately high estimates for the Stanislaus River, 13,000 and 15,000 fish, were based on mark-recovery techniques used in 1947 and 1948.

Another feature of the escapement trend analysis is that escapement was low in all three tributaries, except after major flooding and extended high springtime flows. Furthermore, the peaks in escapement were usually two years after the floods and so flows were probably affecting escapement by controlling the production and survival of juvenile salmon.

Correlation Analyses

To investigate the effects of various habitat and harvest variables on adult escapement, statistical correlations were tested for the Stanislaus and Tuolumne rivers. Correlation analyses were not made for the Merced River because after 1970, recruitment was affected by releases of juvenile salmon reared at the Merced River Fish Facility.

Variables tested include (1) streamflows during smolt emigration in the tributaries and mainstem San Joaquin River at Vernalis, (2) water temperature in the mainstem San Joaquin at Vernalis, (3) the ratio of Delta export rates at the Central Valley Project (CVP) and State Water Project (SWP) to flow rates in the mainstem San Joaquin River at Vernalis during smolt emigration, (4) the Central Valley index of ocean harvest rates (Reisenbichler 1986; PFMC 1998), (5) three ocean climate indices of sea surface temperatures and upwelling, and (6) the northern anchovy (*Engraulis mordax*) and herring (*Clupea harengus pallasi*) landings off the coast of California as indices of ocean prey abundance (California Bureau of Marine Fisheries 1970-1990).

Methods

Because there is a delay of one to two years between high spring flows and the return of high numbers of adults, it was necessary to segregate the escapement estimates into cohorts that reflect the abundance of juvenile fish that all hatched in a given year. To estimate the abundance of cohorts, it is necessary to know the percentage of each age class in the escapement estimates. Cohorts for a given period of juvenile emigration, for example the spring of 1950, are estimated by summing the abundance of two-year-old fish in fall 1951, three-year-old fish in fall 1952, four-year-old fish in fall 1953, and five-year-old fish in fall 1954. The California Department of Fish and Game (DFG) estimated the percentage of two-year-old fish using a standard length criterion of fish with fork lengths less than 24 inches from 1951 to 1987 and a length-frequency analysis thereafter. DFG provided sex-specific length-frequency data collected between 1985 and 1998 for the Stanislaus River and 1981 and 1998 for the Tuolumne River that was used to independently estimate the percentage of two-year-old fish (T. Heyne, personal communication, see "Notes"). A correlation analysis indicated that the estimates based on the length-frequency analysis were 4.3% higher (adj-$R^2 = 0.34$) for the Stanislaus River population and 5.0% higher (adj-$R^2 = 0.99$) for the Tuolumne River population compared to the DFG estimates based on fork length measurements of fish less than 24 inches. Assuming that the estimates based on the DFG standard length criterion were not as accurate as the estimates based on length-frequency data, the DF&G estimates of two-year-old fish were adjusted for this analysis using the following equations developed with the correlation analyses:

Stanislaus River Age 2s = DFG Stanislaus River Age 2s * 0.966 + 0.0433

Tuolumne River Age 2s = DFG Tuolumne River Age 2s * 0.979 + 0.0495

DFG did not estimate the abundances of three-, four-, and five-year-old fish separately but instead estimated their abundances as a group called "adults". Therefore, it was necessary to estimate the percentages of the older age classes using age composition data for fall-run fish from the 1947-49 and 1951 gill-net catches in the Sacramento-San Joaquin Estuary (Reisenbichler 1986), marked fish returning to Tehama Colusa Fish Facility from 1973-1977 (Reisenbichler 1986), and coded-wire tag returns to the San Joaquin Basin from 1988 to 1996 (DFG 1991 to 1998). The percentages of the three-, four- and five-year-old fish in cohorts for the Stanislaus and Tuolumne river populations were then estimated by matching the ratios of the percentages of Age 4:Age 3 fish and Age 5:Age 4 fish in each cohort to the average ratios computed from the age composition data for the same period (Table 1). Ratios for age classes were also estimated for the 1952-1960 and the 1961-1970 periods by assuming that the decline in the percentages of Age 4 and Age 5 fish relative to the percentage of Age 3 fish from 1951 to 1973 was a result of increased ocean harvest (Table 1). These age class ratios were estimated using correlations with the Central Valley Index of ocean harvest for each period. The percentages of Age 2 fish prior to 1951 for both rivers were estimated using a ratio of 1.47 for the percentages of Age 3 to Age 2 fish, which was the average of the 1951 to 1955 estimates. The estimation procedure also required that the sum of all the age class percentages in each cohort equaled 100%.

Table 1 Ratios of Age 4:Age 3 fish and Age 5:Age 4 fish and the Central Valley Index used to estimate the age class percentages for each period

Time period	*Age 4:Age 3*	*Age 5:Age 4*	*Central Valley Index*
1945-1946	1.50	0.22	0.335
1947-1951[a]	1.42	0.20	0.368
1952-1960	0.68	0.10	0.554
1961-1970	0.57	0.08	0.580
1971-1972	0.60	0.09	0.570
1973-1977[a]	0.33	0.05	0.636
1978-1987	0.35	0.05	0.651
1988-1998[a]	0.39	0.00[a]/0.05[b]	0.728

[a] Based on age composition data.

[b] Used in estimations.

DFG was unable to estimate escapement during 1950, 1977, and 1982 for the Stanislaus River and 1945 and 1950 for the Tuolumne River. Because each escapement estimate provides abundance estimates for the two-, three-, four-, and five-year-old fish used to compute recruitment in four different years, it was necessary to fabricate escapement estimates for these years to avoid underestimating cohort abundance that required the missing estimates for two- and five-year-old fish. The missing estimates were fabricated such that they were similar to the estimates in the previous and following years. The recruitment estimates derived from the fabricated estimates for three-and four-year-old fish were usually not used for this analysis because those estimates comprised a large proportion of the recruitment estimate and those for some of the two-year-old estimates were not used because they determined year class strength. The recruitment estimates omitted from the analysis due to the absence of estimates for two-, three-, and four-year-old fish include 1947, 1948 and 1949 for the Tuolumne River and 1947, 1948, 1974, 1975, 1979, 1980, and 1981 for the Stanislaus River. Estimated cohort abundance in the escapement and percentage of each age of fish in each cohort is presented in Table 2.

Recruitment was tested in the correlation analysis that was the combined abundance of the fish that returned to spawn (escapement) and those harvested in the commercial and sport fishery. It was computed by dividing cohort abundance based on escapement by "1 - Central Valley Index of harvest (CVI)." The CVI was weighted toward four-year-old fish from 1939 to 1951 when four-year-olds were relatively abundant and toward three-year-old fish thereafter. The following equations were used for three periods that correspond to the decline in four-year-old fish:

Recruitment = Escapement Cohort/(1 - (CVI Age 4 + CVI Age 4 + CVI Age 3/3)) from 1939-1951;

Recruitment = Escapement Cohort/(1 - (CVI Age 4 + CVI Age 3 + CVI Age 3/3)) from 1952-1969;

Recruitment = Escapement Cohort/(1 - CVI Age 3) from 1970-1995

Recruitment, which is presented in Table 3, is identified according to the year when most of the fish emigrated to the ocean as smolts.

Correlations with Recruitment also considered the abundance of spawners that produced each cohort. The number of spawners, called “Stock” for this analysis, was computed as the equivalent number of three-year-old salmon that returned to spawn during the year prior to the recruitment estimate using the following formula:

Stock = 0.25 * Age 2s + Age 3s + 1.25 * Age 4s + 1.5 * Age 5s

The age-specific escapement estimates were multiplied by an adjustment factor to reflect the relative number of eggs deposited by females in the Stock estimate. For example, the escapement estimate for two-year-old fish (Age 2s) was multiplied by 0.25 because two-year-old fish are primarily males and the two-year-old females produce about half the number of eggs produced by three-year-old females. DFG estimates that 74% of two-year-old fish were males from 1988 to 1998 in the San Joaquin basin (T. Heyne, personal communication, see “Notes”). Two-year-old females, which average 61 cm in fork length, would be expected to produce about 2,800 eggs, whereas three-year-old females, which average about 77 cm in fork length, would produce about 6,000 eggs based on fecundity data presented in DFG (1990).

Correlation evaluations were conducted with the variables presented in Table 3 and with other variables of ocean harvest and northern anchovy landing variables not shown in the table. Table 3 presents the harvest estimates that corresponded to the cohorts when the fish were three-years-old and the northern anchovy landing estimates that corresponded to the cohorts when the fish were two-years-old. The ocean harvest estimates were also tested for the year when the cohorts were four-year-old fish and the anchovy estimates were also tested for the years when the cohorts were three-years-old fish by shifting the estimates up or down in the table by the appropriate number of years. For example, the northern anchovy landing estimate for Age 2 fish in Table 3 for the 1965 cohort (31,140) was also the same estimate for Age 3 fish for the 1964 cohort.

Table 2 DFG estimates of escapement, DFG estimates of percent two-year-olds in escapement (%Age 2), the estimates of percent two-, three-, four- and five-year-olds used in the analyses, cohort abundance (cohort) based on escapement for the spring juvenile emigration period, and stock for the Stanislaus and Tuolumne rivers from 1939 to 1998[a]

	DFG Estimates		*Estimates used in analysis*					
Year	*Escapement*	*%Age2*	*%Age2*	*%Age3*	*%Age4*	*%Age5*	*Cohort*	*Stock*
Stanislaus River								
1946							11,150	20,175
1947	13,000		14%	35%	43%	9%	3,950	15,131
1948	15,000		6%	25%	58%	11%	1,700	13,585
1949	8,000		5%	16%	60%	20%	2,187	17,325
1950	**3,000**		13%	14%	47%	26%	16,792	9,730
1951	4,000	46%	49%	20%	21%	10%	11,525	
1952	10,000	12%	16%	74%	9%	1%	39,302	2,947
1953	35,000	57%	60%	20%	20%	0%	8,878	9,084
1954	22,000	20%	24%	62%	13%	2%	4,555	21,138
1955	7,000	20%	23%	19%	56%	2%	2,972	18,928
1956	5,000	6%	11%	29%	41%	19%	6,025	6,828
1957	4,090	31%	34%	29%	31%	6%	3,439	5,593
1958	5,700	14%	18%	58%	21%	4%	9,624	3,470
1959	4,300	50%	53%	21%	25%	2%	1,179	5,350
1960	8,300	5%	9%	70%	18%	3%	190	2,896
1961	1,900	2%	6%	16%	76%	2%	248	8,247
1962	315	15%	19%	11%	42%	28%	4,268	2,196
1963	200	38%	41%	35%	16%	8%	1,910	347
1964	3,700	11%	15%	82%	3%	0%	2,902	155
1965	2,231	12%	16%	37%	47%	0%	13,107	3,327
1966	2,872	33%	37%	44%	17%	3%	2,248	2,233
1967	11,885	3%	7%	82%	11%	1%	20,810	2,247
1968	6,385	57%	59%	10%	31%	1%	1,825	11,607
1969	12,327	3%	2%	88%	6%	3%	16,748	4,064
1970	9,297	28%	31%	8%	60%	1%	2,759	12,479
1971	13,621	7%	11%	80%	6%	4%	1,423	8,546
1972	4,298	10%	14%	18%	67%	1%	403	12,970
1973	1,234	4%	8%	44%	38%	10%	1,361	4,568

[a] Estimates in bold type were fabricated to fill in gaps in the DFG data.

Table 2 DFG estimates of escapement, DFG estimates of percent two-year-olds in escapement (%Age 2), the estimates of percent two-, three-, four- and five-year-olds used in the analyses, cohort abundance (cohort) based on escapement for the spring juvenile emigration period, and stock for the Stanislaus and Tuolumne rivers from 1939 to 1998[a] (Continued)

	DFG Estimates		*Estimates used in analysis*					
Year	*Escapement*	*%Age2*	*%Age2*	*%Age3*	*%Age4*	*%Age5*	*Cohort*	*Stock*
1974	750	33%	36%	27%	34%	4%	476	1,338
1975	1,200	14%	18%	72%	8%	1%	236	623
1976	600	23%	27%	37%	36%	1%	22	1,069
1977	**100**	0%	**10%**	49%	36%	5%	130	535
1978	50	33%	37%	12%	46%	5%	84	
1979	100	6%	10%	82%	5%	3%	1,379	43
1980	100	17%	20%	52%	27%	0%	1,216	95
1981	1,000	0%	4%	93%	2%	0%	985	92
1982	**2,000**	0%	**25%**	54%	21%	0%	8,370	974
1983	500	0%	**46%**	37%	16%	1%	17,321	
1984	11,439	39%	42%	55%	3%	0%	4,219	348
1985	13,322	9%	14%	73%	13%	0%	3,669	7,924
1986	5,888	17%	24%	30%	45%	1%	16,327	12,384
1987	6,292	36%	67%	22%	9%	2%	1,498	5,546
1988	12,344	4%	7%	85%	7%	0%	265	3,336
1989	1,968	3%	6%	18%	75%	1%	334	11,898
1990	492	39%	15%	19%	42%	24%	227	2,267
1991	321	16%	16%	59%	19%	6%	437	549
1992	254	54%	24%	48%	27%	1%	1,117	306
1993	410	21%	25%	62%	12%	1%	460	226
1994	1,079	17%	14%	74%	11%	0%	374	347
1995	629	26%	30%	36%	34%	1%	6,563	993
1996	160	59%	59%	27%	13%	1%	885	543
1997	5,583	7%	7%	91%	2%	1%	1,177	96
1998	3,147	37%	37%	17%	45%	1%	0	5,367
Average	5,915	21%	23%	43%	29%	5%	5,167	5,321
Tuolumne River								
1939							65,135	
1940	122,000		19%	30%	43%	9%	40,250	
1941	60,000		19%	30%	43%	9%	116,810	122,534

[a] Estimates in bold type were fabricated to fill in gaps in the DFG data.

Table 2 DFG estimates of escapement, DFG estimates of percent two-year-olds in escapement (%Age 2), the estimates of percent two-, three-, four- and five-year-olds used in the analyses, cohort abundance (cohort) based on escapement for the spring juvenile emigration period, and stock for the Stanislaus and Tuolumne rivers from 1939 to 1998[a] (Continued)

	DFG Estimates		*Estimates used in analysis*					
Year	*Escapement*	*%Age2*	*%Age2*	*%Age3*	*%Age4*	*%Age5*	*Cohort*	*Stock*
1942	44,000		29%	20%	43%	9%	84,960	60,263
1943	60,000		20%	47%	25%	9%	92,080	40,975
1944	130,000		19%	25%	52%	4%	48,005	57,225
1945	**75,000**		12%	32%	45%	11%	38,605	130,975
1946	61,000		11%	21%	58%	11%	47,905	**80,813**
1947	50,000		16%	25%	43%	16%	20,175	68,396
1948	40,000		10%	37%	42%	12%	264	53,425
1949	30,000		0%	20%	69%	11%	965	43,550
1950	**15,000**		3%	1%	65%	32%	20,499	36,705
1951	3,000	77%	80%	4%	1%	15%	18,766	
1952	10,000	4%	9%	88%	4%	0%	65,469	1,435
1953	45,000	50%	54%	26%	19%	0%	10,528	9,442
1954	40,000	10%	14%	70%	14%	2%	8,973	28,960
1955	20,000	20%	24%	14%	60%	2%	3,019	37,395
1956	5,500	5%	10%	38%	33%	20%	44,139	19,580
1957	8,170	59%	63%	14%	21%	2%	25,319	6,098
1958	32,500	12%	17%	78%	4%	1%	53,818	4,827
1959	45,900	48%	52%	22%	26%	0%	4,102	28,980
1960	45,000	4%	9%	66%	22%	4%	215	31,128
1961	500	31%	35%	7%	55%	2%	86	45,291
1962	250	9%	13%	4%	41%	43%	1,951	443
1963	100	20%	25%	17%	24%	35%	4,880	303
1964	2,100	32%	37%	61%	2%	0%	3,179	105
1965	3,200	1%	6%	75%	19%	0%	8,069	1,533
1966	5,100	29%	34%	35%	30%	1%	1,953	3,204
1967	6,800	5%	10%	71%	17%	2%	50,580	4,219
1968	8,600	76%	79%	6%	15%	0%	4,432	6,668
1969	32,200	2%	2%	95%	2%	1%	23,501	3,831
1970	18,400	17%	22%	10%	68%	0%	4,572	32,097
1971	21,885	7%	11%	77%	9%	3%	2,604	18,554

[a] Estimates in bold type were fabricated to fill in gaps in the DFG data.

