Population Trends and Escapement Estimation of Mokelumne River Fall-run Chinook Salmon (*Oncorhynchus tshawytscha*)

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Abstract

In 1990 the East Bay Municipal Utility District (EBMUD) began a program to monitor the fall-run chinook salmon (*Oncorhynchus tshawytscha*) populations in the lower Mokelumne River using video and trapping at Woodbridge Dam and weekly redd surveys.

Over the eight years of this monitoring program, the Mokelumne River fall-run chinook salmon escapement showed a trend of increased abundance of both hatchery and natural spawners. The 1997 estimated total spawning escapement (combined hatchery and natural run) was 10,175 compared to a spawning escapement of 497 in 1990 and the 57-year average escapement of 3,434 fish. The estimated natural spawning population fluctuated from a low of 369 in 1991 to a high of 3,892 fish (1,739.3 ± 1,384.9) in 1996. The percentage of natural spawners ranged between 31% to 90% (52.3 ± 19.9) of the total spawning escapement during the 1991–1997 period.

Significant correlations were observed between the number of redds and total escapement (R^2 = 0.941, P < 0.0001) and the hatchery returns and total spawning escapement (R^2 = 0.972, P < 0.001). The later correlation was used to determine the accuracy of past spawning escapement estimates based upon a similar correlation using a narrower dataset.

These results suggest accurate total spawning escapement estimates can be obtained from hatchery returns and from redd counts. Escapement estimates calculated from redd counts and compared with known estimates were accurate in the mid-range while those calculated from hatchery returns were accurate throughout the range of run sizes.

Introduction

East Bay Municipal Utility District (EBMUD) began daily monitoring of the fall-run chinook salmon (*Oncorhynchus tshawytscha*) population in the lower Mokelumne River in 1990. The focus of the monitoring was to document the timing and magnitude of adult salmon upstream migration and the number and distribution of salmon redds on the upstream spawning grounds.

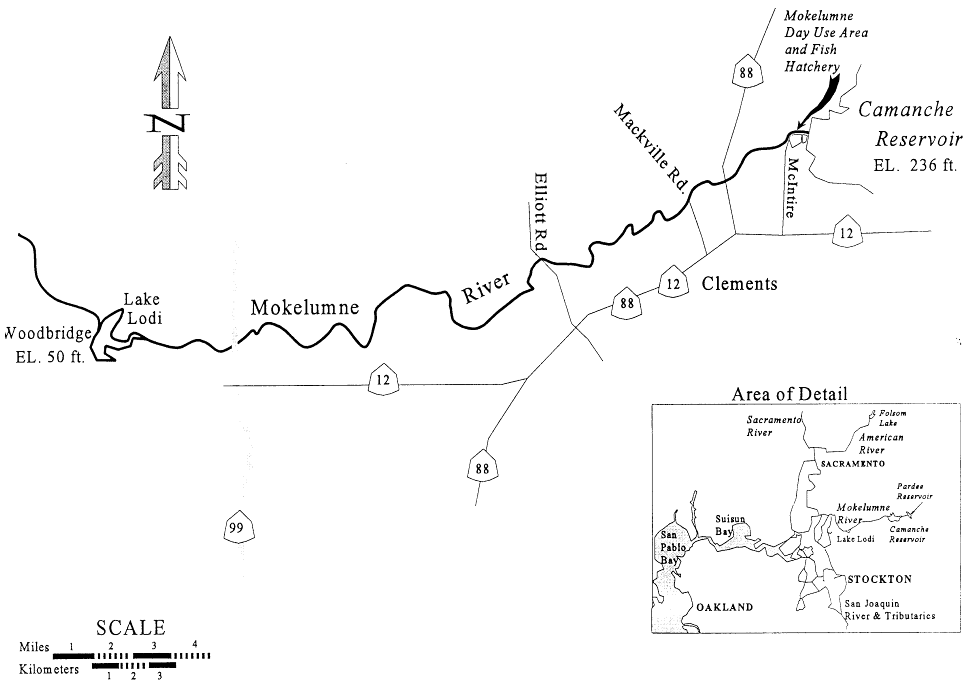

Figure 1 The Lower Mokelumne River between Camanche Dam and Woodbridge Dam, San Joaquin County, California

The Mokelumne River originates in the Sierra Nevada mountains at the Sierra Crest and flows through the Central Valley near the towns of Lockeford, Clements, and Lodi before entering the Delta forks of the Mokelumne just downstream of the Delta Cross Channel (Figure 1). The Mokelumne River watershed drains some 627 square miles. The average annual unimpaired runoff is 720,000 acre-feet with a range of 129,000 to 1.8 million acre-feet. The Mokelumne River watershed has a number of dams and reservoirs. In the upper watershed, Pacific Gas & Electric operates 19 dams, seven storage reservoirs, seven diversions, three regulating reservoirs and two forebays (FEIS 1993). Pardee Dam and Reservoir (river mile 39.6) is owned and operated by EBMUD to provide water for 1.2 million customers in Alameda and Contra Costa counties (EBMUD 1992). The reservoir also provides flood control storage, maintenance of the Camanche Reservoir hypolimnion, and water-based recreational opportunities including both coldwater and warmwater fisheries. Camanche Dam and Reservoir, completed by EBMUD in 1964, provides storage for flood control operations, water to meet agricultural and senior water rights, instream flows for fish needs and a number of water-based recreational opportunities. Camanche Dam (river mile 29.6) represents the upstream limit for anadromous salmonid migration. Historically, salmon and steelhead used the habitat to within one-half mile below Pardee Dam where a natural barrier existed at the Arkansas Ferry Crossing, a distance of some eight and one-half miles above Camanche Dam (EBMUD 1992).

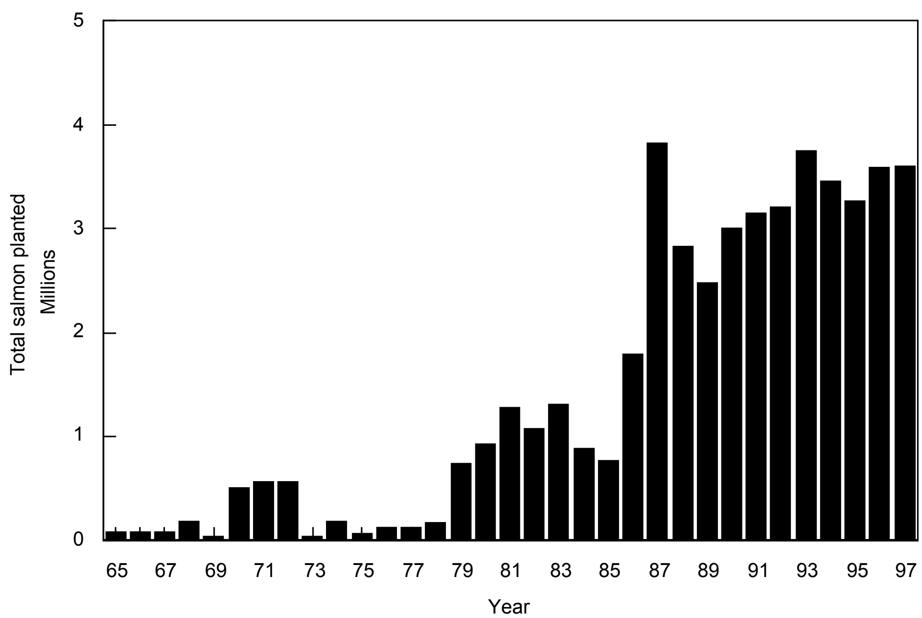

Figure 2 Mokelumne River Fish Hatchery production, 1965–1997. Source: Data from DFG reports. DFG corrections may have modified some previously reported yearly data.

