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The Use of Smolt Survival Estimates to Quantify the Effects of Habitat Changes on Salmonid Stocks in the Sacramento–San Joaquin Rivers, California

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Pages 100–115

Reprinted from

Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks

Edited by C. D. Levings, L. B. Holtby, and M. A. Henderson

Canadian Special Publication of Fisheries and Aquatic Sciences 105

Fisheries and Oceans | Pêches et Océans

Canada

PRINTED IN CANADA

The Use of Smolt Survival Estimates To Quantify the Effects of Habitat Changes On Salmonid Stocks in the Sacramento-San Joaquin Rivers, California

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Abstract

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Mark–recapture studies of smolt survival in the Sacramento–San Joaquin Delta of California provides empirical data on the effects of water development on fall-run chinook salmon (*Oncorhynchus tshawytscha*). Recoveries of coded-wire tagged hatchery fish from the ocean troll fishery and estuarine trawling yielded two survival measures that were positively correlated (r=0.90). Smolt survival from both measures were highly correlated to river flow, temperature, and percent diversion. Survival of fish exposed to diversion was about 50 % less than those not exposed. Study designs to quantify the independent effects of temperature on survival and the survival of wild smolts are presented. Survival results are being used to evaluate estuarine flow standards governing state and federal water project operations and other salmon protective measures. Regressions of survival and flow applied to simulated historical flows at varied levels of water development indicated estuarine survival has decreased a minimum of 30 % in the past 70 yr. Spawner escapements in the Central Valley are positively correlated to flow during their spring smolt outmigration suggesting that flow alterations in upstream and estuarine habitats at that time influences adult stock production.

Résumé

KJELSON, M. A., AND P. L. BRANDES. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento–San Joaquin rivers, California, p. 100–115. *In* C. D. Levings, L. B. Holtby, and M. A. Henderson [ed.] Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks. Can. Spec. Publ. Fish. Aquat. Sci. 105.

Les études de marquage–recapture réalisées afin de déterminer le taux de survie des smolts dans le delta de Sacramento-San Joaquin, en Californie, fournissent des données empiriques sur les effets de la mise en valeur des ressources en eau sur la remontée des saumons quinnats (*Oncorhynchus tshawytscha*) à l'automne. La récupération des poissons d'élevage marqués au moyen de fil de fer codé dans la zone de pêche à la traîne en mer et dans la zone de pêche au chalut en estuaire a abouti à des taux de survie présentant une corrélation positive (r = 0,90). Une étroite corrélation a été établie entre, d'une part, les taux de survie des smolts dans les deux zones de pêche et, d'autre part, les taux de survie des smolts dans les zones de pêche et, d'autre part, le débit du cours d'eau, la température et le volume d'eau détourné. Le taux de survie des poissons exposés à des ouvrages de dérivation était inférieur à celui des poissons non exposés dans une proportion d'environ 50 %. On présente des plans d'étude destinés à quantifier les effets distincts de la température sur les taux de survie et les taux de survie des smoltssauvages. Les résultats servent à évaluer les normes relatives aux débits en estuaire auxquelles sont assujettis les projets de mise en valeur des eaux des États et du gouvernement fédéral et d'autres mesures de protection des saumons. Les coefficients de régression des taux de survie et du débit appliqués à des débits historiques simulés en fonction de divers degrés de mise en valeur des ressources en eau ont révélé que la survie en estuaire a diminué de 30 % au minimum au cours des 70 dernières années. Il existe une corrélation positive entre les échappées de géniteurs dans la vallée Central et le débit des eaux au cours de la dévalaison des smolts au printemps, ce qui laisse supposer que les modifications du débit dans les habitats d'amont et en estuaire pendant cette période influent sur la production des stocks d'adultes.

Introduction

Documenting effects of habitat alterations on salmonid stocks is difficult because each life stage is exposed to varied environmental conditions. Measurement biases and imprecision of estimates also contribute to this problem. Thus quantifying factors affecting adult population levels is often troublesome.