Table 2 DFG estimates of escapement, DFG estimates of percent two-year-olds in escapement (%Age 2), the estimates of percent two-, three-, four- and five-year-olds used in the analyses, cohort abundance (cohort) based on escapement for the spring juvenile emigration period, and stock for the Stanislaus and Tuolumne rivers from 1939 to 1998[a] (Continued)

	DFG Estimates		*Estimates used in analysis*					
Year	*Escapement*	*%Age2*	*%Age2*	*%Age3*	*%Age4*	*%Age5*	*Cohort*	*Stock*
1972	5,100	17%	21%	28%	50%	1%	883	20,817
1973	1,989	5%	10%	50%	31%	9%	1,754	4,944
1974	1,150	9%	13%	41%	42%	4%	1,420	2,089
1975	1,600	9%	13%	72%	13%	2%	659	1,177
1976	1,700	10%	14%	59%	26%	1%	1,276	1,508
1977	450	0%	5%	51%	41%	3%	1,035	1,631
1978	1,300	7%	12%	73%	14%	2%	717	486
1979	1,183	10%	15%	59%	25%	1%	3,798	1,237
1980	559	10%	14%	56%	28%	2%	18,385	1,126
1981	14,253	32%	75%	23%	2%	0%	1,311	544
1982	7,126	5%	12%	82%	6%	0%	23,908	6,253
1983	14,836	82%	86%	2%	12%	0%	42,571	6,611
1984	13,802	52%	63%	36%	1%	1%	7,614	5,704
1985	40,322	4%	12%	73%	15%	0%	1,092	7,385
1986	7,288	7%	10%	29%	59%	2%	20,367	38,242
1987	14,751	93%	93%	2%	4%	1%	787	7,876
1988	6,349	5%	10%	88%	2%	1%	104	4,730
1989	1,274	4%	6%	9%	84%	0%	58	5,923
1990	96	22%	22%	11%	29%	39%	89	1,487
1991	77	15%	35%	35%	22%	9%	548	106
1992	132	62%	62%	31%	7%	1%	414	64
1993	435	30%	17%	79%	5%	0%	616	74
1994	513	25%	29%	48%	23%	0%	433	386
1995	743	38%	33%	53%	13%	1%	7,810	433
1996	160	68%	68%	20%	11%	1%	7,916	585
1997	5,583	6%	6%	90%	2%	1%	8,545	84
1998	3,147	35%	35%	19%	45%	1%	4,478	5,374
Average	20,121	25%	26%	40%	27%	6%	17,907	19,401

[a] Estimates in bold type were fabricated to fill in gaps in the DFG data.

Table 3 Hypothetical minimum instream flow schedule for the Stanislaus and Tuolumne rivers for the spawning and spring emigration periods

Time period	*Streamflow release (cfs)*
Nov 5 to Dec 29	150
Apr 1 to 3	150
Apr 4 to 13	200
Apr 14 to 23	250
Apr 24 to May 3	400
May 4 to 13	700
May 14 to 23	850
May 24 to 28	900
May 29 to Jun 2	950

Four variables, StanMinSpr, StanMinFal, TuolMinSpr, and TuolMinFal, were used to test a ratio of flow releases in the Stanislaus and Tuolumne rivers relative to hypothetical minimum instream flow schedules based on the habitat criteria developed by the U.S. Fish and Wildlife Service for the Stanislaus and Tuolumne rivers. The flow schedules are based on the Physical Habitat Simulation Models (PHABSIM) for each river (USFWS 1993, 1994) and water temperature models for each river (EA 1993; USBR 1993). Flows were selected to provide nearly optimum water depths and velocities and to maintain a 56 F temperature within the upper spawning reach during November and 66 F to the mouth of the river during the spring juvenile rearing and emigration period in April and May. The variable reflects the average of the ratio of flow releases to the hypothetical flow schedule for each day of the spring and fall periods. The development of the hypothetical release schedule, which is presented in Table 4, is discussed further in Carl Mesick Consultants (1996).

Three indices of ocean climate conditions were tested. The means of the November to March values of both the North Pacific Index (NPI) and the Pacific interdecadal Oscillation (PDO) and the mean of the May to July values of the Pacific Fisheries Environmental Laboratory coastal upwelling index (PFEL Upwelling Index) for the San Francisco area (interpolated values to a latitude of 38N) were used in this analysis. The NPI is the anomaly of the of the area-weighted sea level pressure of the Aleutian Low (region 30N-65N, 160E-140W) for the 1925 to 1989 period (Trenberth and Hurrell 1994). The mean of the November to March values of the Pacific interdecadal Oscillation (PDO) is defined by Steven Hare as the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20N for the 1900-93 period). NPI and PDO are both correlated with sea surface temperatures and the ocean harvest of salmon off the Alaska coast and the West coast (Mantua and others 1997). When sea surface temperatures are warm off the entire northeastern Pacific rim, PDO tends to be positive, NPI tends to be negative, Alaska landings of sockeye and pink salmon are relatively high, and West Coast landings of spring-run chinook and coho salmon are low (Mantua and others 1997). The PFEL Upwelling Index is a measure of the intensity of large-scale, wind-induced coastal upwelling along the West Coast and is based on estimates of offshore Ekman transport driven by geostrophic wind stress (PFEL 2001).

The Statistix 7.0 software program (Analytical Software 1995) was used to visually inspect scatter plots to assess whether the relationships were linear and to compare Pearson correlation coefficients (r), Mallows' C_p statistics, plots of standardized residuals relative to fitted values, and stepwise regression analyses to determine the set of variables that maximized the adjusted coefficient of determination (adj-R^2). To inspect the various relationships in scatter plots, it was necessary to minimize the effects of the other test variables. This was done by excluding data sets in the scatter plots in which recruitment was substantially affected by other variables. For example, when evaluating the stock-recruitment relationships for the Tuolumne River, only data sets with Vernalis flows between 8,000 and 15,000 cfs were used in the scatter plots. Similarly when flow and exports were evaluated for Tuolumne River recruitment, only data sets with stock greater than 6,000 spawners were used in the scatter plots as recruitment was relatively unaffected by stock, when stock exceeded 6,000 spawners.

The visual inspections of scatter plots also determined that the relationships with stock and the Delta export ratio were nonlinear. A log transformation of the ratio of Delta exports to Vernalis flows and second degree polynomial terms (square, square root, log, and the inverse of the variables) for both the stock and flow variables were tested in the correlation analyses (page 404 in Snedecor and Cochran 1989).

Table 4 Estimates of recruitment, stock, the average streamflow (cfs) in the San Joaquin River at Vernalis from 15 April to 15 June (VerFloSpr), ratio of Delta exports at the SWP and CVP pumping facilities to Vernalis flows from 15 April to 15 June (ExFloSpr), the Central Valley Index of ocean harvest (CVI) corresponding to Age-3 chinook salmon, the North Pacific Index (NPI) corresponding to Age-1 chinook salmon, the mean Pacific Decadal Oscillation (PDO) from November through March corresponding to Age-1 chinook salmon, the PFEL Upwelling Index corresponding to Age-1 chinook salmon, northern anchovy landings (tons) and herring landings (tons) off the coast of California corresponding to Age-2 chinook salmon, the average streamflow (cfs) in the Stanislaus River at Ripon from 15 April to 15 June, the ratio of flows releases in the Stanislaus River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (StanMinSpr) and for 1-30 November (StanMinFal), the average flow (cfs) in the Tuolumne River at Modesto from 15 April to 15 June, the ratio of flow releases in the Tuolumne River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (TuolMinSpr) and for 1 to 30 November (TuolMinFal), and the average maximum water temperature (F) in the San Joaquin River at Vernalis for April.

Year	*Stan Recruit*	*Stan Stock*	*Tuol Recruit*	*Tuol Stock*	*VerFlo-Spr*	*ExFlo-Spr*	*CVI Age 3*	*NPI Age1*	*PDO Age 1*	*Up-well*	*Anchovy Age 2*	*Herring Age 2*	*Ripon Flow Spring*	*Stan-Min-Spr*	*Stan-Min-Fall*	*Modesto Flow Spring*	*Tuol-Min-Spr*	*Tuol-Min-Fall*	*Max Vernalis Temp*
1939			93,945		1,933	0.00		0.49	0.584		3,159	227							
1940			58,333		13,773	0.00		-5.22	1.258		2,053	395							
1941			170,941	122,534	20,552	0.00		-3.54	1.852		847	95							
1942			126,178	60,263	18,413	0.00		-0.80	0.680		785	315							
1943			138,814	40,975	15,785	0.00	0.33	3.43	-0.200		1,946	211							
1944			72,735	57,225	3,739	0.00	0.34	-1.10	0.260		808	230							
1945			59,698	130,975	11,212	0.00	0.34	-2.82	-0.038		961	241							
1946	17,605	20,175	75,639	80,813	10,475	0.00	0.36	0.43	-0.864	139	9,470	827							
1947		15,131		68,396	1,679	0.00	0.37	1.77	-0.458	109	5,418	4,000							
1948		13,585		53,425	5,483	0.00	0.37	2.44	0.130	114	1,661	190							
1949	3,770	17,325	1,664	43,550	2,890	0.00	0.40	2.02	-1.840	130	2,439	713							
1950	29,808	9,730	36,389	36,705	5,904	0.00	0.43	1.49	-1.560	169	3,477	2,462							
1951	22,163	3,450	36,089	19,457	4,848	0.01	0.44	3.00	-1.544	155	27,891	4,748							

Table 4 Estimates of recruitment, stock, the average streamflow (cfs) in the San Joaquin River at Vernalis from 15 April to 15 June (VerFloSpr), ratio of Delta exports at the SWP and CVP pumping facilities to Vernalis flows from 15 April to 15 June (ExFloSpr), the Central Valley Index of ocean harvest (CVI) corresponding to Age-3 chinook salmon, the North Pacific Index (NPI) corresponding to Age-1 chinook salmon, the mean Pacific Decadal Oscillation (PDO) from November through March corresponding to Age-1 chinook salmon, the PFEL Upwelling Index corresponding to Age-1 chinook salmon, northern anchovy landings (tons) and herring landings (tons) off the coast of California corresponding to Age-2 chinook salmon, the average streamflow (cfs) in the Stanislaus River at Ripon from 15 April to 15 June, the ratio of flows releases in the Stanislaus River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (StanMinSpr) and for 1-30 November (StanMinFal), the average flow (cfs) in the Tuolumne River at Modesto from 15 April to 15 June, the ratio of flow releases in the Tuolumne River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (TuolMinSpr) and for 1 to 30 November (TuolMinFal), and the average maximum water temperature (F) in the San Joaquin River at Vernalis for April.

Year	*Stan Recruit*	*Stan Stock*	*Tuol Recruit*	*Tuol Stock*	*VerFlo-Spr*	*ExFlo-Spr*	*CVI Age 3*	*NPI Age1*	*PDO Age 1*	*Up-well*	*Anchovy Age 2*	*Herring Age 2*	*Ripon Flow Spring*	*Stan-Min-Spr*	*Stan-Min-Fall*	*Modesto Flow Spring*	*Tuol-Min-Spr*	*Tuol-Min-Fall*	*Max Vernalis Temp*
1952		2,947	140,290	1,435	26,123	0.00	0.50	2.20	-1.012	132	42,918	3,901							
1953	25,128	9,084	29,796	9,442	3,047	0.82	0.60	-1.30	-0.496	127	21,205	456							
1954	17,297	21,138	34,074	28,960	5,059	0.64	0.74	0.92	-0.682	143	22,346	973							
1955	8,915	18,928	9,058	37,395	1,431	2.20	0.73	2.32	-0.472	275	28,460	868							
1956		6,828	92,598	19,580	12,645	0.05	0.54	3.40	-2.722	208	20,274	594							
1957	6,878	5,593	50,637	6,098	3,103	1.17	0.49	1.41	-1.172	172	5,801	1,200							
1958		3,470	119,595	4,827	21,324	0.02	0.52	-1.07	0.050	129	3,587	864							
1959	3,024	5,350	10,518	28,980	760	3.86	0.61	1.40	-0.002	253	2,529	900							
1960	456	2,896	517	31,128	540	6.78	0.61	0.36	0.356	122	3,856	701	132	0.02	0.07	228	0.26	4.15	
1961	535	8,247	186	45,291	297	12.96	0.53	-2.03	0.328	144	1,382	653	86	0.01	0.15	164	0.19	3.27	
1962	10,081	2,196	4,610	443	2,793	1.26	0.55	1.79	-1.680	166	2,285	315	1,481	2.27	0.16	257	0.31	1.41	
1963	5,258	347	13,430	303	8,992	0.30	0.63	-1.43	-0.472	173	2,488	175	3,657	7.30	0.41	2,505	2.62	5.80	63.9
1964	7,705	155	8,441	105	722	4.65	0.65	0.18	-0.846	215	2,866	258	135	0.01	4.41	223	0.27	14.34	64.7
1965	30,016	3,327	18,478	1,533	7,229	0.49	0.57	0.99	-0.936	245	31,140	121	2,907	6.25	0.25	1,817	1.38	8.29	
1966	5,071	2,233	4,404	3,204	815	4.36	0.55	2.37	-0.534	214	34,805	136	164	0.02	0.14	245	0.29	13.17	

Table 4 Estimates of recruitment, stock, the average streamflow (cfs) in the San Joaquin River at Vernalis from 15 April to 15 June (VerFloSpr), ratio of Delta exports at the SWP and CVP pumping facilities to Vernalis flows from 15 April to 15 June (ExFloSpr), the Central Valley Index of ocean harvest (CVI) corresponding to Age-3 chinook salmon, the North Pacific Index (NPI) corresponding to Age-1 chinook salmon, the mean Pacific Decadal Oscillation (PDO) from November through March corresponding to Age-1 chinook salmon, the PFEL Upwelling Index corresponding to Age-1 chinook salmon, northern anchovy landings (tons) and herring landings (tons) off the coast of California corresponding to Age-2 chinook salmon, the average streamflow (cfs) in the Stanislaus River at Ripon from 15 April to 15 June, the ratio of flows releases in the Stanislaus River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (StanMinSpr) and for 1-30 November (StanMinFal), the average flow (cfs) in the Tuolumne River at Modesto from 15 April to 15 June, the ratio of flow releases in the Tuolumne River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (TuolMinSpr) and for 1 to 30 November (TuolMinFal), and the average maximum water temperature (F) in the San Joaquin River at Vernalis for April.

Year	*Stan Recruit*	*Stan Stock*	*Tuol Recruit*	*Tuol Stock*	*VerFlo-Spr*	*ExFlo-Spr*	*CVI Age 3*	*NPI Age1*	*PDO Age 1*	*Up-well*	*Anchovy Age 2*	*Herring Age 2*	*Ripon Flow Spring*	*Stan-Min-Spr*	*Stan-Min-Fall*	*Modesto Flow Spring*	*Tuol-Min-Spr*	*Tuol-Min-Fall*	*Max Vernalis Temp*
1967	48,775	2,247	118,546	4,219	20,024	0.08	0.57	2.06	-0.610	233	15,538	179	4,616	8.50	0.20	4,251	4.57	4.12	
1968	4,276	11,607	10,388	6,668	841	6.20	0.58	0.12	-0.422	228	67,639	85	162	0.01	0.69	229	0.27	12.47	
1969	44,074	4,064	61,844	3,831	25,471	0.13	0.56	1.93	-0.884	221	96,243	158	5,010	7.83	0.15	6,273	8.01	2.99	
1970	10,613	12,479	17,586	32,097	2,362	1.88	0.74	-3.16	0.780	191	44,852	120	1,027	0.33	3.46	568	0.74	12.00	
1971	4,743	8,546	8,679	18,554	1,881	2.43	0.70	2.58	-1.418	200	69,101	63	631	0.29	0.49	326	0.35	2.28	
1972	1,118	12,970	2,452	20,817	751	8.73	0.64	2.94	-1.806	207	132,636	1,410	137	0.01	1.41	230	0.25	3.47	
1973	3,489	4,568	4,496	4,944	3,077	2.09	0.61	0.62	-0.266	292	82,717	2,630	1,844	2.41	0.96	299	0.35	4.67	70.8
1974		1338	3,464	2089	4403	1.63	0.59	0.16	-1.268	281	158,511	1,217	2,666	2.98	0.38	333	0.38	4.74	69.1
1975		623	1,831	1177	4505	1.38	0.64	1.13	-0.350	278	124,919	2,410	2,597	2.28	0.60	488	0.59	12.34	66.1
1976	72	1069	4,253	1508	955	5.41	0.70	1.19	-1.528	272	111,477	5,827	97	0.01	4.87	225	0.25	12.24	70.2
1977	382	535	3,044	1631	267	6.54	0.66	-2.95	1.190	254	12,629	4,930	38	0.01	0.00	132	0.16	2.37	75.4
1978	249	104	2,108	486	17559	0.30	0.66	-2.41	0.344	272	53,698	4,693	3,398	6.95	0.01	2,364	3.41	0.61	64.1
1979		43	10,549	1237	2582	2.73	0.64	1.65	-0.422	255	47,339	8,886	875	0.22	0.03	361	0.33	7.94	72.4
1980		95	65,660	1126	9036	0.60	0.72	-1.21	0.472	246	57,659	6,571	3,238	6.81	0.34	2,565	3.13	6.99	64.2
1981		92	3,543	544	2071	2.43	0.63	-4.46	0.662	300	46,462	11,689	766	1.83	0.54	294	0.32	10.96	75.0

Table 4 Estimates of recruitment, stock, the average streamflow (cfs) in the San Joaquin River at Vernalis from 15 April to 15 June (VerFloSpr), ratio of Delta exports at the SWP and CVP pumping facilities to Vernalis flows from 15 April to 15 June (ExFloSpr), the Central Valley Index of ocean harvest (CVI) corresponding to Age-3 chinook salmon, the North Pacific Index (NPI) corresponding to Age-1 chinook salmon, the mean Pacific Decadal Oscillation (PDO) from November through March corresponding to Age-1 chinook salmon, the PFEL Upwelling Index corresponding to Age-1 chinook salmon, northern anchovy landings (tons) and herring landings (tons) off the coast of California corresponding to Age-2 chinook salmon, the average streamflow (cfs) in the Stanislaus River at Ripon from 15 April to 15 June, the ratio of flows releases in the Stanislaus River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (StanMinSpr) and for 1-30 November (StanMinFal), the average flow (cfs) in the Tuolumne River at Modesto from 15 April to 15 June, the ratio of flow releases in the Tuolumne River to a hypothetical minimum flow release schedule based on PHABSIM and a water temperature model for 1 April to 31 May (TuolMinSpr) and for 1 to 30 November (TuolMinFal), and the average maximum water temperature (F) in the San Joaquin River at Vernalis for April.