To mitigate for lost habitat above Camanche Dam, the Mokelumne River Fish Hatchery was constructed in 1964 to produce both fall-run chinook salmon and steelhead trout (*Oncorhynchus mykiss*) (EBMUD 1992). Average production from the facility during the 1990s was 3.0 to 4.0 million fall-run chinook salmon smolts, 500,000 yearling chinook salmon, and 100,000 yearling steelhead (Figure 2). The source of most of the salmon broodstock was Feather River Hatchery fish. Two million salmon were raised to post-smolts each year for an ocean enhancement program. All of the enhancement salmon production was trucked around the Delta for release in San Pablo Bay (Figure 3). Salmon smolts that were Mokelumne origin fish were planted below Woodbridge Dam. In 1992 and 1993, yearling chinook salmon were planted in the

Mokelumne Day Use Area adjacent to the Mokelumne River Fish Hatchery just downstream of Camanche Dam (see Figure 1). After 1994, yearlings were released below Woodbridge Dam. During drought years, naturally produced juvenile salmon were collected at Woodbridge Dam and trucked around the Delta for release at Rio Vista or Carquinez (see Figure 1) (Bianchi and others 1992).

Woodbridge Dam spans the lower Mokelumne River near the City of Lodi and the town of Woodbridge (see Figure 2). Each year in March, flashboards are installed in the dam to create Lake Lodi and raise the water surface elevation to operate the Woodbridge Irrigation District diversion canal. Following the end of the irrigation season in late October or early November, the flashboards are removed to empty Lake Lodi. Fish passage past the dam under either mode of operation is provided by a pool-and-weir system that includes high-stage and low-stage fish ladders. The fish ladders provide a unique opportunity to obtain complete counts of fall-run chinook salmon passing Woodbridge Dam under nearly all flow and operating conditions.

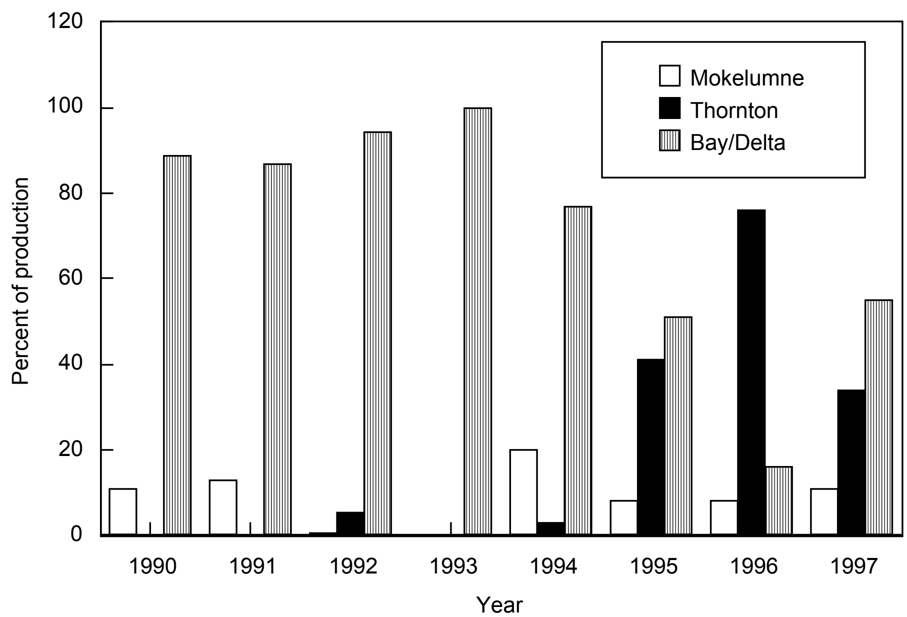

Figure 3 Release locations of Mokelumne River Fish Hatchery chinook salmon production 1990–1997. Production includes smolts, post-smolts, and yearlings. Source: Data from DFG annual reports.

Objectives

Daily video and trap monitoring at Woodbridge Dam provided a new, more reliable method to obtain salmon spawning escapement in the lower Mokelumne River. One of the objectives of this study was to compare results from this monitoring program to historical escapement estimators. These historical estimators are based on linear regression of hatchery return and estimated annual spawning escapement derived from carcass surveys.

Another objective of this study was to determine if alternate methods could be used to estimate spawning escapement based on the 1990–1997 dataset. The statistical relationships between the number of redds and total spawning escapement, and hatchery returns and total spawning escapement were examined for this purpose.

Methods

Escapement Estimation

From 1940 to 1990, the California Department of Fish and Game (DFG) estimated and/or counted the numbers of chinook salmon migrating upstream to spawn in the lower Mokelumne River. Several methods have been used to estimate spawning escapement (Table 1). These methods included carcass surveys of spawning grounds as well as projections of the natural run using linear regression equations based on the relationship between numbers of hatchery and natural spawners. Direct counting methods included observations of the number of salmon ascending the fish ladders at Woodbridge Dam (Fry 1961).

Table 1 Mokelumne River stock estimates

Period of sampling	*Sampling method*
1940 – 1942, 1945	Visual count at Woodbridge
1943, 1944, 1946, 1947	No estimate
1948 – 1971	Visual count at Woodbridge
1972 – 1981	Carcass survey
1982, 1983	Regression
1984 – 1990	Carcass survey
1990 – 1997	Video and trap monitoring

In 1990, a video and trap monitoring system was installed by EBMUD in both the upper and lower ladders of Woodbridge Dam. An overhead video camera was mounted in the high-stage fish ladder, and a waterproof enclosure housing a camera mounted for a side view was installed in the low-stage fish ladder. Both video cameras shot footage against a 1.2 m^2 plywood backboard covered with a white plastic sheet and marked with black grid lines spaced five centimeters apart. Four 150-watt flood lamps mounted above the water surface illuminated the backboard. Video camera recording was conducted 24 hours per day, seven days per week, throughout the fall upstream migration. The tapes were reviewed and count data were recorded. The start date of the video monitoring varied between 1 September and 26 October and the ending date each year was 31 December, except for 1997 when high flows ended operations on 10 December.