Mark/recapture experiments provide opportunity to measure effects of specific environmental conditions on survival. This eliminates the need to base evaluations on abundance changes which may reflect earlier environmental conditions or population levels (Stevens and Miller 1983). Evaluating factors influencing smolt survival afford a more direct means to assess habitat alteration/stock effects. In the absence of subsequent density dependent mortality (Junge 1970) these factors would directly affect the ocean recruitment and escapement.

Results of our studies on the survival of fall-run chinook salmon, *Oncorhynchus tshawytscha*, during their spring outmigration through the Sacramento–San Joaquin Estuary of California (Fig. 1) provides empirical ata on the effects of water development activities that ve changed the magnitude, distribution and timing of er flows. This work is part of the Interagency Eco- ical Study Program designed to document the needs stuarine fishes, the impacts of water project diver- s from the delta and the means to better protect fish wildlife resources. Agencies within that program le the California Departments of Fish and Game, Resources, the State Water Resources Control the U.S. Geological Survey, the U.S. Bureau of ation, and the U.S. Fish and Wildlife Service.

...al spawning chinook stocks have shown a gen- al decline parallel with increased water development upstream and in the estuary. Chinook salmon wn in the major rivers of the Central Valley g. 2). Total fall-run escapement has fluctuated eatly, ranging from 125 000 to 584 000 spawners between 1953 and 1986 (Dettman et al. 1987). Runs in the upper Sacramento River have declined to about 50% of those in the 1950s. Conversely, long term escapement to the American and Feather rivers has been maintained or slightly increased (average about 40 000 in both systems) over the past thirty years. These tributaries are heavily supported by hatcheries and since the 1970's hatchery production from those rivers has been trucked downstream to the lower estuary for release, thus avoiding upstream and delta mortalities. Spawning levels in the San Joaquin tributaries have fluctuated greatly from about 2 000 to 84 000 since the 1950's.

A mark/recapture program based on coded-wire nose tagged (Jefferts et al. 1963) hatchery fish released under a variety of environmental conditions is being used to develop estimates of smolt survival in the Delta. These survivals are being correlated against river flows, percent diversion and river temperatures to investigate effects of environment on juvenile stocks. Tagged fish released above and below a major diversion point on the Sacramento River and in the diversion channels themselves provide direct measures of effects of physical changes in the migratory pathways. Correlations between escapement and river flow during smolt outmigration are being used to investigate effects of flow alterations on resulting adult stocks.

The major purpose of this paper is to (1) describe the survival methodology and evalute its validity, (2) share knowledge on the effects of estuarine water development on smolt survival, and (3) discuss management applications of resulting information.

Study Area

The Sacramento–San Joaquin Estuary (Fig. 1) consists of the tidally influenced freshwater delta where the Sacramento and San Joaquin rivers join. It is comprised of 30 major man-made islands and about 1 200 km of channel, and a series of downstream embayments, Suisun, San Pablo, and San Francisco bays. Conomos (1979) and Kelley (1966) provide more detailed descriptions of the physical and biological characteristics of the estuary.

The historical annual flow passing through the estuary from its 163 000 km^2 drainage basin averaged about 1 100 $m^3 \bullet s^{-1}$ in 1900, but consumptive uses upstream and diversions from the Delta by 1960 had reduced that flow by about one-half (Chadwick 1977). The present pattern of seasonal river inflow to the Delta is modified by water storage in upstream reservoirs in the winter and spring. When natural runoff is less than reservoir storage capacity, delta inflow is controlled by project operations. This process often reduces inflows during the April–June outmigration period of salmon smolts.

The delta is the pivot point in the transfer of water from northern to southern California. The major out-of-basin diversions are made via the Federal Central Valley Project (CVP) and State Water Project (SWP) pumping plants in the southern delta (Fig. 1). The average percent of total delta inflow that has been diverted by the two projects during April through June since 1970 has ranged from about 16% in wet years to 44% in dry years. Typical May–June export rates of the two projects substantially exceed the delta inflow from the San Joaquin River, thus CVP/SWP export needs are not met by the San Joaquin basin runoff, and remaining project demands must be achieved by diversions of Sacramento River water.