Year	*Stan Recruit*	*Stan Stock*	*Tuol Recruit*	*Tuol Stock*	*VerFlo-Spr*	*ExFlo-Spr*	*CVI Age 3*	*NPI Age1*	*PDO Age 1*	*Up-well*	*Anchovy Age 2*	*Herring Age 2*	*Ripon Flow Spring*	*Stan-Min-Spr*	*Stan-Min-Fall*	*Modesto Flow Spring*	*Tuol-Min-Spr*	*Tuol-Min-Fall*	*Max Vernalis Temp*
1982	19,930	974	56,924	6253	18396	0.39	0.58	1.70	0.440	215	4,880	8,845	605	0.38	0.50	5,942	6.90	3.23	66.7
1983	34,643	1731	85,142	6611	31734	0.12	0.50	-5.44	0.764	207	3,184	4,241	4,186	9.47	7.17	9,345	11.59	13.27	67.0
1984	13,185	348	23,792	5704	3243	2.03	0.68	-2.62	1.438	257	1,792	8,801	806	1.23	8.12	573	0.66	13.31	72.7
1985	14,111	7924	4,200	7385	2197	2.94	0.74	1.11	0.862	171	1,692	8,442	693	1.14	3.24	366	0.43	7.60	73.5
1986	74,215	12384	92,577	38242	10371	0.66	0.78	-4.10	0.908	174			1,323	2.29	1.50	2,969	3.25	3.67	69.8
1987	5,992	5546	3,146	7876	2265	2.43	0.75	-2.93	1.854	180			835	1.51	2.92	473	0.48	7.87	73.8
1988	1,261	3336	495	4730	1889	3.60	0.79	-0.77	1.266	183			825	1.57	1.15	213	0.17	1.99	70.8
1989	1,152	11898	198	5923	1893	3.73	0.71	2.84	-0.650	227			972	1.76	2.82	246	0.21	1.06	76.8
1990	782	2267	306	1487	1283	3.74	0.71	2.01	-0.456	128			562			218			
1991	1,561	549	1,959	106	922	3.50	0.72	2.34	-1.574	232			316			386			
1992	4,295	306	1,590	64	892	2.10	0.74	-2.44	0.308	158			389			310			
1993	2,089	226	2,801	74	3381	1.21	0.78	-0.15	0.492	163			1073			750			
1994	1,039	347	1,204	386	1783	0.95	0.64	1.46	0.982	222									
1995	19,302	993	22,970	433	19537	0.24	0.66	-0.33	-0.606	150									

Results

Before environmental variables and harvest variables could be evaluated, it was necessary to determine the nature of the stock-recruitment relationship. The stock-recruitment relationship for the Tuolumne River population (Figure 3) is similar to those described by Ricker (1975) whereas the relationship for the Stanislaus River population (Figure 4) is relatively flat after stock exceeded about 2,500 spawners, which is intermediate to those described by Ricker and Beverton-Holt (Ricker 1975).

To control the effects of stock, correlations between habitat variables, harvest variables, and recruitment were tested in two ways. First to minimize the effects of stock, analyses were conducted that excluded data when stock was less than 2,500 spawners for the Stanislaus River and 6,000 spawners for the Tuolumne River. Second, the analyses were conducted with all the data and the stock estimate and the square root of stock were forced into a stepwise regression analysis to account for the quadratic polynomial shape of the stock-recruitment relationship.

Based on the analysis that excluded low stock estimates, recruitment to both the Stanislaus and Tuolumne rivers were significantly correlated with all spring streamflow variables, the ratio of SWP and CVP exports to Vernalis flows during smolt emigration (15 April to 15 June) and stock (Table 5). The correlations with flow were strongest at Vernalis (Figures 5 and 6), particularly for the Stanislaus River, compared to flows in the tributaries. Modesto flows were highly correlated with Tuolumne River recruitment, but the effect was probably a reflection of conditions at Vernalis as Modesto flows are highly correlated with Vernalis flows ($r = 0.998$).

The correlations coefficients for Stanislaus River recruitment are higher with Vernalis flows than with the ratio of Delta exports to Vernalis flows when data are included from 1946 to 1959. However, this difference is suspect because the correlation coefficients for Tuolumne River recruitment with these two variables are quite similar and the results for the Tuolumne River are probably more accurate because the data set was larger for Tuolumne River prior to 1959.

Tuolumne River recruitment was also significantly correlated with the Central Valley Index of harvest that corresponded to Age-3 and to a lesser degree Age-4 chinook salmon, and northern anchovy landings for both Age-2 and Age-3 fish (Table 5). Recruitment for either river was not correlated with ocean climate conditions, fall streamflow in the tributaries or maximum water temperatures at Vernalis (Table 5).

Table 5 Pearson correlation coefficients (*r*), probability (*p*), and sample size (*n*) for correlations between Tuolumne River recruitment that excluded data sets with stock less than 6,000 spawners and Stanislaus River recruitment that excluded data sets with stock less than 2,500 spawners and the variables in Table 3

	Tuolumne River			*Stanislaus River*		
Variable	*r*	*p*	*n*	*r*	*p*	*n*
VerFloSpr	0.766	0.000	23	0.769	0.000	26
ExFloSpr	-0.790	0.000	23	-0.414	0.035	26
CVI Age 3	-0.629	0.001	23	-0.010	0.963	26
CVI Age 4	-0.548	0.007	23	0.171	0.403	26
NPI Age 1	-0.067	0.763	23	-0.252	0.214	26
NPI Age 3	-0.188	0.391	23	0.116	0.573	26
PDO Age 1	-0.020	0.927	23	0.019	0.926	26
PDO Age 3	0.305	0.158	23	0.156	0.448	26
Upwell Avg.	-0.055	0.823	19	0.032	0.879	26
Upwell May	-0.229	0.346	19	0.069	0.738	26
Upwell June	0.001	0.998	19	-0.219	0.283	26
Upwell July	0.177	0.468	19	0.196	0.338	26
Anchovy Age 2	-0.474	0.035	20	-0.014	0.955	20
Ln Anchovy Age 2	-0.517	0.020	20	0.173	0.465	20
Anchovy Age 3	-0.496	0.026	20	-0.012	0.960	20
Ln Anchovy Age 3	-0.577	0.008	20	0.330	0.155	20
Herring Age 2	0.067	0.778	20	0.001	0.998	20
VerFloSpr	0.838	0.001	11	0.780	0.000	17
ExFloSpr	-0.871	0.001	11	-0.794	0.000	17
TuolMinFall	0.139	0.685	11	---	---	---
TuolMinSpr	0.818	0.002	11	---	---	---
Modesto Flow Spr	0.834	0.001	11	---	---	---
Log Modesto Flow Spr	0.992	0.000	11	---	---	---
StanMinFall	---	---	---	-0.154	0.554	17
StanMinSpr	---	---	---	0.670	0.003	17
Ripon Flow Spr	---	---	---	0.657	0.004	17
Log Ripon Flow Spr	---	---	---	0.609	0.010	17
Max Vernalis Temp	-0.804	0.101	5	-0.214	0.645	7

The regression model for Tuolumne River recruitment developed from a stepwise analysis of the data set without low stock estimates included Vernalis flows (student's t-value = 3.7, p = 0.002) and the log of the ratio of exports to Vernalis flows (student's t-value = -2.7, p = 0.016). The adj-R^2 was 0.69.

$$\text{Recruitment} = 2.35\ \text{VerFloSpr} - 12{,}515\ \text{Log(ExFloSpr)} + 17{,}210$$

The regression model for the entire data set for Tuolumne River recruitment included Vernalis flows (student's t-value = 5.4, p = 0.000), the log of the ratio of exports to Vernalis flows (student's t-value = -2.6, p = 0.013), and stock (student's t-value < 1.51 and p = 0.14 and 0.31 for the two variables required to fit a quadratic polynomial regression). The adj-R^2 was 0.71.

$$\text{Recruitment} = 2.89\ \text{VerFloSpr} - 11{,}556\ \text{Log (ExFloSpr)} - 0.668\ \text{Stock} + 233.4\ (\text{Stock})^{1/2} - 4{,}170$$

The regression model for Stanislaus River recruitment developed from a stepwise analysis of the data set without low stock estimates included only Vernalis flows (student's t-value = 5.9, p = 0.000). The adj-R^2 was 0.57.

$$\text{Recruitment} = 2.35\ \text{VerFloSpr} + 4{,}295$$

The regression model for the entire data set for Stanislaus River recruitment included Vernalis flows (student's t-value = 5.4, p = 0.000) and stock (student's t-value < 1.11 and p = 0.10 and 0.27 for the two variables required to fit a quadratic polynomial regression). The adj-R^2 was 0.45.

$$\text{Recruitment} = 1.46\ \text{VerFloSpr} - 1.556\ \text{Stock} + 348.7\ (\text{Stock})^{1/2} - 9{,}224$$

The correlations with Stanislaus River recruitment were relatively weak compared to those with Tuolumne River recruitment partially due to errors in the segregation of escapement into cohorts. Recruitment abundance was determined by escapement size and the percentage of two-year-old fish (%Age 2s) and error in the %Age 2s had a substantial influence on the correlation analysis when escapement was high. For example, recruitment to the Stanislaus River in 1986 appears to be abnormally high compared to earlier estimates in Figure 6, but the 1986 estimate is probably more accurate. The size of recruitment for the 1986 estimate is determined by the percentage of %Age 2s in the 1987 escapement. The length-frequency analysis indicates that the %Age 2s for 1987 was 67% whereas the %Age 2s for 1987 based on the standard length criterion was only 36% (Table 2). This suggests that at least some of the high recruitment estimates for the Stanislaus River prior to 1985 were low, particularly those for 1956, 1958, and 1969, due to underestimation of the %Age 2s based on the standard length criterion. This did not appear to be as great a problem for the Tuolumne River correlations as the %Age 2s estimates were similar between the length-frequency estimates and the standard length criterion estimates for all the large cohorts in 1982, 1983, and 1986. Other sources of error in the recruitment estimates includes errors in the escapement estimates and the use of the age ratios in Table 1, which ignore interannual variability in ocean mortality. On the other hand, it is also possible that the relatively weak correlations with Stanislaus River recruitment occurred because important environmental factors that affected the Stanislaus River population were not included in the analysis.

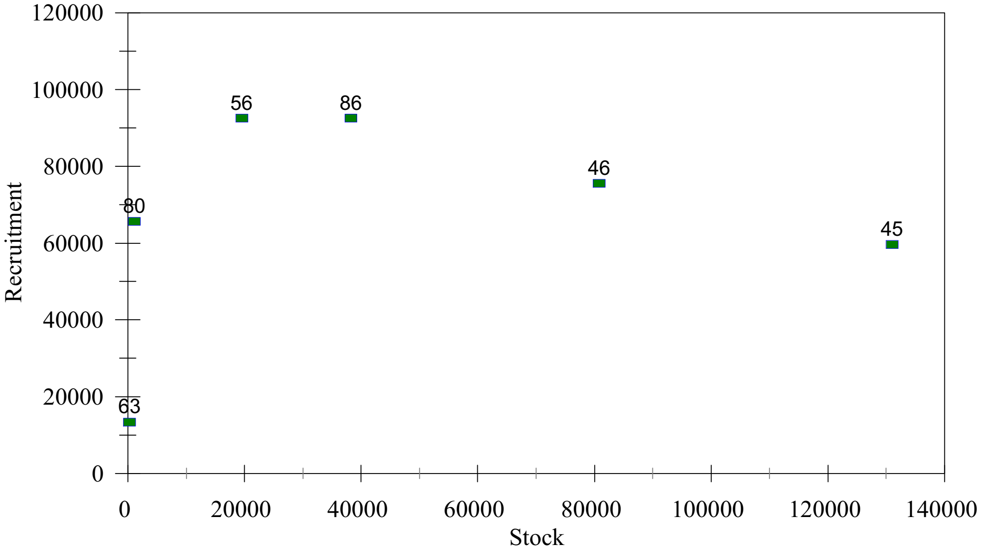

Figure 3 The relationship between stock and recruitment for the Tuolumne River for 1939 to 1995. To minimize the effects of flow in the stock-recruitment relationships, only data sets with Vernalis flows between 8,000 and 15,000 cfs are shown. Recruitment is identified according to the year when the fish emigrated as juveniles.

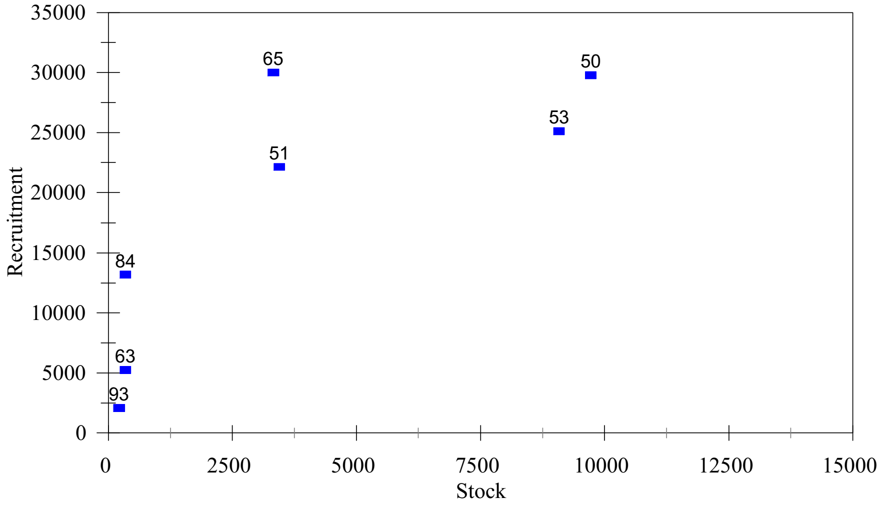

Figure 4 The relationship between stock and recruitment for the Stanislaus River for 1945 to 1995. To minimize the effects of flow in the stock-recruitment relationships, only data sets with Vernalis flows between 3,000 and 10,000 cfs are shown. Recruitment is identified according to the year when the fish emigrated as juveniles.

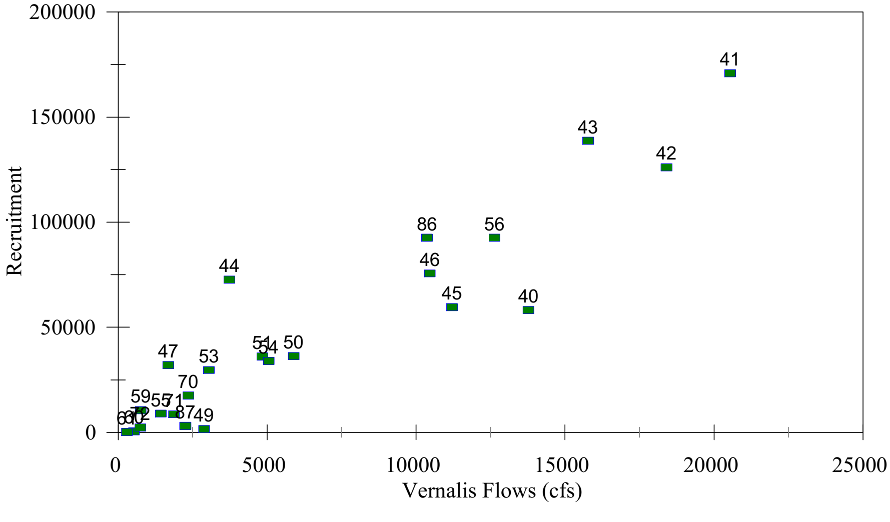

Figure 5 The relationship between recruitment to the Tuolumne River and the average flow in the San Joaquin River at Vernalis between 15 April and 15 June from 1939 to 1995. To minimize the effects of low levels of stock in the flow relationships, only data sets with stock greater than 6,000 spawners are shown. Recruitment is identified according to the year when the fish emigrated as juveniles.