The sex ratios and age composition of the salmon spawning escapement at Woodbridge Dam were determined by reviewing the videotapes from the underwater camera in the low-stage fishway and collecting data from trapped fish. Sex ratios and age composition of hatchery fish were obtained from DFG Mokelumne River Fish Hatchery personnel.

Upstream migrant traps were installed each year between 1990 and 1997 and operated in the Woodbridge low-stage fishway in pool 8a (Figure 4). The traps were checked two to four times per day, depending on the number of fish captured. The two primary trap checks were one-half hour before sunrise and one-half hour after sunset. The traps were operated intermittently to verify results from the video monitoring program or when highly turbid conditions precluded the use of video cameras.

For a complete description of the video equipment, setup of the video monitoring stations, trap equipment and operations protocol see Bianchi and others (1992) and Marine and Vogel (1996).

Physical and environmental data collected included river flow, river temperatures from Campbell recorders at each gauging station and from a Ryan RTM 2000 thermograph in pool 6a of the Woodbridge low stage fishway (see Figure 4), National Weather Service data on barometric pressure from Stockton and local watershed precipitation from Camanche Dam, and water transparency measured by Secchi disk from pool 9a or from the left abutment of Woodbridge Dam (Marine and Vogel 1996).

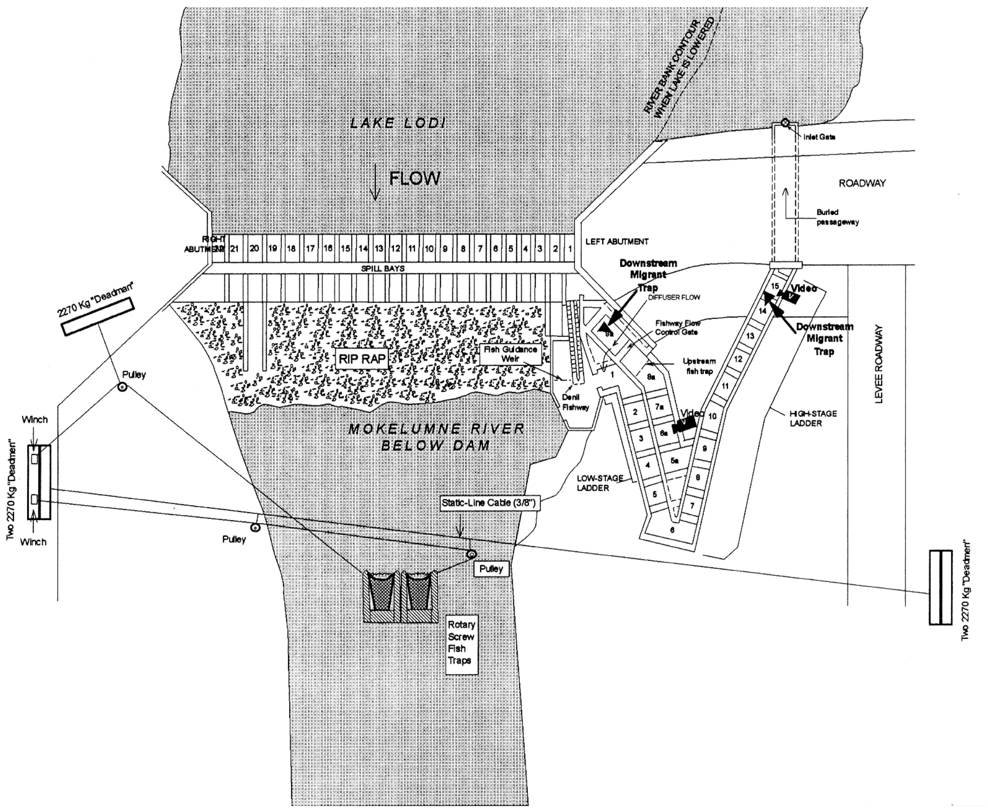

Figure 4 Plan view of Woodbridge Dam showing video monitoring sites and location of upstream migrant fish trap

The percentage composition of grilse and adult salmon in the run was based on a length criterion. A fork length of 61 cm was used to separate grilse from adults. Marine (1997) found this length to be conservative criterion for Mokelumne coded wire tagged hatchery fish recovered in Central Valley streams and hatcheries during 1992–1995. Using this criterion, Marine (1997) found that 20% of the two-year-old fish were greater than 61 cm and 5% of the three-year-old fish were less than 61 cm. The Mokelumne River Fish Hatchery used the 61-cm criterion, except in 1993 when a large number of grilse (57%) returned to the hatchery and the criterion was increased to 65 cm (Marine and Vogel 1994).

Salmon Redd Abundance Analysis

Salmon redd surveys were conducted weekly in the lower Mokelumne River from 1990 to 1997 (Hagar 1991; Hartwell 1996; Setka 1997). The surveys typically began in early to late October and ended the first week in January, except in 1996 when flood flows ended the surveys on 3 December. For recording the distribution of salmon redds, the lower Mokelumne River was divided into three reaches (Reach A: Camanche Dam to Highway 88, Reach B: Highway 88 to Mackville Road, and Reach C: Mackville Road to Elliott Road.) (Figure 5). The surveys involved teams of three biologists canoeing or boating and wading down the river in search of redds. Each redd was marked with a fluorescent colored brick and assigned a unique number. During the surveys, data were also collected on redd characteristics including the redd size, water depth, velocity, habitat characteristics, degree of redd superimposition, and usage of prior gravel enhancement sites. The different levels of redd superimposition were based upon the degree of overlap between adjacent estimated redd egg pockets and tail-spills (Hartwell 1996). Habitat types were characterized according to a modified Bisson system (Bisson and others 1981) and included glide, riffle, riffle-glide complex, side-channel glide, and side-channel riffle.

Physical and environmental data collected included water temperature, dissolved oxygen, and stream flow. Water temperatures were collected using hand held thermometers and Campbell data loggers at EBMUD gauging stations (see Figure 5). Total Camanche Dam and powerhouse releases were combined to determine streamflow in the spawning reaches (Hartwell 1996; Setka 1997).

To evaluate alternate methods for determining spawning escapements, linear regression equations were computed for the hatchery return and total escapement past Woodbridge Dam, hatchery return and natural spawning escapement, and total number of redds and total escapement.

The escapement at Woodbridge Dam includes both hatchery and naturally spawning fish. The natural spawning escapement estimate was derived by subtracting the hatchery fish return from the total escapement.

Results

Escapement Estimation

During the first year of the video and trap operations in 1990, the counts at Woodbridge Dam were compared with the DFG escapement estimate based upon the carcass survey. The results showed that substantially more salmon passed Woodbridge Dam than estimated by DFG using carcass survey data (497 actual count compared to 64 from carcass survey estimator) (Bianchi and others 1992). Because the accuracy of the carcass surveys was influenced negatively by environmental conditions such as streamflow and turbidity, DFG discontinued the carcass surveys on the lower Mokelumne River in favor of the more reliable daily video and trap monitoring.