Much of that flow is diverted from the Sacramento River at Walnut Grove into the central delta and southward toward the water project pumps via the Delta-Cross Channel (constructed by the CVP in 1951), Geor-

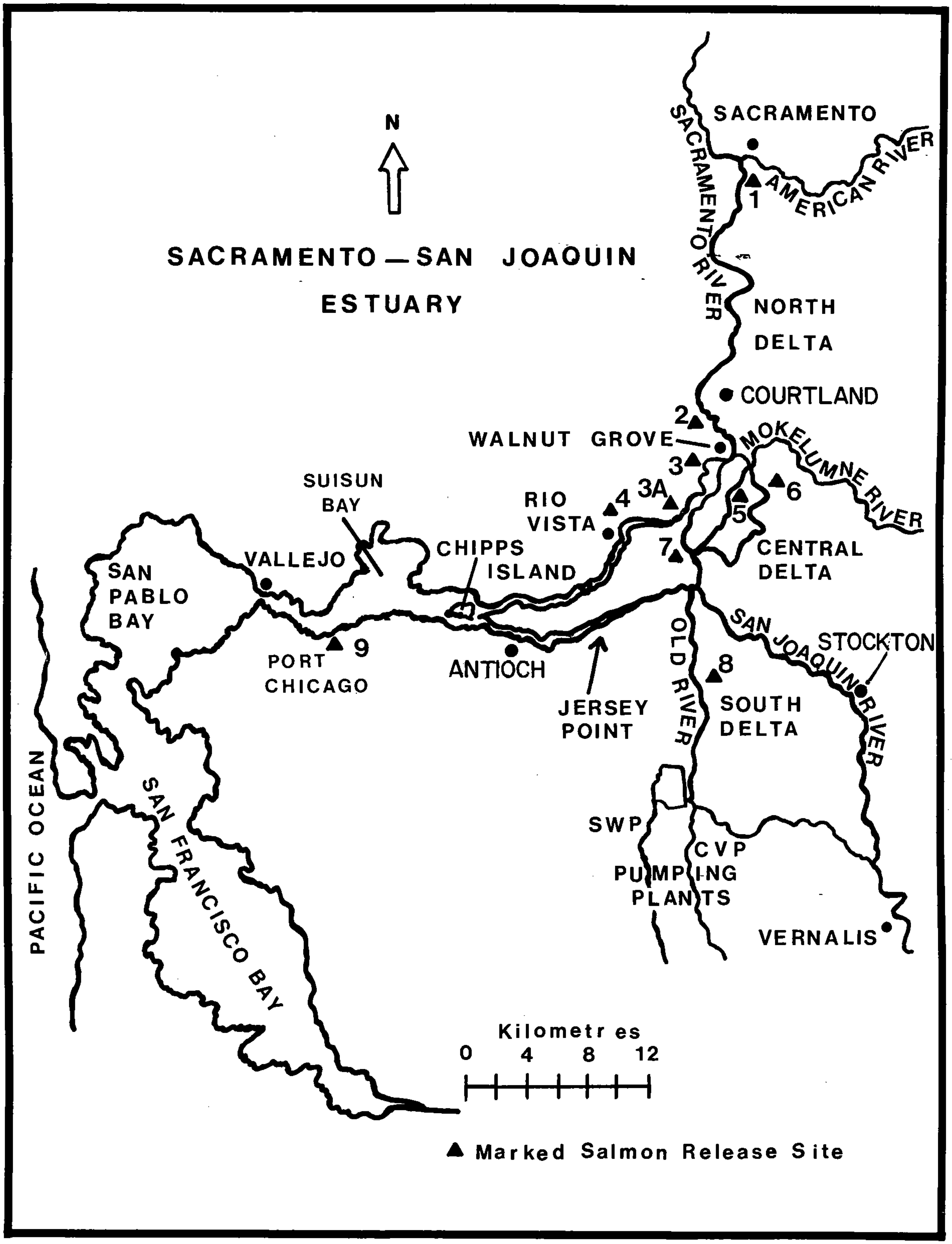

FIG. 1. The Sacramento–San Joaquin Estuary of California including marked salmon release sites.