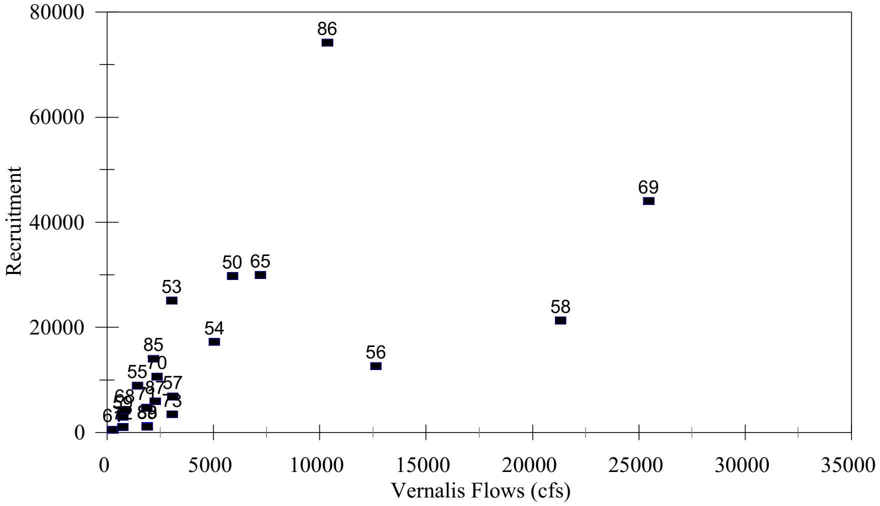

Figure 6 The relationship between recruitment to the Stanislaus River and the average streamflow in the San Joaquin River at Vernalis between 15 April and 15 June from 1946 to 1995. To minimize the effects of low levels of stock in the flow relationships, only data sets with stock greater than 2,500 spawners are shown. Recruitment is identified according to the year when the fish emigrated as juveniles.

Discussion

The correlation analyses suggest that flow in the San Joaquin River, sport and commercial harvest of chinook salmon, and to a lesser extent the harvest of northern anchovies have affected recruitment to the Tuolumne and Stanislaus rivers. Although recruitment may be affected by Delta exports, the correlation analysis cannot distinguish between the effects of exports and those of streamflow. An inspection of the scatter plots between recruitment and Vernalis flows indicates that the populations responded to flow in the 1940s as they did in the 1980s, which suggests that the habitat has not changed substantially during the period of study.

In addition to the variables included in the correlation analysis, the chinook salmon populations may have been affected by other factors that include instream gravel mining, dredging and reclamation of the Delta, sedimentation of spawning and rearing habitat, freshwater predators, disease, contaminants, unscreened diversions, instream harvest of spawners, and hatchery management. The mechanisms by which these factors and the variables tested in the correlation analyses may have affected chinook salmon recruitment are discussed below.

Streamflow and Delta Exports

The operation of Friant Dam, which began in 1947, blocked access to about one-third of the spawning habitat in the mainstem San Joaquin River, eliminated perennial flows below the dam, and coincided with the rapid decline in the spring-run chinook population (Fry 1961, Yoshiyama and others 1998) and recruitment of fall-run chinook salmon to the Tuolumne River. However, the decline in Tuolumne River recruitment during the mid to late 1940s was probably more of a response to a change from a wet climate to a dry climate than due to the operations of the dam. During the ten years before the completion of Friant Dam (1937 to 1946), the San Joaquin Valley 60-20-20 Index (SJVI) averaged 3.791 maf[1] and springtime Vernalis flows were relatively high (mean 14,439 cfs) whereas spring Vernalis flows and the SJVI were low during the previous 7-year-period (mean of 7,097 cfs and 2.544 maf, respectively from 1930 to 1936) and the subsequent 10-year-period (mean of 6,911 cfs and 3.108 maf, respectively from 1947 to 1956). The reduction in Vernalis flows during spring due to the operation of Friant Dam was relatively minor compared to the climate change as indicated by the ratio of Vernalis flows to the SJVI, which was 12.5% lower for the 1947 to 1956 period compared to the 1937 to 1946 period.

The effect of constructing a large reservoir on each of the three tributaries between 1966 and 1981 also appears to be negligible. All three tributaries had relatively small reservoirs that blocked upstream migration of adult salmon since of the construction of Wheaton Dam on the Tuolumne River in 1871; Tulloch Dam on the Stanislaus River in 1858; and Crocker-Huffman diversion dam on the Merced River in the 1920s. In 1966, New Exchequer Dam was completed on the Merced River; it provides 1.0 maf of storage, which is about 100% of mean annual runoff. In 1971, New Don Pedro was completed on the Tuolumne River; it provides 2.0 maf of storage, which is about 100% of mean annual runoff. In 1981, New Melones was approved for filling on the Stanislaus River; it provides 2.4 maf of storage, which is about 240% of mean annual runoff. Although, the large storage capacity of these reservoirs reduces the frequency of winter flood flows, mean springtime flows have changed little since their construction. After all three large reservoirs had been constructed, the mean spring Vernalis flow and the SJVI was 6,791 cfs and 2.938 maf respectively from 1981 to 1995. This is a slightly greater flow compared to the 19-year-period prior to their construction from 1947 to 1965, when the mean Vernalis flow was 6,046 cfs and the mean SJVI was similar at 2.986 maf.

The proportion of Vernalis flows exported by the CVP and SWP pumping facilities in the Delta is also strongly correlated with recruitment to the Stanislaus and Tuolumne rivers. The export of water from the south Delta began in

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[1] Million acre-feet.

1940 at Rock Slough by the Contra Costa Water District, which has a capacity of 350 cfs. Exports began in 1951 at the CVP's Tracy Pumping Plant, which has a capacity of 4,600 cfs. The Delta Cross Channel was completed in 1951 to allow Sacramento River flow to pass through Snodgrass Slough, the lower Mokelumne River, and the South Delta. The State Water Project (SWP), which has a capacity of 10,000 cfs, came on-line in 1967. The combined permitted export capability of the CVP and SWP facilities is about 11,000 cfs. Since 1966, the combined exports at the SWP and CVP has gradually increased from about 500,000 acre-feet to about 3,500,000 acre-feet in the 1990s.

One effect of Delta pumping is that the percentage of San Joaquin River flow that passes through the Old River increases from about 60% when there is no pumping to about 90% when the total exports are about four times the San Joaquin River flow at Vernalis (DWR 1962). It is generally believed that the river channels leading to the export facilities have high densities of black bass and striped bass, which prey on juvenile salmon. Particularly high predation rates at Clifton Court Forebay, which began operating in 1968 to control the head at the SWP, are thought to cause higher mortality rates at the SWP compared to the CVP. DFG estimates that for smolts salvaged at the screens, mortality due to handling is 37% at the CVP facility and 39% at the SWP facility (EA 1992). To help minimize entrainment into the Old River, a rock barrier was installed at the head of the Old River from 23 April to 2 June 1992, 23 April to 18 May 1994, 11 to 16 May 1996, and 16 April to 15 May 1997 when two 48-inch culverts were installed. The rock barrier cannot be installed when Vernalis flows exceed about 5,000 cfs. In addition, the USFWS Biological Opinion on delta smelt assumes that the barrier increases entrainment of delta smelt and juvenile winter-run chinook salmon from the Sacramento basin at the SWP and CVP pumping facilities, and so the barrier cannot be installed prior to 15 April or later than 15 May (30 May in special circumstances).

Smolt Survival in the Delta

The downstream migration of chinook salmon smolts in the San Joaquin basin generally begins in early April, peaks between late April and mid May in dry years (or in late May in normal and wet years), and then rapidly declines in June as determined by trawling at Mossdale (DFG 1991 to 1998) and with screw traps in the lower Stanislaus River (Demko and others 1999). Most smolts migrated when they reached a fork length of 65 to 100 mm.

Smolt survival has been studied by the U.S. Fish and Wildlife Service (USFWS) and DFG since 1982 by releasing groups of about 25,000 to 100,000 hatchery reared juveniles with coded-wire-tags (CWT) at various locations in the tributaries and Delta in April and May and recapturing them with a trawl at Mossdale and Chipps Island to investigate the effects of flows and exports. The results indicate that smolt survival is lowest in the Old River and in the mainstem between the Old River and the mouth of the Mokelumne River and that survival in this mainstem reach is strongly correlated with flow, water temperature, and to a lesser degree exports. In addition, the installing a barrier at the head of Old River (HORB) appears to ameliorate the impacts of exports by preventing entrainment of smolts in the Old River and by increasing flow and reducing water temperatures in the mainstem below the Old River.

Evaluations of smolt survival in different reaches in the Delta were made using an estimate of absolute smolt survival, which was computed as a ratio of an index for an upstream release group (e.g., Dos Reis) divided by the index for a downstream release group (e.g., Jersey Point). Presumably the ratio estimate permits comparisons between years because the ratio factors out the influence of gear efficiency (GE) and fish behavior and health (FB&H) that might occur between tests made in different years. One assumption of this ratio-based estimate is that the trawl efficiency (TE) and the influence of fish behavior and health are the same for both the upstream and downstream release groups. For trawl efficiency to be the same for both groups, the upstream group would have to be released several days before the downstream group was released so that both groups arrived at the recapture point at the same time. For the fish behavior and health influences to be the same for both groups, all test fish would have to be reared under the same conditions (namely, at the same hatchery, from the same parent stock, and released at similar sizes and health). The mathematical equation for the ratio estimate for a Dos Reis upper release group and a Jersey Point lower release group is as follows:

$$\frac{\mathrm{SSI(DR)}}{\mathrm{SSI(JP)}} = \frac{\mathrm{SS(DR-JP)} \times \mathrm{SS(JP-CI)} \times \mathrm{GE} \times \mathrm{FB\&H}}{\mathrm{SS(JP-CI)} \times \mathrm{GE} \times \mathrm{FB\&H}} = \mathrm{SS(DR-JP)}$$

where,

SSI(DR) = Smolt survival index for fish released at Dos Reis and recaptured at Chipps Island.

SSI(JP) = Smolt survival index for fish released at Jersey Point and recaptured at Chipps Island.

SS(DR–JP) = The percentage of fish that survive between Dos Reis and Jersey Point.

SS(JP–CI) = The percentage of fish that survive between Jersey Point and Chipps Island.

GE = The percentage of fish that survived to Chipps Island that were captured by the trawl.

FB&H = The percentage of fish that didn't arrive at Chipps Island due to the behavior and/or health of the hatchery fish. (For example, one year's study fish might be relatively small, causing them to migrate at different rates, suffer different predation rates, or be captured at different rates than study fish released in a different year.)

The result of computing this ratio is an absolute survival estimate for fish migrating between the upper release site and the lower release site, SS(DR-JP).

The absolute survival estimates for juveniles migrating through the Delta in the mainstem San Joaquin River were much lower between the head of Old River and the mouth of the Mokelumne River than in the reach between the mouth of the Mokelumne and Jersey Point in spring 1991 (USFWS 1992). Absolute smolt survival for Feather River hatchery fish in mid-April was 63.7% between Dos Reis and Stockton (Buckley Cove), and 15.7% between Stockton and the Mokelumne River, 34.3% between Empire Tract and the Mokelumne River, and 91.7% between the mouth of the Mokelumne River and Jersey Point. During this test, Vernalis flows averaged 1,150 cfs, total Delta exports averaged 4,283 cfs, dissolved oxygen averaged 6.3 ppm at Rough and Ready Island near Stockton, water temperature was about 60 F near Stockton, flows in the Delta Cross Channel and Georgiana Slough averaged about 4,000 cfs, and recoveries of CWT fish ranged from 17 for Dos Reis releases and 94 for Jersey Point releases. It is likely that the relatively high flows from the Delta Cross Channel, Georgiana Slough, and the Mokelumne River improved conditions for smolt survival in the Delta downstream of the Mokelumne River compared to the reach near Stockton. Absolute smolt survival during early May increased to 29.7% between Stockton and the mouth of the Mokelumne River but decreased to 37.7% between the mouth of the Mokelumne and Jersey Point. During this test, Vernalis flows averaged 959 cfs, total Delta exports averaged 2,613 cfs, dissolved oxygen averaged 5.4 ppm at Rough and Ready Island near Stockton, water temperature was about 65 F near Stockton, flows in the Delta Cross Channel and Georgiana Slough averaged about 3,500 cfs, and recoveries of CWT fish ranged from 20 for Buckley Cove releases and 89 for Jersey Point releases. The lower smolt survival estimates between the Mokelumne River and Jersey Point that occurred in May compared to April was probably a response of the Feather River hatchery fish to increased temperatures, lower flows, lower dissolved oxygen concentrations, and perhaps increased predation.

Other correlations were tested between the absolute survival estimates for juveniles migrating in the mainstem river between Dos Reis and Jersey Point from 1990 to 1997 and ten-day averages of (1) flow at Stockton (Brandes 1998),

(2) water temperatures at Stockton (Interagency Ecological Program continuous monitoring station at Rough and Ready Island), and (3) the ratio of the combined CWP and SWP pumping rates to flow at Stockton (Table 6). Streamflow at Stockton was estimated by Brandes (1998) using three sets of equations incorporating flows at Vernalis, Delta consumptive use, and Delta exports that are presented in DWR (1986). An arc-sine transformation was made to the smolt survival variable to minimize bias that would otherwise result from the distribution of the variance of the percentages being a function of their mean (Sokal and Rohlf 1995). When the head of Old River barrier was installed in 1994 and 1997, it was assumed that it would increase CVP and SWP exports by about 20% in the downstream channels compared to tests when the barrier was not installed. This is based on the rough estimate that approximately 20% of the flow that is exported is conveyed through the Old River (R. Oltmann, personal communication, see "Notes"). To correct for this effect, the flow-to-export ratios for 1994 and 1997, when the test fish were released at Mossdale and the barrier was installed, were divided by 1.2. All the smolt survival ratios used for this analysis consisted of about 100,000 Feather River Hatchery fish releases at Dos Reis and at Mossdale if the barrier was installed, and at least 50,000 Feather River Hatchery fish at Jersey Point.

Paired studies with Feather River Hatchery fish and Merced River Hatchery fish in May 1996 and April 1997 indicate that the absolute survival for the Merced River fish was about twice that of the Feather River fish for the same environmental conditions (Figures 7, 8, and 9). Therefore, survival estimates for Merced River fish were not included in the correlation analysis.

Study results from spring 1989 were also not included in this analysis, because the average length of the fish for the release group at Jersey Point was much smaller than for the release group at Dos Reis, a condition that probably violated the assumption of the survival equation that the fish in both the upper and lower release groups must behave similarly. The spring 1989 smolt survival ratio was unusually high for the environmental conditions suggesting that the relatively large fish released at Dos Reis survived at higher rates than did the smaller fish in the control group released at Jersey Point.

Results from spring 1998 tests with Feather River fish were not included because 30% to 40% of the Feather River fish had died at the hatchery from the viral disease Infectious Hematopoietic Necrosis and many of the test fish showed symptoms of the disease. Further, survival estimates were unusually low (13%) considering Vernalis flows were about 20,000 cfs and exports were about 1,800 cfs.

Absolute survival estimates for Feather River juveniles migrating in the mainstem river between Dos Reis and Jersey Point were positively correlated with high flows at Stockton (Figure 7) and negatively correlated with average daily water temperatures at Rough and Ready Island (Figure 8) for studies conducted between 1990 and 1997 (Table 6). The correlations were strongest with the flow at Stockton; the adj-R^2 for a model of the square of the flow at Stockton and smolt survival for Feather River fish released at Dos Reis is 0.868. Smolt survival was also correlated with water temperature, except that the April 1991 estimate was relatively low possibly in response to a high export-to-flow ratio. Smolt survival was poorly correlated with the export-to-flow ratio, except that survival was consistently less than about 0.10 when exports exceeded about 65% of the flow at Stockton (Figure 9). Survival was relatively low at 0.06 in May 1996 when 44% of the flow at Stockton was exported, possibly because the average water temperature was high at 66.2 F.

The relationships between smolt survival and flows, temperatures, and exports were similar for the Feather River fish and the estimates for Merced River fish in 1996, 1997, and 1998, except that the estimates for the Merced River fish were slightly higher than comparable estimates with Feather River fish. The April 1999 estimate for Merced River fish may have overestimated the true survival rate because trawling at Chipps Island was suspended for about a day due to equipment problems just as many of the fish released at Jersey Point were arriving at the recapture site (Brandes 2000). An overestimate would have occurred if the Jersey Point fish were not sampled with the same probability as the Dos Reis fish.

Table 6 Smolt survival estimates for juvenile Feather River chinook salmon released at Dos Reis and Mossdale and 10-day average flow at Stockton (Dayflow), export-flow ratios, and water temperature at Stockton from 1990 to 1997

Date of release	*Upper release site*	*Smolt survival ratio unadjusted*	*Stockton flow (cfs)*	*Exports unadjusted/ Stockton flow*[a]	*Water temperature at Stockton (°F)*
16 Apr 90	Dos Reis	0.066	100	95.24	66.6
02 May 90	Dos Reis	0.039	490	5.03	70.2
15 Apr 91	Dos Reis	0.094	60	86.21	61.2
26 Apr 94	Mossdale[b]	0.130	2484	0.65 – 0.78	64.2
17 Apr 95	Dos Reis	0.326	7345	0.52	58.5
01 May 96	Dos Reis	0.057	3424	0.44	66.2
29 Apr 97	Mossdale[b]	0.183	4780	0.49 - 0.59	64.2

[a] Divided by 1.2 in 1994 and 1997 for head of Old River barrier (HORB).