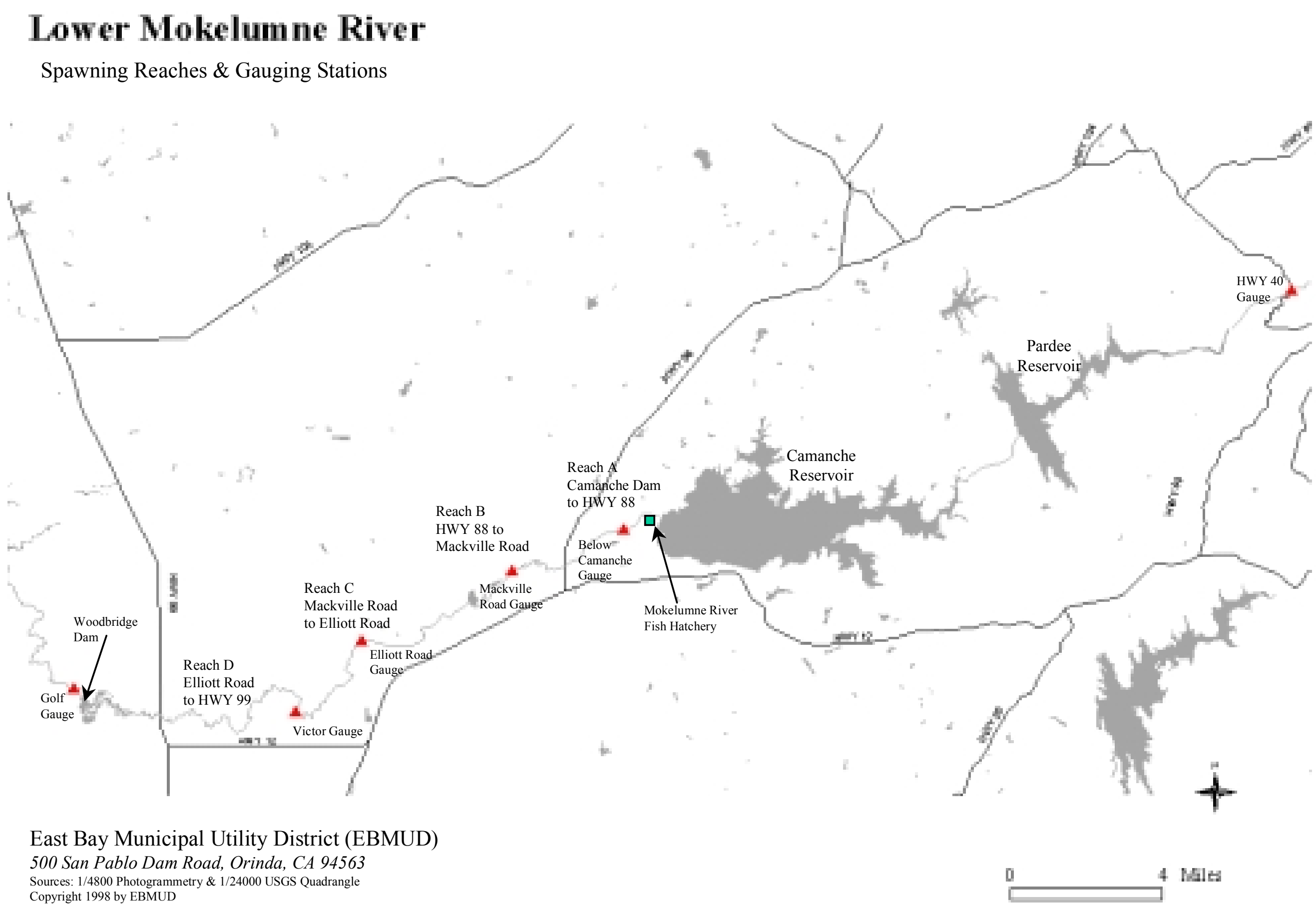

Figure 5 Location of US Geological Survey and EBMUD gauging stations

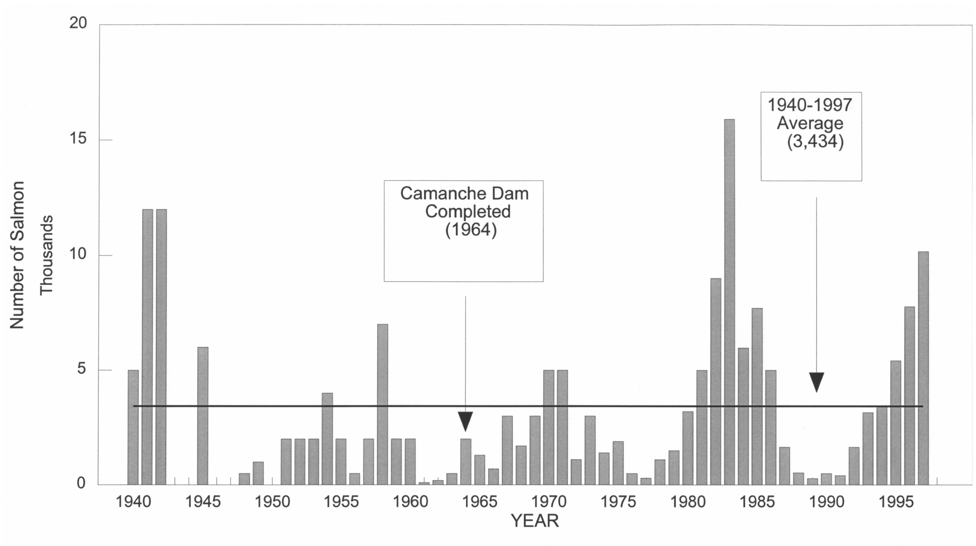

Figure 6 Lower Mokelumne River fall-run chinook salmon escapement, 1940–1997. Source: Data are from DFG, Biosystems, and NRS, Inc. Monitoring of salmon escapement in 1996 was discontinued early (on December 10, 1996) due to high flows. No data were collected in 1943, 1944, 1946, 1947, and 1950. Calculated from the average of the salmon escapement values from 1940 to 1997, excluding 1943, 1944, 1946, 1947, and 1950.

The estimated annual spawning escapement of fall-run chinook salmon over the 57-year period of record is shown in Figure 6. Estimates of spawning escapement during this period have varied from 100 fish in 1961 to 15,900 fish in 1983 (average = 3,434). The 1983 count was based upon an estimate projected from the regression between the hatchery returns and total escapement (Meinz 1983). This regression was based on hatchery return numbers ranging from 17 to 1,386 (average = 463). Over the course of the daily video and trap monitoring (1990 to 1997), the counts of fall-run chinook salmon have ranged between 410 and 10,175 fish (average = 4,062) (Marine 1997). So, the average spawning escapement estimated from 1940 to 1989 was 3,434 fish and average escapement counted by video trap and monitoring from 1990 to 1997 was 4,062.