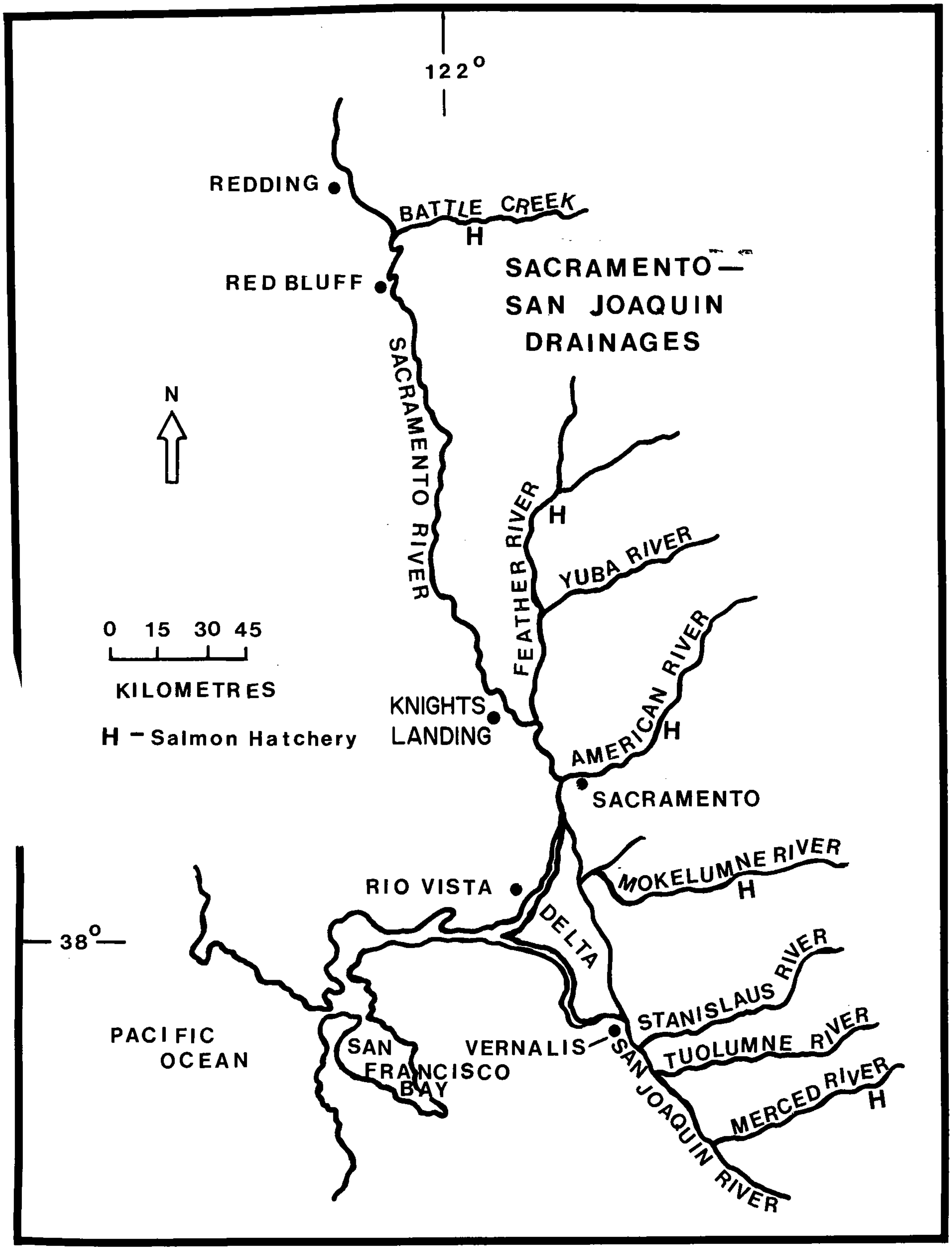

FIG. 2. Major chinook salmon spawning streams in the Sacramento–San Joaquin drainages of California.

giana Slough, and the natural channels of the central delta (Fig. 1 and 3). The percent taken from the Sacramento River at Walnut Grove during April through June has averaged 44 % (range 23–61 %) from 1978 to 1986.