[b] HORB installed.

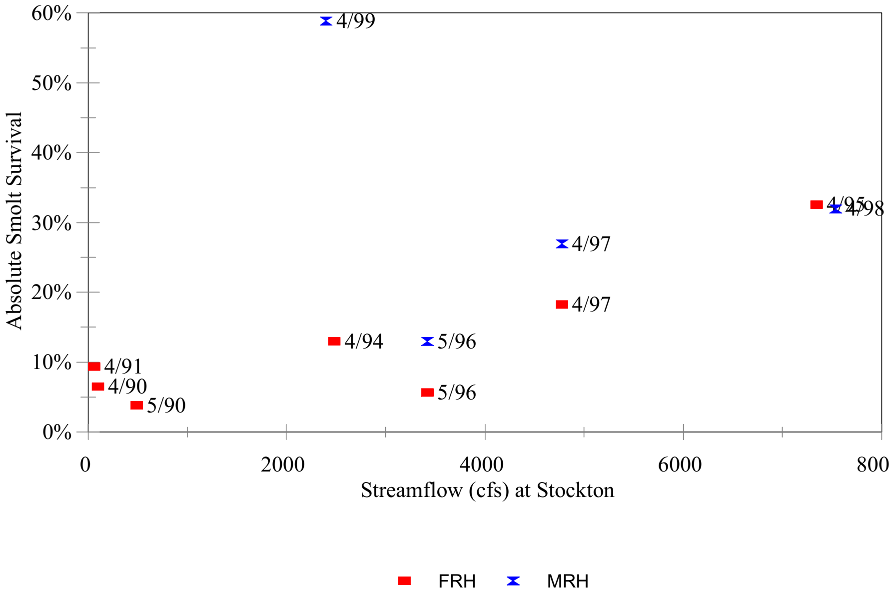

Figure 7 The relationship between streamflow at Stockton and the absolute smolt survival estimate for fish reared at the Feather River Hatchery (FRH) and Merced River Hatchery (MRH) and released at Dos Reis or at Mossdale with a barrier at the Head of the Old River, and subsequently recaptured at Chipps Island from 1990 to 1999. Data points are identified by the release date.

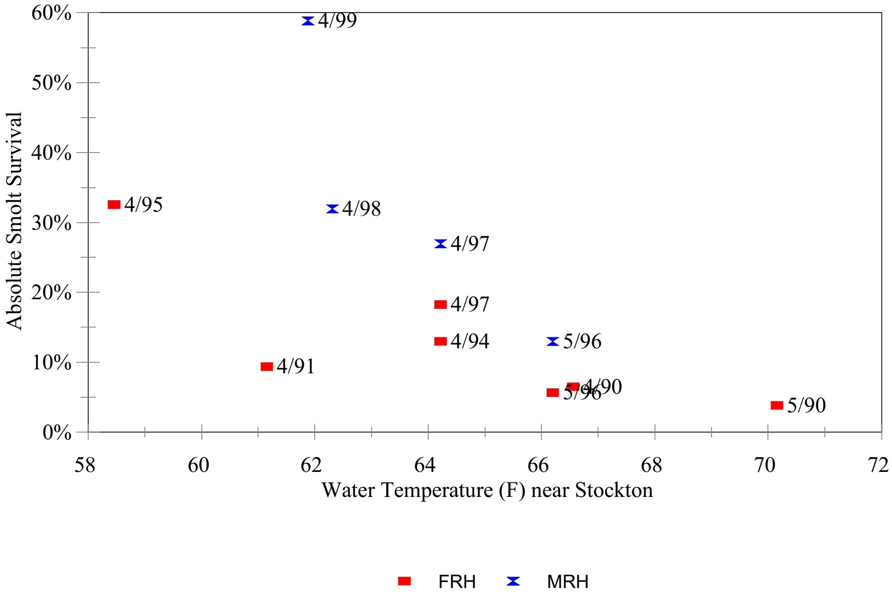

Figure 8 The relationship between average water temperature at Stockton and the absolute smolt survival estimate for fish reared at the Feather River Hatchery (FRH) and Merced River Hatchery (MRH) and released at Dos Reis or at Mossdale with a barrier at the Head of the Old River, and subsequently recaptured at Chipps Island from 1990 to 1999. Data points are identified by the release date. The low survival estimate for May 1991 was probably a result of a low Export-Flow ratio (see Figure 9).

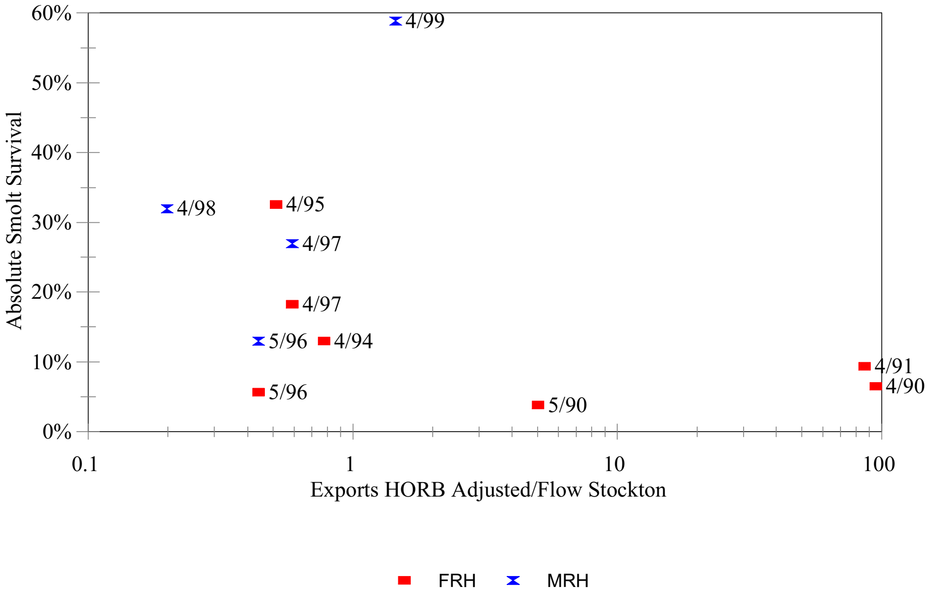

Figure 9 The relationship between the adjusted ratio of Delta CVP and SWP exports to streamflow at Stockton and the absolute smolt survival estimate for fish reared at the Feather River Hatchery (FRH) and Merced River Hatchery (MRH) and released at Dos Reis or at Mossdale with a barrier at the Head of the Old River, and subsequently recaptured at Chipps Island from 1990 to 1999. Data points are identified by the release date. The relatively low May 1996 survival estimate was probably a result of high water temperatures (see Figure 8).

USFWS studies suggest smolt survival in the Delta is lower for fish that enter the Old River than for those that remain in the mainstem although the effect of flow and exports on survival in the Old River are uncertain. When Vernalis flows were 1,900 cfs and exports were about 10,000 cfs in mid-April 1989, the ratio of Chipps Island recoveries for Feather River fish released in the upper Old River to the recoveries of fish released at Dos Reis was 0.64. This suggests that survival rates for the fish migrating in the Old River were 64% of the survival rates for the Dos Reis fish, although the accuracy of the estimate is highly questionable because only a total of 13 fish was recovered from both groups. A comparison of studies conducted in 1995, 1998, and 1999 during which fish were released upstream of Old River at Mossdale and downstream of Old River at Dos Reis and no barrier was installed at the head of Old River (HORB) suggests that smolt survival in the Old River was similar to the survival in the mainstem San Joaquin River when exports averaged 1,800 cfs but were low when exports exceeded about 3,000 cfs. The relative survival in Old River averaged 0.73 for three tests with Feather River fish in April and May 1995 (a total of 80 fish recovered), when Vernalis flows were between 18,400 and 23,000 cfs and exports were between 3,300 and 3,700 cfs. Similarly the relative survival in Old River averaged 0.65 with Merced River fish in April 1999 (75 fish recovered), when Vernalis flows averaged 7,000 cfs and exports averaged 3,500 cfs. However, the relative survival in the Old River was 0.93 (181 fish recovered) with Merced River fish in April 1998, when Vernalis flows were about 22,000 cfs and exports were 1,800 cfs. It was apparent during the 1998 studies that approximately 45% of the fish released at Mossdale entered the Old River while 55% remained in the main channel as indicated by the low recoveries of Mossdale fish at the Jersey Point trawl site compared to the Mossdale recoveries at Chipps Island (USFWS unpublished data). The low survival rates in Old River in 1995 compared to 1998 appear to have been caused by unsuitable conditions in the Old River in 1995 because the absolute survival estimates for fish migrating through the mainstem San Joaquin River between Dos Reis and Jersey Point were 0.33 for 1995 and 0.32 for 1998. Multiplying the absolute survival estimates in the mainstem by the relative survival estimates for the Old River to the mainstem gives a result of an absolute survival estimate in the Old River of 0.21 for 1995 and 0.30 for 1998. This suggests that the lower export rates of 1,800 cfs in April 1998 resulted in a 39% higher survival estimate than the export rate of 3,300 to 3,700 cfs in April 1995. In comparison, reducing the ratio of exports to Vernalis flows from 0.175 in 1995 to 0.080 in 1998 would have increased recruitment to the Tuolumne River by about 20% based on the regression model that included stock.

Installing a rock barrier at the head of the Old River has increased the survival of juveniles migrating through the Delta in two ways. First, it prevents fish from being entrained in Old River where survival appears to be about 60 to 70% of the survival rate of fish that remain in the main channel. Second, the barrier more than doubles the flow in the mainstem San Joaquin between the head of the Old River and the mouth of the Mokelumne River, a reach where survival rates are usually low. Smolt survival studies conducted in spring 1996 and 1997 provide a good test of a barrier, because

1. The barrier was installed with two unscreened 48-inch culverts that passed about 300 cfs in 1997 whereas there was no barrier in 1996 until the last few days of the test.

2. Vernalis flows were similar, about 6,500 cfs in 1996 and about 6,200 cfs in 1997.

3. Delta exports were similar, about 1,500 cfs in 1996 and about 2,000 cfs in 1997.

4. Separate tests were conducted with fish from the Feather River and Merced River hatcheries.

The absolute smolt survival estimate for Feather River Hatchery fish released at Dos Reis on 29 April 1997 when the barrier was installed was 18% (10 fish recovered) which was about triple the survival estimate of 6% (2 fish recovered) for Feather River fish released at Dos Reis on 1 May 1996 when the barrier had not been fully installed until 11 May. Paired releases with Merced River Hatchery fish indicated that smolt survival was 27% in 1997 (15 fish recovered), about double the survival estimate of 13% for 1996 (10 fish recovered).

The total benefits of a head of Old River barrier that "leaked" no more than about 300 cfs could be to increase smolt survival by about 225%. Eliminating entrainment into the Old River would increase absolute survival by about 25% to 35% when exports are about 3,000 cfs or greater, and increasing flows and reducing water temperatures in the mainstem near Stockton would gain another 200% increase in survival based on the paired survival studies with Merced River and Feather River hatchery fish.

Juvenile Survival in the Tributaries

Historically, flow releases for fishery needs were very low until 1987 for the Stanislaus River and 1995 for the Tuolumne River when flow requirements were increased based on IFIM and water temperature studies. Flow releases in the Stanislaus River were less than 50% of minimal levels required to provide suitable habitat based on the IFIM and water temperature studies in 12 of 28 years (43%) during April and May and in 15 of 28 years (54%) during November from 1960 to 1987 (StanMinSpr and StanMinFal in Table 3). In the Tuolumne River, flow releases were less than 50% of minimal levels in 18 of 30 years (60%) during April and May and in 1 of 30 years (3%) in November from 1960 to 1989 (TuolMinSpr and TuolMinFal in Table 3). Since the flow requirements were increased in the Stanislaus and Tuolumne rivers, base flows are expected to be adequate in all but dry and critical years. However, the increase in the minimum required flows between 1987 and 1997 has not increased escapement.

Smolt survival studies were conducted intermittently with coded-wire-tagged (CWT) fish from the Merced River Hatchery in the Stanislaus, Tuolumne, and Merced rivers beginning in 1986 (DFG data). Absolute survival estimates in the tributaries and upstream of the Old River are usually higher than the survival estimates for fish migrating downstream of the Old River near Stockton. Low survival rates occurred during the drought of 1987 through 1990 when flows were low and water temperatures were usually high. Survival in the Stanislaus River was much higher in 1988, when the mean water temperature during the test was 60 F than in 1989 when the mean water temperature was 64 F.

Table 7 Absolute smolt survival based on Mossdale recoveries (Moss) and Chipps Island recoveries (Chipps), flow at the downstream boundary of study reach (lower release point), and the number of recoveries (n) for the upper and lower release sites for the Stanislaus River between Knights Ferry and Naco West, the Tuolumne River between the Old La Grange Bridge and Mapes, the Merced River between the fish hatchery and the mouth, and the mainstem San Joaquin River between the mouth of the Merced River and Dos Reis and between the mouth of the Merced River and the mouth of the Tuolumne River

Upper and lower release sites	Date of release at upper site	Absolute survival (Moss) recoveries (n)	Absolute survival (Chipps) recoveries (n)	River flow (cfs)
Upper & Lower Stanislaus River	28-Apr-1986	0.59, n = ?	0.61, n = 37 & 60	1,200
Upper & Lower Stanislaus River	26-Apr-1988	0.54, n = 278 & 828	0.78, n = 11 & 13	900
Upper & Lower Stanislaus River	20-Apr-1989	0.37, n = 471 & 1,033	0.28, n = 7 & 11	900
Upper & Lower Stanislaus River	18-May-2000	0.57, n = 217 & 250	?	1,500
Upper & Lower Tuolumne River	14-Apr-1986	---	1.48, n = 35 & 20	5,500
Upper & Lower Tuolumne River	16-Apr-1987	0.31, n = 128 & 317	0.28, n = 5 & 18	560
Upper & Lower Tuolumne River	30-Apr-1990	0.30, n = 63 & 169	1.00, n = 4 & 1	600
Upper & Lower Tuolumne River	23-Apr-1994	1.73, n = 207 & 72	0.75, n = 3 & 2	1,200
Upper & Lower Tuolumne River	04-May-1995	0.80, n = 58 & 46	1.14, n = 21 & 12	7,600
Upper & Lower Tuolumne River	26-Apr-1996	0.31, n = 64 & 156	0.57, n = 3 & 4	2,700
Upper & Lower Tuolumne River	22-Apr-1997	0.44, n = 32 & 56	0.23, n = 3 & 12	2,300
Upper & Lower Merced River	22-Apr-1994	0.34, n = 147 & 354	3.00, n = 6 & 2	985
Upper & Lower Merced River	03-May-1995	0.71, n = 82 & 105	0.75, n = 18 & 18	3,950
Upper & Lower Merced River	25-Apr-1996	0.82, n = 112 & 102	1.00, n = 1 & 1	1,200
Upper & Lower Merced River	20-Apr-1997	0.33, n = ?	0.29, n = 5 & 16	1,390
San Joaquin River Tuolumne-Dos Reis	14-Apr-1986	---	0.79, n = 20 & 35	21,500 at Vernalis
San Joaquin River Tuolumne-Dos Reis	16-Apr-1987	---	0.19, n = 16 & 80	2,790 at Vernalis
San Joaquin River Merced-Tuolumne	03-May-1995	---	0.91, n = 21 & 12	17,700 at Vernalis
San Joaquin River Merced-Tuolumne	22-Apr-1997	---	0.82, n = 16 & 12	5,800 at Vernalis
San Joaquin River Tuolumne-Dos Reis	17-Apr-1998	---	0.66, n = 38 & 93	22,000 at Vernalis

High flows trigger juvenile salmon, particularly the fry, to migrate from the rivers into the San Joaquin River and Delta where survival rates are believed to be low compared to those in the tributaries. Studies by Erkkila and others (1950) indicate that many more chinook salmon fry (about 40 mm long) were collected by trawling in the San Joaquin Delta in March 1949 when Vernalis flows ranged between 1,340 cfs and 4,100 cfs compared to the number of large juveniles and smolts collected from April through June of the same year. This suggests many salmon migrate as fry into the Delta even during dry winters. Recent screw trapping studies indicate that the fry migrations coincided with the onset of peak flows in February and March in the Stanislaus River in 1996 and 1998 (Demko and Cramer 1997, Demko and others 1999, S.P. Cramer & Associates, Inc. 1997) and the Tuolumne River in 1998 (DFG Region 4, unpublished data). It is generally assumed that juvenile mortality rates are higher in the Delta than in the tributaries due to the high densities of predators, such as black bass and striped bass, large number of small unscreened diversions, riprapping and channelization of shallow water habitat, and direct mortality at the State and federal pumping facilities in the Delta. However, studies have not been conducted to test this assumption.