During the daily video and trap monitoring at Woodbridge Dam (1990 to 1997), the percentage of total spawners ranged between 31% and 90%, with an average of 52.3% (Figure 7).

Adult salmon migrating into the lower Mokelumne River are primarily two- and three-year-old fish. The percentage of grilse in the spawning run has been highly variable, ranging between 7% and 57% over the eight-year monitoring period with an average of 26.8% (Figure 8) (Marine 1997).

The sex ratio of adult salmon counted at Woodbridge Dam over the 1990–1997 period varied between 46% and 57% female with an average of 50.4%. For the Mokelumne River Fish Hatchery, the sex ratio of adult fish varied between 33% and 53% females with an average of 44.9%.

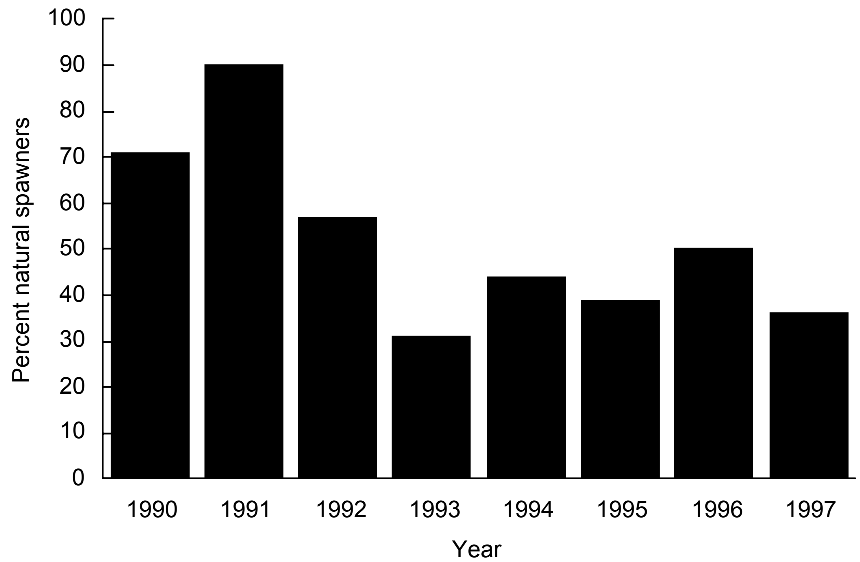

Figure 7 Percent of fall-run chinook salmon spawning naturally in the lower Mokelumne River. Source: Data from Biosystems and NRS, Inc. taken at WID.

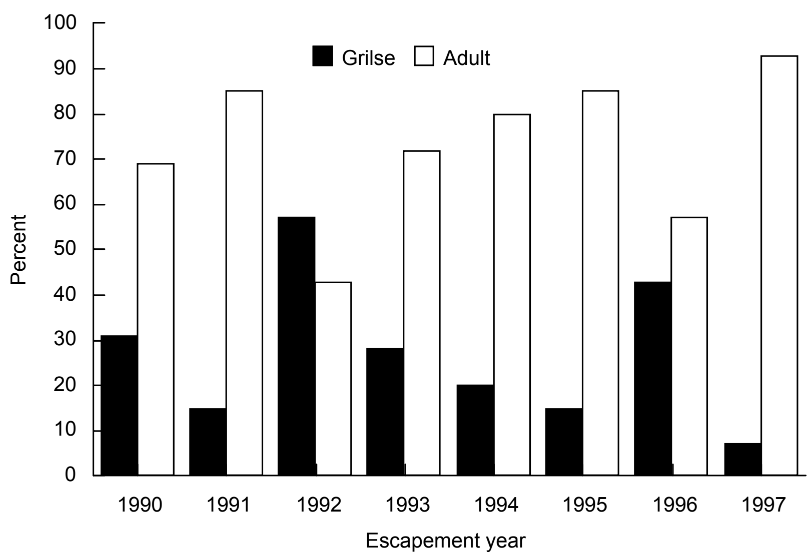

Figure 8 Percent of fall-run chinook salmon passing Woodbridge Dam that are grilse, 1990–1997

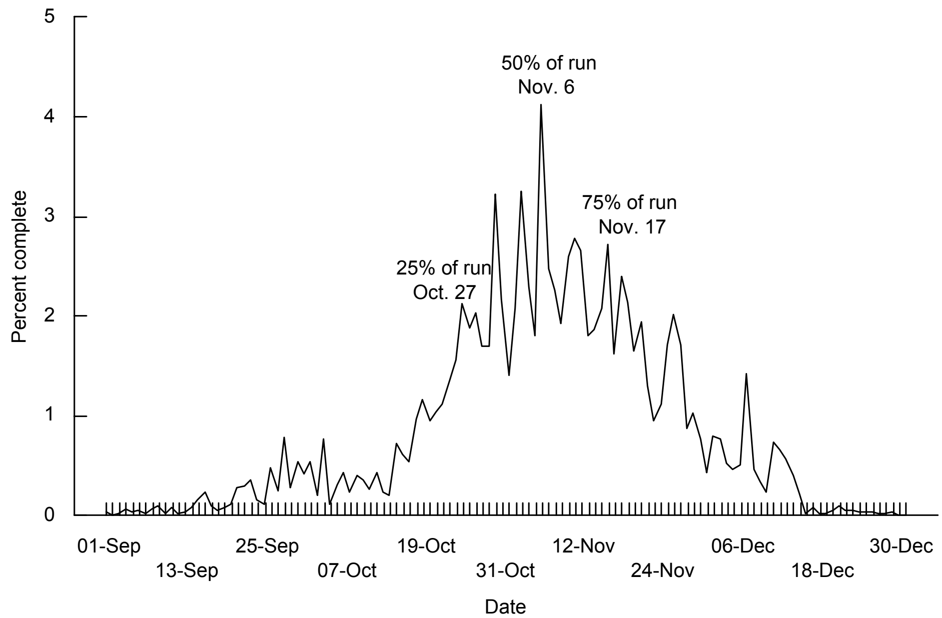

Figure 9 Daily average percent of fall-run chinook salmon escapement in the lower Mokelumne River, 1990–1997

The duration of the salmon run has expanded with increases in salmon spawning escapement from 1990 to 1997. Video and trap monitoring at Woodbridge Dam initially began in October, but was started in early September beginning in 1995 as spawning escapement increased. Except for 1996, when high flood flows ended monitoring on 3 December, the video and trap monitoring ended on 31 December of each year (Bianchi and others 1992; Marine and Vogel 1996; Marine 1997). The mean dates for the 10%, 50%, and 90% completion of the average upstream migration run timing were 27 October, 6 November, and 17 November, respectively. The average daily percentage of adult salmon migration past Woodbridge Dam from 1990 to 1997 show a peak in late October to mid-November (Figure 9).

Salmon Redd Abundance Analysis

Redd surveys show that chinook salmon use all three reaches from Camanche Dam to Elliott Road for spawning (Figure 10). The years with the greatest percentage of redds constructed in Reach A occurred during the highest spawning escapements (Hartwell 1996; Setka 1997).