Delayed Adult Migration

Hallock and others (1970) showed that radio-tagged adult chinook salmon delayed their migration at Stockton whenever dissolved oxygen (DO) levels were less than 5 mg/l in October during the 1960s and there are concerns that delays may reduce egg viability and increase harvest of adults before spawning occurs. Hallock reported that DO levels usually increased to suitable levels by November. DO levels near Stockton in October and November were greater than 5 mg/l from 1983, when DWR began monitoring, to 1990, but were substantially lower than 5 mg/l for most of October in 1991 and 1992. The Head of the Old River Barrier was installed in fall 1992, but it did not correct the problem. In 1993, DO levels were low until about 10 October and it is likely that pulse flows that raised Vernalis flows to about 4,000 cfs on 7 October were responsible for increasing DO levels at Stockton. Similarly in 1994, DO levels were low until 15 October when pulse flows raised Vernalis flows to about 2,000 cfs. In 1995, DO levels were near 5 mg/l in mid to late September until Vernalis flows increased from about 3,000 cfs to 6,000 cfs through mid October. Low DO levels also occurred in 1996 until 12 October when pulse flow releases increased Vernalis flows from 2,000 to about 3,000 cfs.

Low DO levels in the ship channel during summer and early fall months are partly (if not primarily) a result of the decomposition of algal biomass that is produced in the comparatively shallow, nutrient-rich water upstream of Mossdale and subsequently transported into the much deeper waters of the ship channel (McCarty 1969; E. Van Nieuwenhuyse, personal communication, see "Notes"). The algae, mostly diatoms, are not adapted to deep water conditions and quickly settle out and decompose on the streambed. Simulations performed using the City of Stockton's DO model (Schanz and Chen 1993) indicate that increasing flow at Vernalis with the head of Old River barrier closed generally improves DO conditions at Stockton during most months. But in October, warm temperatures and the DO demand exerted by ammonia from the Stockton wastewater plant, the rotting algal biomass, and other organic matter usually keep DO levels well below the 6 mg/l standard.

The chlorophyll levels at Vernalis are literally among the highest ever recorded for streams worldwide and much of this production may be fueled by feedlot operations in the catchment. On the other hand, it is possible that the nutrient loading responsible for the high algal production stems from much more diffuse processes, such as tile drainage from row crops or orchards. An EPA-style TMDL (total maximum daily load) analysis for nutrients (especially phosphorus) for the San Joaquin catchment would be the first step toward resolving these issues (Lee and Jones-Lee 2001).

The Stockton DO model does not yet explicitly include algae, however, so its predictions about the effects of increased flow should be viewed with healthy skepticism. It is conceivable that under some circumstances sending more Vernalis water to the ship channel could make matters worse by increasing its organic matter loading rate. Ideally, the continuous monitoring stations upstream of the ship channel would be equipped with fluorometers calibrated to measure chlorophyll concentration (an indirect measure of algal biomass). Such a system would alert managers when algal biomass levels at Vernalis or further upstream are extremely high and give them time to take appropriate action.

Under most circumstances, the loading of algal biomass produced naturally in the San Joaquin river upstream is probably a much more serious problem for DO in the ship channel than organic matter loading from the Stockton wastewater treatment ponds. The loading of dissociated ammonium from the wastewater facility, however, may pose a potential toxicity problem. When algae are abundant and DO upstream becomes supersaturated (due to photosynthesis), pH levels also increase. High pH and high ammonium concentration lead to higher levels of undissociated ammonia, which is toxic to fish and aquatic invertebrates. It is possible that the salmon are responding to this toxicity rather than to low DO.

There is concern that pulse flow releases in mid October to attract adult salmon may cause the fish to enter the rivers earlier than they would otherwise, which may expose them to high water temperatures when the pulse flows cease. The number of adults collected at the trap operated by DFG at the Orange Blossom Bridge (river mile 47) in 1965 and 1967, when there were suitable DO levels near Stockton during migration, gradually increased from mid

October to a high in mid November, when suitable temperatures typically occur only in the upstream reaches (Hallock and others 1970). However, surveys conducted in the Stanislaus River in fall 1994 and 1995 suggest that few adult salmon had entered the river before early November even when DO concentrations were about 7 ppm and Vernalis flows ranged between 6,000 and 7,000 cfs during the first half of October 1995 (Thomas R. Payne & Associates 1997). Instead of flow, the appearance of salmon on the spawning riffles in Stanislaus River has coincided with the first major storms (i.e., declining barometric pressure and air temperatures without flow changes), particularly in 1997 when many fish arrived in mid October. Although the adults also tend to arrive at the spawning riffles in substantial numbers in late October or early November in the Tuolumne and Merced rivers, salmon were observed migrating in the San Joaquin River at the Hills Ferry Barrier near Newman in late September and early October 1995 (DFG 1997). These observations along with those of Hallock and others (1970) suggest adult salmon migrate through the Delta to the spawning riffles at a very slow rate, taking approximately two months to migrate from Antioch to the spawning riffles. If true, then migratory cues such as pulse flows or storm related influences (e.g., barometric pressure) could influence the salmon anywhere along their migration route and their response may not be observed in the tributaries for several weeks.

Upstream migrating adult salmon that are delayed in the mainstem San Joaquin River and Delta are subject to sport harvest, whereas adults that migrate into the tributaries are somewhat protected by regulations that prohibit angling from 15 October through 31 December.

Adult Straying

Delta export rates at the State Water Project and Central Valley Project were increased to near maximum (about 9,600 cfs) in fall 1996 and in subsequent years to "make-up" for reduced pumping rates during the spring emigration period to improve salmon smolt survival. The adult fall-run salmon are migrating upstream through the Delta primarily in October typically when San Joaquin flows measured at Vernalis are low. It is likely that when exports are high relative to San Joaquin flows, little if any San Joaquin River water reaches the San Francisco Bay where it may be needed to help guide the salmon back to their natal stream. An analysis of the recovered adult salmon with coded-wire-tags (CWT) that had been reared at the Merced River Fish Facility and released in one of the San Joaquin tributaries suggests straying occurred when the ratio of exports to flows was high (Mesick 2001a). The analysis, which included an adjustment to the estimated number of fish examined for CWTs in some rivers (Mesick 2001a), indicates that during mid October from 1987 through 1989 when export rates exceeded 300% of Vernalis flows, straying rates ranged between 11% and 17%. In contrast, straying rates were estimated to be less than 5% when Delta export rates were less than about 300% of San Joaquin River flow at Vernalis during mid-October. Since 1993, pulse flow releases from the San Joaquin tributaries for 8 to 10 days in mid-October appear to have kept straying rates below 2%.

Delta Migration Barriers

In the South Delta, rock barriers are installed to maintain hydraulic head for small pump diversions and these barriers are impassible for adult salmonids. Hallock and others (1970) found that when the head of Old River barrier was installed in fall 1964, adult salmon migrated through the mainstem San Joaquin River. However, when the barrier was not installed in fall 1965 through 1967, some of the salmon migrated through the South Delta. Their study suggests the rock barriers block the flow of water that attracted migrating adults and so few, if any, adults would be expected to migrate into channels where rock barriers have been installed.

Fluvial Geomorphic Processes

The large reservoirs in the San Joaquin tributaries have reduced the frequency and magnitude of winter peak flows and peak flows may be needed to mobilize riffle substrate thereby sorting fines from spawning-sized gravel. New Melones Reservoir has the capacity to impound about 240% of the annual runoff in the Stanislaus River basin, whereas the main reservoirs on the Tuolumne and Merced rivers can impound about 100% of their annual runoff. The hydrograph of the Stanislaus River is further altered by a maximum flow of about 1,800 cfs from spring to fall to protect the permanent crops in the floodplain. These conditions have resulted in heavy encroachment of riparian vegetation, particularly exotic species, along much of the Stanislaus River.

Many biologists and fluvial geomorphologists assume that the loss of peak flows results in the accumulation of fine sediments in spawning riffles. The potential benefits of peaking flows, namely the sorting of fines from spawning sized gravel, cannot occur unless there is (1) an adequate rate of gravel recruitment to replace the mobilized gravel; and (2) a functional floodplain where fines are deposited as flows recede. DFG estimated that approximately 35% of the spawning gravel in the Stanislaus River had been lost or otherwise made unavailable for spawning by vegetation encroachment, scouring flood flows, and gravel extraction operations between their 1961 survey and their 1972 survey (DFG 1972). There is a need to evaluate the effectiveness of managing peak flow releases to reduce the concentration of fine sediment in spawning riffles relative to the rate of gravel recruitment, the rate of fine sediment input, the influence of spawning salmon, and floodplain function (Kondolf and Wilcock 1996).

Water Temperature

High water temperatures can result from (1) low reservoir storage resulting in surface water releases into the spawning reach; (2) high air temperatures; and (3) low flows as occurred in the Stanislaus River in the early 1990s (Loudermilk 1996). The presence of Old Melones Dam within New Melones Reservoir causes the release of warm surface water from New Melones whenever storage levels fall below about one million acre-feet, a problem that occurred in 1991 and 1992. Reregulation reservoirs, such as Tulloch Reservoir on the Stanislaus River, can be warmer than 56 F through the end of October although cold water releases are made from the main reservoirs upstream (DFG 1998). Water temperature models have either been completed or are planned for the near future for most of the San Joaquin tributaries. Although these models provide the means to manage flow releases and reservoir operations to control water temperatures, they do not provide the ability to accurately evaluate the effect of restoring riparian forests on water temperatures. Although a narrow strip of riparian vegetation is known to have little detectable effect on air and water temperatures, clear-cutting 41% of the riparian forests along Carnation Creek, a relatively small stream on Vancouver Island, substantially elevated water temperatures by increasing the exposure of the stream surface to incident solar radiation (Holtby 1988). The riparian forests along the San Joaquin tributaries are confined to narrow strips due to agricultural practices.

A model that predicts water temperature has been developed for the mainstem San Joaquin River between the head of the Old River to Disappointment Slough (Schanz and Chen 1993, Chen and Tsai 1997); a proposal has been submitted to extend the model upstream to Mud and Salt Sloughs. The relationship between streamflow at Vernalis and the daily range in water temperature at Vernalis for periods in April, May, and early June in 1962, 1963, 1970, and 1973 to 1994 are shown in Figures 10 to 12. These relationships suggest a flow of about 3,500 cfs from mid April (Figure 10) to mid May (Figure 11) are adequate to maintain maximum daily water temperatures below 65 F at Vernalis. Usually adequate water temperatures occurred in the San Joaquin River except during drought years (1977 and 1987 to 1992), and when high flows entered the San Joaquin River from the James Bypass upstream of Newman during spring 1986. By the end of May, water temperatures exceeded 65 F even at flows that exceeded 30,000 cfs; whereas flows greater than about 3,000 cfs were sufficient to keep water temperatures between 65 F and 70 F (Figure 12), which equates to an 80% survival rate for the juveniles (Baker and others 1995).

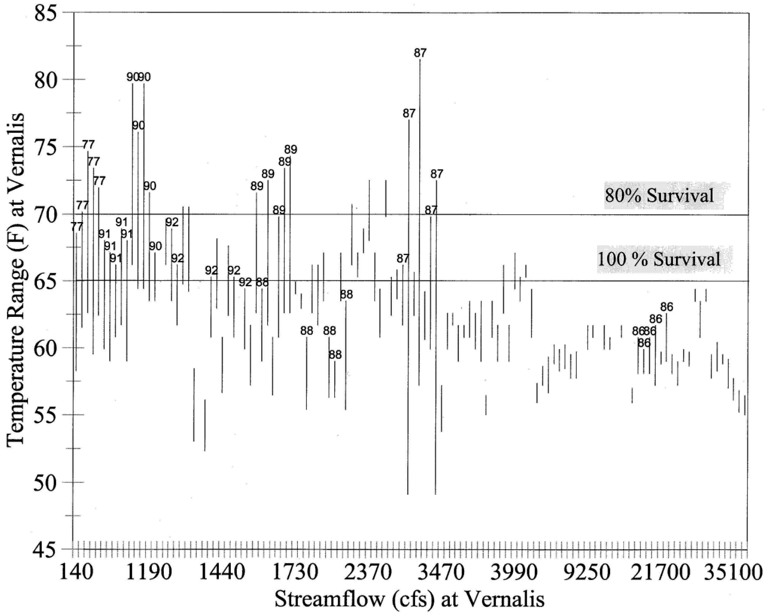

Figure 10 Range in daily water temperatures (F) relative to streamflow in the San Joaquin River at Vernalis from the period 13 to 17 April in 1962, 1963, 1970, and 1973 to 1994

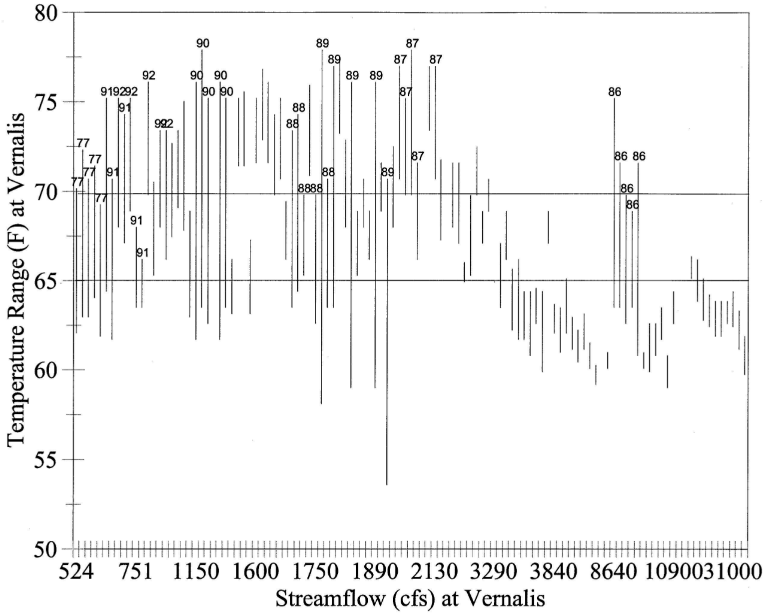

Figure 11 Range in daily water temperatures (F) relative to streamflow in the San Joaquin River at Vernalis from the period 13 to 17 May in 1962, 1963, 1970, and 1973 to 1994

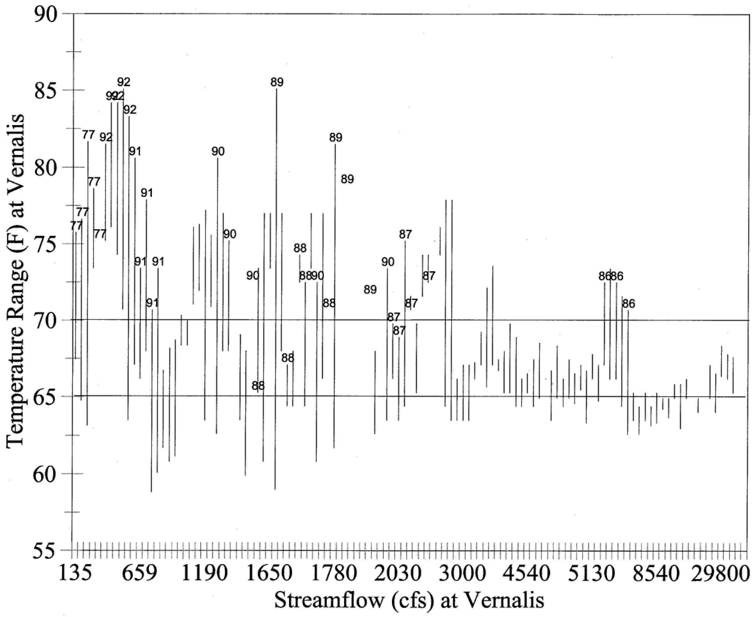

Figure 12 Range in daily water temperatures (F) relative to streamflow in the San Joaquin River at Vernalis from the period 28 May to 2 June in 1962, 1963, 1970, and 1973 to 1994

Spawning and Egg Incubation

Observations in the Stanislaus, Tuolumne and Merced rivers indicate that before mid to late November, adult salmon migrate to the upper reaches near the flow release point where water temperatures are usually suitable (<56 F) for spawning. Fall-run chinook eggs incubate for about 43 days at 52 F whereas cooler temperatures increase the incubation period. After hatching, the alevins remain in the gravel until most of their yolk sac has been absorbed, about 45 to 90 days after hatching (Alderdice and Velsen 1978). Based on this information and the timing of spawning, incubation and alevin development occurs from late October through March.

The mortality of chinook salmon eggs taken from the Sacramento River fish increased significantly at water temperatures above 57 F (Healey 1979). Regulatory agencies typically gauge temperatures below 50 F as optimum, temperatures greater than 56 F as stressful, and temperatures that exceed 60 F as lethal for chinook salmon. Although water temperatures can exceed 56 F throughout much of the spawning reaches in October and early November, if flow releases are low and air temperatures are high (USBR 1993; EA 1993), most salmon spawn in the upper reaches where cold water releases from the dams provide suitable water temperatures. By mid November, air temperatures usually decline substantially which causes water temperatures to drop below 56 F regardless of flow, and greater numbers of adult salmon begin spawning in the lower reaches.

The viability of chinook salmon eggs collected at the Merced River Hatchery was relatively low when water temperatures were high during October and November, particularly for the early arriving fish collected during the 1977 drought (DFG unpublished data). The effect of temperature on the viability of unfertilized eggs is uncertain (Marine 1992) and it is possible that high temperatures affect sperm viability as well.

Juveniles

The upper incipient lethal temperature for juvenile chinook salmon from Washington is about 75 F under laboratory conditions (Brett 1952); whereas the highest growth rates occur between 60 F and 65 F (Banks and others 1971). However, the San Joaquin basin has higher water temperatures than most other rivers that support chinook salmon and studies conducted by Chris Myrick at the University of California at Davis in the mid-1990s suggest Central Valley fish have evolved to grow well at temperatures higher than previously reported. Myrick's studies were not completed and there is a need for additional work.

Groundwater Inflow

Historically, most rivers in the Central Valley increased in flow in a downstream direction due to accretion from groundwater flow. Today, groundwater pumping in the watershed has lowered the groundwater and reduced accretion rates. In some rivers, such as the Cosumnes River, streamflows decline in a downstream direction. Groundwater inflow temperature is typically between 55 and 60 F which may be lower than the river temperatures after early May. It is possible that the groundwater inflow helps to maintain suitable water temperatures for juvenile salmon in the downstream reaches after early May or at least provide small temperature refugia for emigrants.

Gravel Recruitment and In-River Gravel Mining

The amount of gravel available to maintain spawning and incubation habitat has been reduced by the blockage of gravel recruitment by upstream dams and by direct removal by gravel mining operations. Gravel recruitment has been reduced by about 95% in Central Valley rivers with large upstream reservoirs (Vick 1997). Major gravel mining operations from 1930 to the 1970s, which peaked during the 1930s and early 1940s, removed large amounts of gravel directly from streambeds in San Joaquin County (Clark 1955; DFG 1972; Jensen and Silva 1988) that left large in-river pits and long stretches of deep, flat streambed. Drag lines were used to dredge the gravel from the riverbed throughout much of the spawning reaches in the Stanislaus and

Merced rivers, whereas large, boat-mounted dredgers were used in the Tuolumne River (P. Frymire, personal communication, see "Notes"). Exposed point bars were also mined along much of the upper reaches, which required the construction of dikes along the river margin. Dikes were also constructed when the dredge spoils were deposited in long rows along the river margins. DFG (1972) estimated that about 750 of 3,300 (23%) acres of riparian habitat and floodplains in the Stanislaus River were lost to expanding agricultural practices and to a lesser degree, gravel mining, between 1958 and 1965 and that the losses had continued through 1972. Based on maps made in the 1960s by DFG (1972), approximately 55% of the channel in the primary spawning reach between Knights Ferry and the Orange Blossom Bridge was excavated. Usually a few riffles were left in the dredged areas to provide road crossings for heavy equipment. In the dredged areas, there was an average of three riffles per mile in the 1960s, whereas there was an average of about 12 riffles per mile in the undredged reaches. Based on surveys conducted in 1995 and 1996 (Carl Mesick Consultants and others 1996), many of the riffles identified as spawning habitat in the DFG maps in the 1960s have become armored and shortened. Gravel permeabilities at 24 natural riffles in the Stanislaus River averaged 2,245 cm/hr (range <80 to 12,300 cm/hr) in August 1999 (Carl Mesick Consultants 2000). Similar gravel permeabilities were observed in the Tuolumne River in 1999 (D. Mierau, personal communication, see "Notes").

Few adult salmon spawn in the dredged channels that have relatively flat, uniform streambeds, lacking diversity of water depths and velocities. In contrast, complex streambed morphology increases the rate of downwelling of surface flow into the substrate, a cue thought to be used by adult salmon to select spawning habitat (Vaux 1962, 1968; McNeil 1969). Adult salmon preferred to spawn adjacent to large boulders placed on short steep berms of newly placed gravel (Merz 2000) and near large woody debris in unenhanced sites in the Mokelumne River (Merz 1998a).

The effects of gravel mining on juvenile rearing habitat have not been studied, but the impacts are probably important. In the Mokelumne River, fry begin to disperse within the upstream tributary river rearing areas and begin foraging on aquatic and terrestrial invertebrates after they reach 30 to 50 mm (Merz 1998b). However, in the Stanislaus River in 1999, few juvenile salmon dispersed from the primary spawning reach, a 2-mile long section between Knights Ferry Bridge and Willms Pond, to rear in the river downstream of Willms Pond (Fisheries Foundation, unpublished data). In addition, juveniles congregated at restoration riffles constructed upstream of Willms Pond in summer 1999, which suggests that the excavation of riffle habitat degraded the rearing habitat.

The lack of gravel recruitment in the Stanislaus River is believed to be causing channel widening (Schneider 1999). A comparison of channel surveys made in

1996 and again in 1999 at five study sites indicated that the channel widened from 2.3 to 13.4 feet (mean 7.6 feet) at all five sites. The loss of sediment creates "hungry water" which can cause lateral erosion of the banks as the river attempts to regain part of its sediment load (Kondolf 1997). Over-widening of the river channel can modify bed shear stresses by changing pool and riffle sequences in the channel (Knighton 1984).

Sedimentation

High concentrations of fine sediments in spawning riffles reduce intragravel flow and egg survival and entombs embryos (Waters 1995). Unsuitably high concentrations of fines have been documented at a substantial number of spawning riffles in the Stanislaus (DWR 1994; Mesick 2000c) and Tuolumne rivers (EA 1992, Stillwater Sciences, unpublished data). Potential sources of fine sediments include erosion within the lower watershed, the release of accumulated fine sediments from upstream reservoirs when storage levels are low, and the gravel pits and mined channels in the spawning and rearing reaches that have stored thousands of tons of fines. The Stanislaus River becomes quite turbid, 20 to 44 Nephelometric Turbidity Units in February 1998, during heavy rainstorms (Demko and others 1999). Substantial erosion has been recently observed along the Stanislaus River below the Orange Blossom Bridge from residential construction and urban runoff, incorrectly designed and inadequately maintained roads and culverts, and to a small degree from streambank erosion. There are a few large and many small mine pits that were dug to a depth of about 50 feet for gravel excavation between 1930 and 1950. These pits are within the spawning and rearing reaches of the Stanislaus River and almost all have filled with fines. Fines have also accumulated in the long stretches of deep, flat streambed that were mined during the 1930s and 1940s. Riffles constructed with clean gravel in summer 1999 that are immediately downstream of several of the small pits and long stretches of mined channels have been completely filled with fines by the summer of 2000 whereas restoration riffles immediately upstream of these mined areas had relatively few fines (Mesick, unpublished data). The porosity of the clean gravel added to the restoration sites ranged between 26% and 35% (Mesick, unpublished data) and filling of all the pore space with fines in the nine restoration riffles immediately downstream of the mine pits would have required at least 1,800 tons of fines. As no other substantial source of sedimentation was observed in the area immediately downstream of the mined areas, the mined areas were the most likely source of the fines.

Although spawning salmon reduce the concentration of fines in their redds, high rates of fine sediment intrusion occur after redd construction due to storm runoff, transport of fines during high flows, construction activities from other nearby salmon, and possibly from intragravel movement of fines (Mesick 2001b). The mean permeability was 33,070 cm/hr in 30- to 60-day-old chinook salmon redds in the Stanislaus River, which corresponds to an egg survival to emergence rate of 71%, whereas it was 3,700 cm/hr in adjacent undisturbed gravel (Mesick unpublished data). Emergence trap studies on the Tuolumne River indicate that egg survival-to-emergence rates ranged between 0% and 68% (mean of 34%; EA Engineering, Science, and Technology 1992). Studies in Mill Creek, a tributary to the Sacramento River, indicated that sedimentation from storm runoff substantially reduced streambed permeability which resulted in nearly total mortality of eggs in artificial redds in natural riffles (Gangmark and Bakkala 1960).

Oxygen-poor Groundwater in the Intragravel Environment

Studies in the Stanislaus River indicate that intensive rain storms in January 1996 were correlated with elevated intragravel water temperatures and lowered intragravel dissolved oxygen (DO) concentrations; DO concentrations decreased by 25% to 75% of saturation levels at about 30% of the piezometer sites in highly used spawning riffles (Mesick 2001b). The increased temperatures and reduced DO levels appear to have been temporary storm effects because DO levels increased at two undisturbed piezometers resampled nine months later. Neither increased water temperatures nor lower DO concentrations were observed at riffles where the percentage of fines was low (Mesick 2000c) and so it is likely that a high rate of fine sediment intrusion that formed a sealing layer in the substrate during intensive rain storms was necessary for groundwater inflow to dominate the intragravel environment. Beschta and Jackson (1979) reported that the upper layer of substrate trapped sand 0.5 mm in diameter and formed a thin barrier or seal against the further intrusion of sand. It is likely that this layer of sand could become clogged with soils during rainstorms.

Predation

Several studies suggest that predation of juvenile salmon by (*Micropterus salmoides*) and smallmouth bass (*M. dolomieui*) is a major source of mortality in the tributaries and probably the Delta as well. Radio tagging studies of smolts in the Stanislaus River in spring 1998 suggest substantial mortality occurs in captured gravel mine pits, probably from predation (SP Cramer & Associates 1998). However, the overall mortality rates of radio tagged fish were higher than observed for natural fish caught with screw traps and so the tagging procedure or the tag's exterior antennae may have increased the fish's vulnerability to predators. DFG electrofishing surveys in early March during the late 1980s indicate that there were largemouth bass and smallmouth bass in the large captured mine pit near river mile 49 in the Stanislaus River. Some had juvenile salmon in their stomachs. Studies in the Tuolumne River (EA 1992) suggest predation rates by black bass in mined riverbeds (called special run-pools by EA) substantially reduce the survival of hatchery juveniles migrating during a 500 cfs pulse flow in spring 1990. Although several long-term Stanislaus River residents report that black bass fishing was excellent in the captured mine pits during the 1987 to 1992 drought when summer flows were low, they also say that the bass fishery has been greatly diminished after the high flows of spring 1995.

There is a substantial run of striped bass (*Morone saxatilis*) in the San Joaquin tributaries from March to early May. In 1999, stripers were collected in the Stanislaus River that had radio tagged juvenile salmon in their stomachs (SP Cramer & Associates, unpublished data). Whether the abundance of stripers or their predation rates are influenced by the instream gravel mining is unknown.

There are also large schools of Sacramento pikeminnow (*Ptychocheilus grandis*) in the long stretches of mined channel in the Stanislaus River and many of their stomachs are full of juvenile salmon and steelhead during winter and spring (S. Walser, personal communication, see "Notes").

Densities of black bass and striped bass are about three times higher in the central Delta downstream from Rough and Ready Island near Stockton and in the Mokelumne River (eastern Delta) than in the northern or southern areas of the Delta based on the DFG resident fish study conducted from 1980 to 1983 (Table 8; DFG, unpublished data). DFG introduced Florida largemouth bass into the Delta in the early 1980s and again in 1989 and catch rates of black bass have increased since 1993 (Lee 2000). Although predation of juvenile salmon in the Delta has not been well studied, it would account for the low survival rates of juvenile salmon migrating between Dos Reis and Jersey Point and for Sacramento River juveniles migrating into the Mokelumne River through the Delta Cross Channel.

Table 8 Number and mean fork length of largemouth bass, smallmouth bass, and striped bass per kilometer that were collected during DFG electrofishing surveys in the Sacramento-San Joaquin Delta, 1980 to 1983. The sampling sites in each region of the Delta are shown in Figure 1 of Schaffter (2000)

Location	*Largemouth bass 208 mm FL*	*Smallmouth bass 225 mm FL*	*Striped bass 140 mm FL*
Central Delta	12.81	0.02	0.03
Eastern Delta	12.92	0.20	0.19
Southern Delta	4.42	0.36	0.03
Northern Delta	3.83	0.78	0.03
Western Delta	5.97	0.08	0.00

Ocean Harvest

California chinook salmon are harvested in both ocean and river fisheries. The commercial ocean troll fishery for California chinook salmon primarily occurs from Monterey northward to Coos Bay, Oregon (Reisenbichler 1986). The troll fishery grew rapidly in the mid 1940s with an increase in the number and size of boats and use of power puller mechanisms for the lines, called gurdies (California Bureau of Marine Fisheries 1949). The commercial salmon landings off the California coast increased from a mean of 2,556 tons from 1932 to 1943 to 5,254 tons from 1944 to 1949 probably in response to the increased fishing pressure and an increase in salmon production in the Sacramento River basin (California Bureau of Marine Fisheries 1949; Fry 1961). From 1950 to 1995, harvest averaged about 3,500 tons of salmon.

There was a commercial drift gill net fishery in the Pittsburg-Martinez area that increased from about 150 boats in the mid-1930s to 240 boats in 1947 (California Bureau of Marine Fisheries 1949). The season was legally closed from June 16 to August 9 and again from September 27 to November 14 (California Bureau of Marine Fisheries 1949). The annual chinook salmon catch of the gill-net fishery averaged 1,141 tons from 1946 to 1952. The gill net fishery was completely closed in 1958.

The catch of the ocean sport fishery was about 20% of the total ocean catch (Reisenbichler 1986). Catch data are not available for the sport fishery prior to 1947.

The Central Valley Index of ocean harvest (CVI), which includes the commercial and sport harvest for chinook salmon, was well correlated with recruitment to the Tuolumne River but not with Stanislaus River recruitment. The primary effect of ocean harvest was that the abundance of four-year-old fish declined from an average of 53% between 1947 and 1951 when about 37% of the population was harvested to about 20% of escapement from 1988 to 1998 when about 73% of the population was harvested.

A substantial reduction in the number of four-year-old fish returning to spawn has several implications (D. Vogel, personal communication, see “Notes”). First, the loss of multiple-age populations causes the salmon runs to be particularly vulnerable to natural disasters (e.g., floods and droughts) that devastate single-age spawning stocks. The combined loss of four-year-old spawners due to ocean harvest and the loss of three-year-old spawners due to low juvenile survival when spring flows were low substantially reduced population fecundity. Second, the large four-year-old females tend to dig deeper redds that probably protect eggs from bed scour during high flows and helps improve the permeability of the spawning beds. Finally, four-year-old females produce more eggs than do three-year-olds and the reduction in their numbers has reduced the fecundity to the overall populations. Reduced fecundity was a particular problem whenever environmental conditions reduced juvenile survival to very low levels and consequently stock was reduced two and possibly three years later. Stock was less than 1,500 spawners, which probably limited recruitment, during 46% of the years in the Stanislaus River and 39% of the years in the Tuolumne River from 1958 to 1998.

Ocean Prey

The diet of two-year-old and older chinook salmon captured in the ocean sport troll fishery off San Francisco in 1954 and 1955 primarily consisted of northern anchovy (29.1%), various juvenile rockfishes (22.5%), euphausiids (14.9%), and herring (12.7%) as reported in Merkel (1957). Anchovies dominated the diet from August to November, rockfishes during June and July, herring in February and March, and invertebrate foods in April and May. Salmon caught in water shallower than 38 meters had fed primarily on anchovies (91% to 92%) whereas those caught in deeper water fed primarily on rockfishes (71% to 74%).

Northern anchovy landings during the year when the fish were three years old were negatively correlated with recruitment to the Tuolumne River although the correlation became nonsignificant when stock, Vernalis flows and Delta exports were included in the model. Herring landings were not correlated with recruitment to either river probably because they averaged less than 10% of the northern anchovy landings from 1939 to 1985. The effects of ocean prey abundance on the survival of adult salmon has not been studied, but it is likely that prey abundance primarily affects the growth rate of adult fish and not mortality.