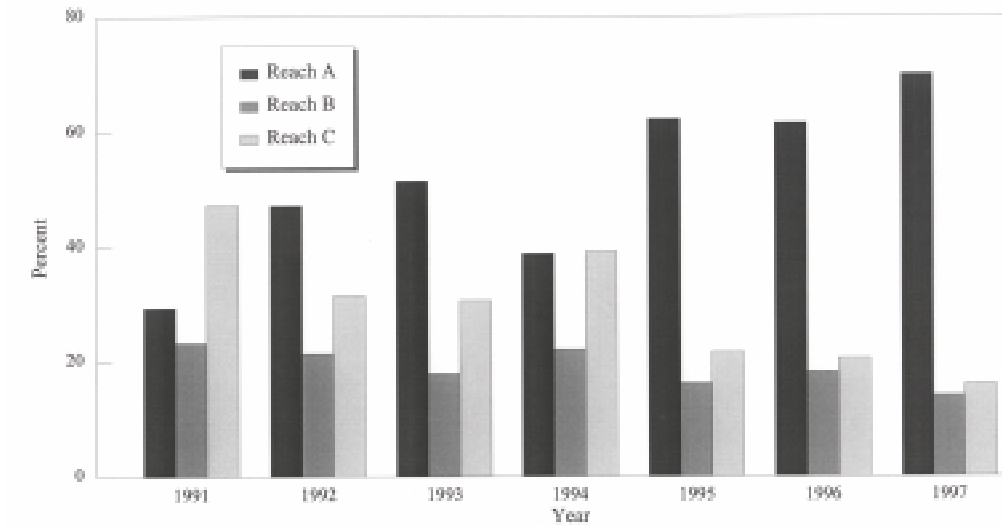

Figure 10 Lower Mokelumne River fall-run chinook salmon redd construction by reach, 1991–1997

The salmon redds in the lower Mokelumne River during the monitoring period increased from 71 redds in 1990 to 1,316 in 1997. The 1996 estimate of 1,284 redds is a projection based on the average percentage of redds completed on 3 December (the last date of the partial redd survey), from 1991–1995 (Setka 1997). The peak redd construction activity occurred from early November to mid-December.

The amount of redd superimposition increased with increased spawning escapement and ranged between 3% and 17%. There was a dramatic increase in redd superimposition from 3% in 1993 to 14% in 1994 (Hartwell 1996). Natural spawning escapement between these years increased from 993 to 1,503 fish (Figure 11). Between 1991 and 1997 no distinct relationship was evident between redd superimposition and other factors such as flow, temperature, or number of in-river females (Hartwell 1996; Setka 1997).

The relationship between the number of redds constructed and total escapement by linear regression (R^2 = 0.941, P < 0.0001) is shown in Figure 12. The database used to generate the linear regressions includes a range of salmon redds from 71 to 1,316 and total spawning escapements based upon video and trap counts of 410 to 10,175 salmon. The ratio of female spawners to redds during the study period ranged between 0.9:1 to a high of 2.3:1. The highest ratios were obtained at both lowest and highest spawning escapements during the study period (Figure 13).

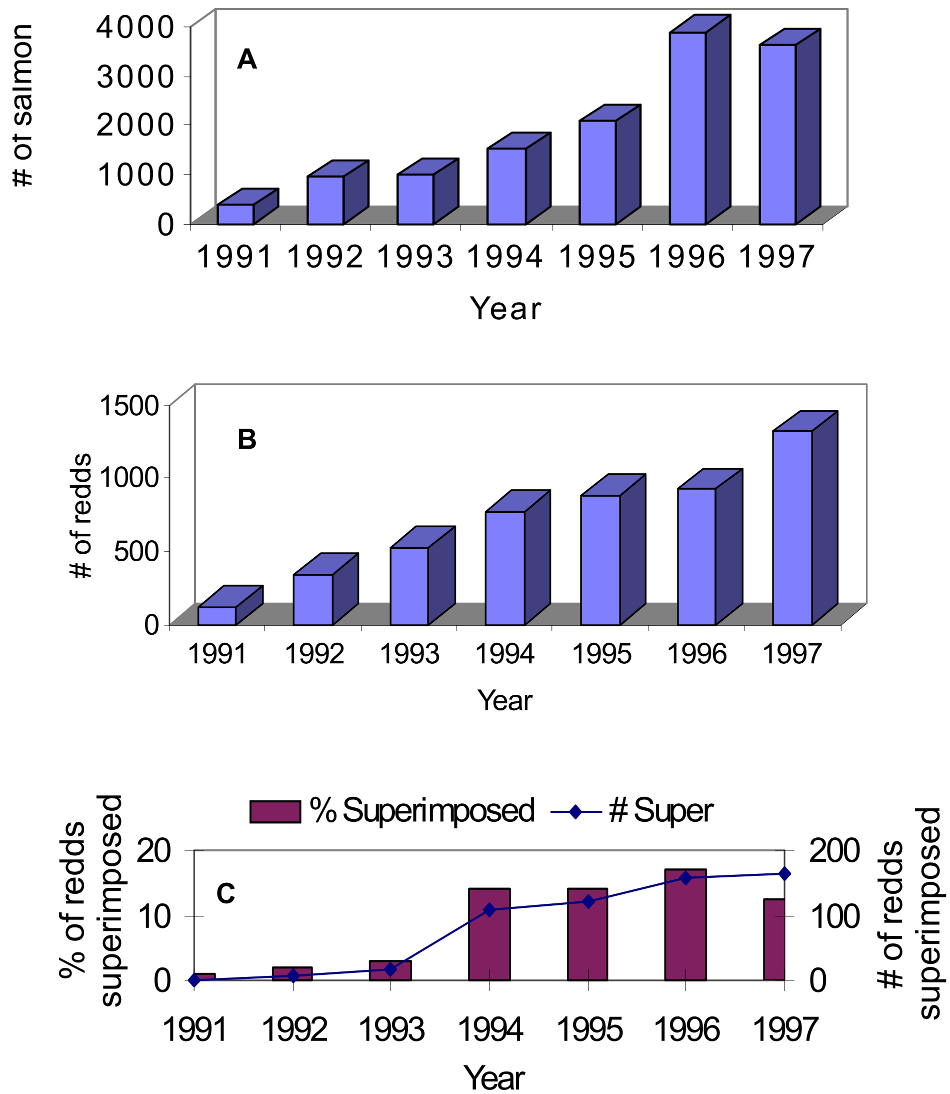

Figure 11 Comparison of salmon redd superimposition with spawning escapement, 1991–1997: (A) number of in-river spawners in Mokelumne River; (B) number of redds constructed per year in Mokelumne River; (C) percent and number of superimposed redds in Mokelumne River.