Ocean Climate

Long-term records indicate that there are 15- to 25-year cycles of warm and cool periods in the northeastern Pacific Ocean that are strongly correlated with marine ecosystem productivity. Cool cycles prevailed from 1890-1924 and again from 1947-1976 while warm cycles dominated from 1925-1946 and from 1977 through at least the mid-1990s (Mantua and others 1997). During the mid 1970s, a major shift occurred from a colder to warmer-than average regime in the California current (MacCall and others 1992, Francis and others 1998). This shift was accompanied by a drop in zooplankton abundance by as much as 70%, vigorous recovery of the depleted sardine population off Southern California (Hayward and others 1992, Francis and others 1998), and decreases in the harvest of spring-run chinook and coho salmon off the coast of Washington, Oregon, and California (Mantua and others 1997). Salmon landings off the California coast, which includes mostly chinook salmon and relatively few coho, followed a similar pattern to the one reported by Mantua and others (1997) for West Coast coho and spring-run salmon: California salmon landings were high during the cool cycles from 1916 to 1925 (mean 5,062 tons) and from 1944 to 1982 (mean 4,100 tons) and low during the warm cycles from 1926 to 1943 (mean 2,632 tons) and from 1983 to 1997 (mean 2,865 tons). The coastal warming that occurred in the mid 1970s is believed to have caused increased stratification in the California Current, a sharper thermocline with less vertical displacement of nutrient rich water due to coastal upwelling, a reduction in the duration of upwelling conditions, and a reduction in nutrients and/or zooplankton abundance carried by the California Current (Francis and others 1998). Although most researchers report that zooplankton abundance declines in the California Current during the warm regime, coastal euphausiids (*Thysanoessa spinifera*) declined while oceanic euphausiids (*T. pacifica*) increased during the warm cycle (Francis and others 1998). Such changes in ocean climate appear to affect salmon early in their marine life history (Hare and Francis 1995) and coastal invertebrate species would be important prey for ocean-type juveniles, such as fall-run chinook salmon. Conversely, pelagic fish species such as sardines, which feed on oceanic invertebrates, would be expected to decline during cool cycles as occurred during the mid 1940s. The PDO index used in this study is strongly correlated with long-term cycles in sea-surface temperatures.

Short-term cycles in ocean currents and coastal upwelling are associated with El Nino/Southern Oscillation (ENSO) events. The ENSO event during the winter of 1982-1983, which was associated with a strengthening of the Aleutian Low, caused severe storms along the California coast. The result during the 1982-1983 winter was increased rainfall, increased vertical mixing, and increased onshore Ekman transport, which typically increases upwelling and nutrient inputs to the surface layer (Hayward and others 1992). However, El Nino events are usually associated with decreased upwelling and reduced nutrient input (Hayward and others 1992). The NPI index is correlated with short-term cycles associated with El Niño/Southern Oscillation events. The mean PFEL Upwelling Index for May through July when juvenile chinook salmon enter the ocean (MacFarlane 1999) provides a direct index of upwelling and nutrient availability during a critical phase of ocean survival for chinook salmon. The PFEL upwelling index was low from 1946 to 1954, high from 1955 to 1981, and moderate and highly variable from 1982 to 1995 (Table 3).

The correlations were weak between recruitment to the Tuolumne and Stanislaus rivers and all three ocean climate indices tested here, although there were inconsistent patterns. The transition from the non-productive warm-cycle to a productive cool cycle in 1947 corresponded to a substantial decrease in recruitment to the Tuolumne River. Mean recruitment to the Tuolumne River was 117,642 fish from 1941 to 1946, which was the highest observed although it occurred during a non-productive warm cycle in the California Current. It then declined to 31,143 fish from 1947 to 1976, which was the productive cool cycle. It then declined further to 20,116 fish from 1977 to 1997 during a warm non-productive cycle as expected. Mean recruitment to the Stanislaus River declined as expected from 13,768 fish for the productive 1946 to 1976 period to 10,791 fish for the non-productive 1977 to 1997 period. The decline in Tuolumne River recruitment during the mid 1940s was probably in response to the unusually high flows that persisted from 1935 to 1946; whereas the relatively small decline in recruitment to both the Tuolumne and Stanislaus rivers in 1977 was probably in response to a decline in productivity in the coastal areas.

Negative correlations between NPI and recruitment were observed in some years, particularly from 1970 to 1995. Recruitment to both the Tuolumne and Stanislaus rivers were high in response to the strong ENSO event during the 1982-1983 winter when the NPI value was very low. There were many intensive storms during the 1982-1983 winter that resulted in flooding. Considering the strong correlation between recruitment and streamflow and the lack of correlation with the upwelling index, it is likely that recruitment responded primarily to increases in streamflow during the 1982-1983 winter rather than to ocean conditions associated with the ENSO event.

Delta Reclamation and Dredging

Prior to 1850, the Sacramento-San Joaquin Delta, an area of nearly 750,000 acres, was mostly a tidal marsh that consisted of a network of sloughs and channels during low flows and a large inland lake during flooding. The development of the Delta into farmland began in 1850 when the Swamp Land Act conveyed ownership of all swamp and marshes from the federal government to the State. Initial reclamation consisted of the construction of levees with peat soils on Rough and Ready Island and Roberts Island. These initial levees failed and in the 1870s steam-powered dredges were used to excavate alluvial soils to construct much larger levees. By the 1930s, reclamation was considered complete and the number of operating dredges declined greatly. However, due to continued subsidence of the peat soils, the Army Corps of Engineers continually adds material to maintain the levees, many of which range between 15 and 25 feet high.

The Port of Stockton and the deepwater ship channel in the San Joaquin Delta were completed in 1933. Activity at the Port of Stockton increased greatly in 1942 with the construction of military ships, mine sweepers, and landing craft. Shortly thereafter, large passenger cruise ships began navigating through the Delta. Currently the river is dredged to a depth of 35 feet to allow passage of deep draft ships; whereas upstream of the ship channel, depths range between 8 and 12 feet.

The unusually low survival of salmon smolts near Stockton and the beneficial effect of flood flows on recruitment suggests that dredging the deepwater ship channel may have indirect effects related to increased predator habitat, low DO concentrations, and contaminants. It is also possible that increased flows downstream of the Mokelumne River due to the diversion of Sacramento River water through the Delta Cross Channel since 1951 was partially responsible for the relatively high smolt survival rate in the deepwater ship channel downstream from the Mokelumne River during April 1991 compared to survival rates upstream of the Mokelumne River.

Juvenile Food Supply

Food supply and growth rates of juvenile salmon have not been extensively studied in most of the tributaries. Stomach content analysis of juvenile chinook salmon in the lower American (Brown and others 1992; Merz and Vanicek 1994) and Mokelumne rivers (Merz 1998b) suggest zooplankton from the upstream reservoirs and terrestrial macroinvertebrates occasionally supply as much as 50% and 25% of the fishes' diet, respectively. Invertebrate surveys have also been conducted in the Tuolumne River. Although the studies have not resolved whether the food supply limits the growth and survival of juvenile salmon in the San Joaquin tributaries, there are concerns that habitat degradation and contamination has reduced the supply of food from macroinvertebrates in the benthos and drift, plankton from reservoirs, and terrestrial invertebrates.

High concentrations of fine sediments in the substrate may have shifted the benthic invertebrate populations toward smaller species, which may be less useful as food for juveniles. It is also likely that channel incision, degraded riparian vegetation, and degraded streambed complexity have reduced the supply of organic detritus that is required by many invertebrate species for food (Allan 1995). The supply of zooplankton from reservoirs may be affected by contaminants in runoff in the upper watershed and by reservoir management that affects plankton distribution relative to the location of the intake for fish flow releases. If zooplankton contribute substantially to the diet of juveniles, then it may be necessary to balance the benefits of deep, cold water releases from reservoirs with those of mid- to upper level releases that may contain high concentrations of zooplankton. The supply of terrestrial invertebrates may be affected by the spraying of pesticides near the floodplain and by levees and channel incision that reduce flooding which allows juveniles to feed in terrestrial zones and helps flush terrestrial invertebrates into the river.

Disease

The disease *Ceratomyxa* causes a high mortality rate of chinook smolts migrating through the lower Willamette River, Oregon. *Ceratomyxa* is also present in the Central Valley. Recent studies have established that this disease relies on tubifix worms for an intermediate host. These worms flourish in organic sediments and they are likely to multiply in years when organic sediments are not flushed by high flows. There are indications that mortality of smolts due to this disease increases in drought years and decreases in wet years. This disease is a particular concern for the Stanislaus River because there is a tubifix worm farm near the Orange Blossom Bridge. It is also possible that organic sediments accumulate and produce tubifix worms in captured mine pits.

Contaminants

Mud and Salt sloughs and many small agricultural return channels contribute a variety of contaminants to the mainstem San Joaquin River and the tributaries, particularly during the winter when dormant sprays are applied to crops and rain storms flush the contaminants into the rivers in a pulse. However, experimental studies have indicated that there were no detrimental effects of agricultural return flow from the west side of the San Joaquin on the growth and survival of chinook salmon reared at the Merced Fish Facilities when the return flows were diluted by 50% or more with San Joaquin River water (Saiki and others 1992). Bioassays with fathead minnows with water samples from the San Joaquin, Merced, Tuolumne, and Stanislaus rivers showed little evidence of toxicity (Brown 1996). Low or no detectable concentrations of organochlorine pesticides and polychlorinated biphenyls were detected in fish collected from Don Pedro Reservoir on the Tuolumne River, San Joaquin River at Fremont Ford and Mossdale (Goodbred and others 1997). Although contaminants in the San Joaquin basin may not have had direct effects, a study conducted in Puget Sound, Washington, (Arkoosh and others 1998) indicates that emigrating juvenile chinook salmon exposed to contaminants, polycyclic aromatic hydrocarbons and polychlorinated biphenyls, suffered increased susceptibility to common marine pathogens (*Vibrio anguillarium*).

Unscreened Diversions

There are 44, 36, and 68 small unscreened screened diversions on the Stanislaus, Tuolumne, and Merced rivers, respectively. In addition, there are six inadequately screened, medium-sized diversions on the Merced River. The entrainment rates at these sites have not been studied. The radio tagging study in the Stanislaus River, which tagged 49 fish, did not detect any entrainment of tagged fish at several moderately sized unscreened pumps in the lower river (SP Cramer & Associates 1998). Studies in the Delta suggest entrainment rates increase exponentially with increases in diversion rate. If true, a majority of entrainment would occur at the four large unscreened diversions in the mainstem San Joaquin River downstream from the confluence with the Merced River. The El Soyo diversion, just downstream of the mouth of the Tuolumne River, has a maximum capacity of 80 cfs. The Banta-Carbona diversion, downstream of the mouth of the Stanislaus River, and the West Stanislaus diversion and Patterson diversions, both below the mouth of the Merced River, each have a maximum capacity of 240 cfs. Screens were installed in the late 1970s but were later abandoned due to maintenance problems.

Prespawning Mortality

Prespawning mortality has not been estimated for the Central Valley basin, but estimates in other streams, such as the Rogue River, indicate that this mortality can range from 5% to 75% annually (Cramer and others 1985). Common causes of this mortality are thermal stress, disease, and angler harvest.

Instream Harvest and Harassment of Spawners

Angler harvest of adult salmon before and during spawning reduces the number of eggs deposited. The angling season is closed on the San Joaquin tributaries from 16 October through 31 December to protect spawners. New regulations that require artificial lures and barbless hooks have just been implemented on the San Joaquin tributaries to protect steelhead and juvenile salmon. The effectiveness of the fishing regulations to protect spawning salmon in the San Joaquin tributaries is unknown.

Disturbance to riffle substrates during incubation from anglers, rafters, livestock, jet boats and prop boats may reduce egg survival. This may be a particular problem for the Stanislaus River in January when anglers begin fishing for steelhead in Goodwin Canyon while chinook eggs are incubating. In the Mokelumne River, dozens of cows have been observed walking on redds during the incubation season (J. Merz, personal communication, see “Notes”). Heavily rafted streams, such as the Stanislaus River, receive heavy foot traffic at some shallow riffles.

Altered Genetics Due to Hatchery Fish

The percentage of hatchery reared salmon in the populations returning to the San Joaquin tributaries has been high in recent years, and the effect of interbreeding between the hatchery and naturally produced fish on the gene pool of the naturally produced fish is unknown. Since 1990, the percentage of Merced River Hatchery salmon with coded-wire-tags that were recovered in the escapement surveys as adults has ranged between 8% and 38% of the total population in the San Joaquin River tributaries (Mesick 2001a). Since not all of the hatchery fish were tagged, the percentage of hatchery fish may constitute a much higher portion of the population than estimated by CWT returns. The effect of interbreeding with hatchery fish is probably greatest when Feather River Hatchery fish return to the San Joaquin River and eastside tributaries because the Feather River fish, and others from the Sacramento basin, have evolved under different flow and water temperature regimes. Furthermore, although the hatchery environment may allow some fish to survive that would not survive under natural conditions, interbreeding with naturally produced fish may not adversely affect the survival of the offspring.

Conclusions

The correlations analyses of recruitment and smolt survival studies suggest that low flows during dry years, degraded habitat particularly in the Delta near Stockton, low spawner abundance caused by high harvest rates of salmon, and the indirect effects of Delta exports were responsible for the decline in the fall-run chinook salmon populations observed in the Stanislaus and Tuolumne rivers between 1940 and 1998.

Recruitment to the Stanislaus and Tuolumne rivers is strongly correlated with flow. The smolt survival studies conducted by the USFWS and DFG suggest that juvenile mortality rates are highest in the Old River and the mainstem San Joaquin River near Stockton between the head of the Old River and the mouth of the Mokelumne River. These studies also indicate that juvenile survival is strongly correlated with flow and water temperatures in the mainstem below the Old River, although fewer than 33% of the hatchery-reared smolts survive even at high flows. The cause of mortality in the reach between the Old River and the Mokelumne River is most likely either predation by black bass or striped bass or entrainment at unscreened diversions, because both would decline during high flows and both could impact juveniles during their relatively rapid migration through this reach. It is also possible that dredging the channel from a depth of 8-12 feet to a depth of about 35 feet to allow passage of ocean cargo ships to the Port of Stockton has worsened the problem.

The impact of Delta exports at the CVP and SWP facilities is difficult to separate from the impact of low flows in the Delta with the existing data although recruitment declined in the mid to late 1950s in apparent response to the commencement of exports. If exports do affect smolt survival, it must be primarily an indirect effect because entrainment at the pumping facilities has been negligible compared to the total number of juveniles migrating through the Delta. The percentage of CWT juveniles released at Mossdale, the lower Stanislaus River, or the lower Tuolumne River and recovered at the CVP and SWP pumping facilities in April and May ranged from 1.0% to 15% (mean 7.3%) between 1986 and 1992 when exports were high and flows were low (DFG, unpublished data) and presumably direct mortality rates would be less than half of the total percentage of fish recovered. From 1993 to 1998, when exports were low and flows were relatively high, indirect mortality at the CVP and SWP facilities averaged about 1% (range of 0 to 8%, DWR unpublished data). There are several mechanisms by which exports could indirectly result in the mortality of smolts: (1) redirecting migrating juveniles into the Old River or Clifton Court forebay where predation rates are probably high; (2) reducing flows in the main channel of the San Joaquin River between the Head of the Old River and the mouth of the Mokelumne River, and (3) increasing agricultural return flows, particularly from Mud and Salt Sloughs, to the San Joaquin River that contain pesticides, other contaminants, and raise water temperatures. The installation of a barrier at the head of the Old River substantially reduces the impacts of exports on juvenile salmon.

The reduction in the abundance of four-year-old fish that return to spawn due to high rates of ocean harvest undoubtedly reduces recruitment in many years by reducing the fecundity of the spawning population and by reducing the cleansing action that the large fish have on the spawning beds. Although poaching of adult fish prior to spawning occurs in all three San Joaquin tributaries, the rates must be inconsequential compared to legal harvest rates.

Mean recruitment to both the Stanislaus and Tuolumne rivers was slightly higher during cool, productive cycles of ocean conditions compared to warm, nonproductive cycles, as reflected by the PDO index. However, correlations with PDO were weak because the influence of streamflow was an overriding factor.

Instream gravel mining that primarily occurred during the 1930s and early 1940s, degraded spawning and rearing habitat, decreased invertebrate productivity, and increased predator abundance. Although it is impossible to quantify these impacts because escapement surveys began after most of the instream mining occurred, restoration of mined areas should improve recruitment. Restoring riffle habitat in the mined areas not only increases the amount of spawning and rearing habitat, but also reduces predation. Observations by fishing guides familiar with all three tributaries suggest that restoration of the long stretches of 4-10 foot deep channel would provide the greatest reduction in predation compared to restoration of the large deep pits. The long stretches of deep channel provide habitat for numerous Sacramento pikeminnow which feed on both fry and smolts of both chinook salmon and steelhead whereas the large pits provide habitat for relatively few largemouth bass and striped bass which primarily begin feeding after water temperatures increase and smolts are migrating. On the other hand, restoration of the large deep pits, which are typically filled with fines that are mobilized during high flows, should help improve spawning habitat and increase invertebrate productivity.

Other relatively recent factors that may be significant sources of mortality are (1) sedimentation from the construction of new housing which is rapidly increasing along the Stanislaus River corridor; (2) encroachment of riparian vegetation on floodplains as a result of flattened hydrographs; (3) exports during the fall when adults are migrating through the Delta; (4) contaminants; and (5) disease. The turbidity of storm runoff has increased substantially in the Stanislaus River probably in response to a rapid increase in new housing construction in recent years. Spawning habitat is severely degraded in the Stanislaus and Tuolumne rivers and probably in the Merced River as well and sedimentation and the lack of high flows and functional floodplains to help remove fines from spawning habitat are continuing to degrade the habitat. Furthermore, it is highly likely that food production is also limited by the highly compacted nature of the mined streambeds. A future concern is that there are plans to increase the capacity of the Delta pumping facilities and high rates of pumping during the fall can cause adult chinook salmon to stray. Contaminants and disease may be limiting the salmon populations, but further research is needed.

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