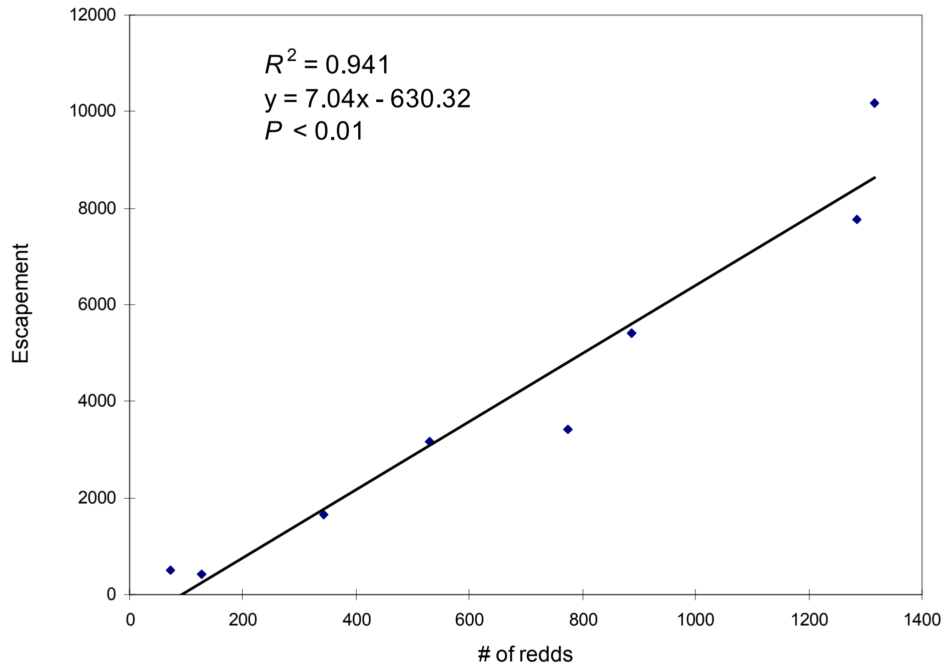

Figure 12 Linear regression of Mokelumne River total escapement compared with number of redds constructed, 1990–1997

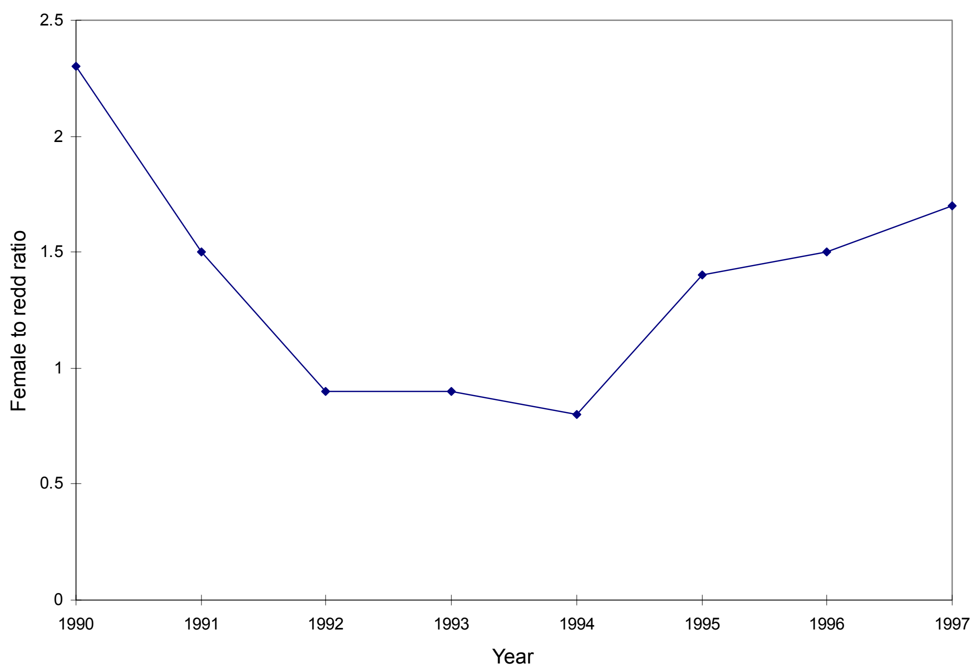

Figure 13 Female to redd ratio, 1990–1997

Discussion

Escapement Estimates

From 1972 to 1990 (with the exception of 1982 and 1983), DFG estimated the total salmon spawning escapement in the lower Mokelumne River from carcass survey recovery data. The recovery rates of marked carcasses were used to calculate the total number of spawners. The recovery rates ranged between 0% and 25%. In one-half of their surveys, DFG used the recovery rate for carcasses in the lower Mokelumne River. In 1976 and 1979, a rate of 20% was used when no carcasses were recovered. The 20% rate was based upon the average historic recovery rate for Sacramento River systems (DFG 1978). In 1990, DFG and EBMUD biologists conducted five carcass surveys between Camanche Dam and the Mackville Road Bridge (Reaches A and B). During the surveys, three carcasses were found including one grilse. The two adult carcasses were tagged and released and only one tagged carcass was recovered in subsequent surveys, resulting in a 50% recovery rate. Based upon this recovery rate, the 1990 spawning escapement estimate including 64 hatchery fish was 70 salmon (Fjelstad 1991). The daily count at Woodbridge Dam in 1990 totaled 497 fish.

One limitation of the 1990 carcass survey was that the survey was only conducted from Camanche Dam to Mackville Road. The shortened survey reach in 1990 may have contributed to the low spawning escapement estimate. Subsequent redd surveys conducted by EBMUD have shown that as many as 47% of the salmon redds are constructed below Mackville Road during low escapement years (Hartwell 1993). If as for 1976 and 1979, a Sacramento River system 20% recovery rate is used, the resulting escapement estimate of 94 salmon would still fall short of the total number counted at Woodbridge Dam.

During 1982 and 1983, Camanche flood control releases in excess of 2,000 cfs made it impossible to conduct carcass surveys (DFG 1986). The spawning escapement during these years was estimated using a statistical relationship between the number of salmon entering the Mokelumne River Fish Hatchery and the spawning escapement estimate from carcass survey data. A linear regression was established using data from the 1972 to 1981 runs (1977 was excluded because the ladder to the fish hatchery was closed). The 1982 and 1983 estimates were generated by extrapolating the hatchery returns to the regression line to obtain an estimate of total escapement (Meinz 1983; Figure 14). This methodology resulted in two of the highest spawning escapement estimates for the lower Mokelumne River (9,000 fish for 1982 and 15,866 for 1983). The hatchery returns for these years of 2,677 and 4,573 fish respectively were outside the range of the 1972 to 1981 database. In addition, the spawning stock estimates from carcass surveys used to generate the linear relationship may have been low because of the use of incomplete surveys in some of the years during the base period.

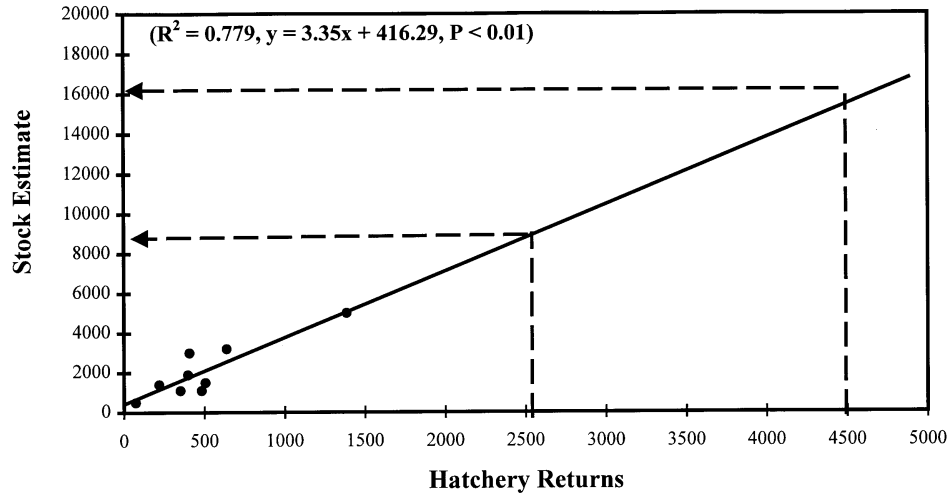

Figure 14 Mokelumne River stock estimates compared with hatchery returns, 1972–1981. 1997 data are omitted because no hatchery returns were reported.

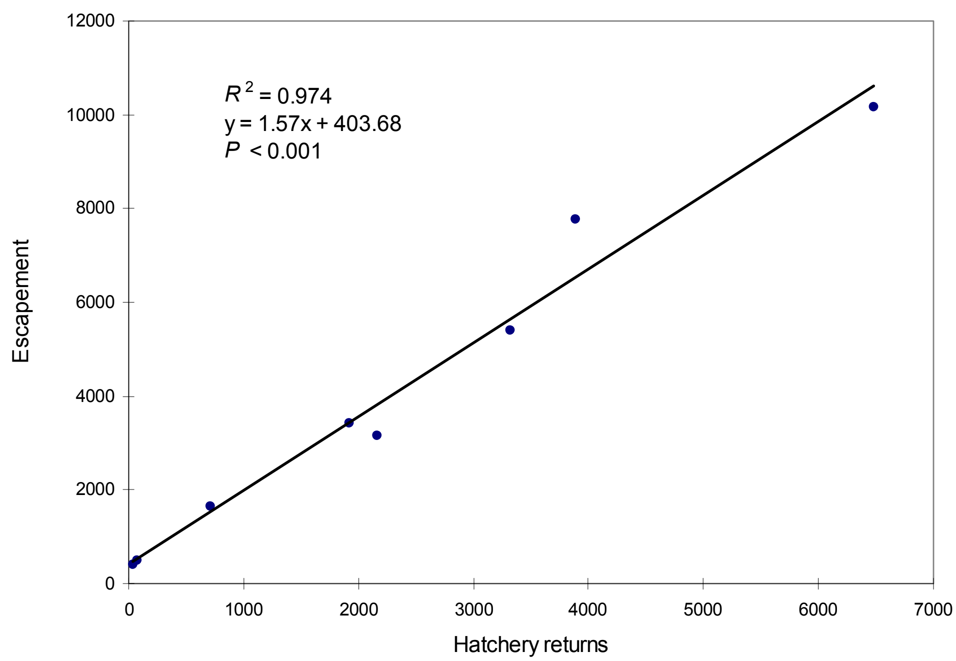

Figure 15 Linear regression of Mokelumne River escapement compared with hatchery returns, 1990–1997

Using the salmon spawning escapement data collected in the 1990–1997 monitoring program, a highly significant positive linear regression is obtained ($R^2 = 0.972$, $P < 0.001$) for the relationship between the number of salmon entering the Mokelumne River Fish Hatchery and the total spawning escapement (Figure 15). The Mokelumne River Fish Hatchery fish returns during this period ranged from 41 to 6,408 (DFG 1998). Using this relationship produces a spawning escapement estimate for 1982 of 4,590 and for 1983 of 7,548 (Table 2).

Table 2 1982 and 1983 spawning

Year	*Hatchery return*	*DFG regression estimate*	*1991–1997 regression equation estimate*
1982	2,677	9,000	4,590
1983	4,573	15,866	7,548

Salmon Redd Abundance Analysis

Fjelstad (1991) suggested that observations of the number of salmon redds could be used to generate a broad estimate of run size. Using the data collected in this monitoring program, the highly significant statistical relationship that was found between the number of redds and total escapement (see Figure 12) confirms this suggestion. This relationship regresses one empirical number on another, and because these values represent both the entire population and all salmon spawning in the river, includes spawning grilse in the estimation. Predictions of total escapement based on this relationship produces reasonable estimates at escapements in the 1,000 to 8,000 range. Multiple redds constructed by a single female, multiple superimpositions, and multiple female redds are all factors that may reduce the accuracy of these predictions. Linear regressions using redd counts and hatchery returns both provide reasonable estimates of the spawning escapements for the lower Mokelumne River (Table 3). The linear regression using hatchery returns provides the better estimate at both high and low levels of spawning escapement within the range of the database. Whether this relationship holds up in the future may depend upon the response of the natural population to habitat improvements or changes in the operation of future fish hatchery programs such as stocking levels, release locations or source of broodstock.

Table 3 Mokelumne River fall-run chinook salmon escapement, 1990–1997

Year	Number of redds	Hatchery returns	Natural spawners	Escapement (WID)	Predicted escapement [a]	Predicted escapement [b]
1990–1991	71	68	429	497	–131	511
1991–1992	127	41	369	410	264	468
1992–1993	343	711	934	1,645	1,784	1,523
1993–1994	530	2,164	993	3,157	3,100	3,810
1994–1995	774	1,918	1,503	3,421	4,817	3,422
1995–1996	888	3,323	2,094	5,417	5,620	5,634
1996–1997	1,284[c]	3,883	3,892	7,775	8,407	6,516
1997–1998	1,316	6,485	3,624	10,175	8,633	10,612

[a] Based on redds.

[b] Based on hatchery returns.

[c] 929 redds were observed through the first week of December 1996 when redd surveys were discontinued due to high flows. The value of 1,284 (±8.1%) is an estimate based on total 1992-1995 end-of-run average added to the observed number.

Acknowledgements

We thank the following people: Keith Marine for providing the size-at-age analysis to the Mokelumne River Technical Advisory Committee; EBMUD biologists Joe Merz and Jim Smith for their review of the draft; redd survey team leader Jose Setka, Bert Mulchaey, Christine Tam and the balance of the EBMUD Fisheries and Wildlife staff for accurate data and long hours in the field; the Natural Resource Scientists staff for producing reliable video and trap counts; and Jim Dunne, Bert Mulchey, and Christine Tam for data management and graphics production.

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