Project export rates and central delta channel volume limitations causes additional Sacramento River water to be drawn upstream via the lower San Joaquin River past Antioch to the northern end of Old River (Fig. 1 and 3). Such net upstream (reverse) flows are typical in late May and June of dry years.

Methods

Physical Conditions

Flow and diversion rates in key delta channels were from published California Department of Water Resources (DWR) DAYFLOW records and formuli. Water temperature data were from the California Departments of Fish and Game (DFG) and Water Resources (DWR), U.S. Geological Survey and from our own measurements. DWR operational studies using hydrological models were used to simulate historic flows in the Delta at various levels of water project development by time period.

Smolt Survival

Marking

Fall-run hatchery chinook from the DFG Feather River Hatchery of a size similar to wild smolts (70–100 mm) (Kjelson et al. 1982) were marked with fin clips in 1969–71 and coded wire nose tags (CWT) and adipose clips from 1978 to 1987. During six study years, individual release groups were tagged with multiple codes to assess the precision of survival measures. From 50 000 to 250 000 smolts per release group were marked for release at selected sites in the delta and Suisun Bay.

Releases

Fall-run chinook salmon smolts in the Central Valley typically migrate to sea from April through June with the majority seen in the delta in May and early June (Kjelson 1982). Therefore, our marked smolt releases were made primarily in late May and early June. Fish released in the north delta at Sacramento or Courtland (Sites 1 and 2, Fig. 3) and at Rio Vista and Port Chicago (Sites 4 and 9, Fig. 1 and 3) were used to estimate survival in the delta. A single release was also made in May 1981 at Knights Landing (Fig. 2). Differences in recovery rate for those released above (Site 2) and below (Site 3) Walnut Grove were used to assess effects of the Cross channel–Georgiana Slough diversions. Tagged fish released in the central and southern delta (Sites 5, 6, 7, and 8, Fig. 3) represented those that had been diverted off the Sacramento River and were moving toward the pumping plants.

Similar procedures were used in the trucking, handling and releases of hatchery fish during each year although some unavoidable differences in truck temperatures (range 1–5 °C) and travel time between hatchery and release site were observed (range 2–3 h). General condition of each release group at time of release was observed to assure no significant direct mortality had occurred. Tag codes were verified by sampling tagged fish at release sites.

We compared water temperatures between hatchery truck and release sites, and fish sizes for the treatment (Sacramento or Courtland sites) and control groups (Port Chicago Site 9, Fig. 1) to evaluate if release conditions might have biased survivals. Data were not available to test for specific differences in predation or food at release sites.

Recovery

Recoveries of tagged smolts were made within a few weeks after release by midwater trawling at Chipps Island (Fig. 1) and by sampling the ocean troll and sports fishery 2–5 yr later. Ten 20-min tows per day were made during day-light usually beginning the day the first fish of a tag group was recovered until no tagged fish of that group were recovered (this ranged from 5 to 36 days for each release group).

The midwater trawl had a 9.1 by 7.9 m mouth opening with a 3.2 mm mesh cod end, increasing to 102 mm mesh wings. It was spread by two surface and two midwater doors. The trawl fished approximately the upper one-half of the water column which is where over 90 % of the smolts were found during daylight (Wickwire and Stevens 1970). We assumed that survival indices from only daylight sampling represented survival for the total smolt migration (day and night). Engine speed was held constant during each tow to keep sample volume consistent. Flow meter reading varied by about ±10 % per tow (average coefficient of variation) indicating sample volumes were similar. Tows were typically made against the current except at slack tide. Water depth trawled ranged from about 8 to 15 m and channel width was about 1 200 m. Samples were taken across the entire channel with an equal number in south, middle, and north portions. This same trawl methodology was used to quantify the seasonal distribution and relative abundance of unmarked fall-run smolts migrating past Chipps Island for April, May, and June from 1978 to 1986.

Ocean tag recovery for 1969–71 was based on port sampling by the California Department of Fish and Game with tag recoveries expanded using reciprocals

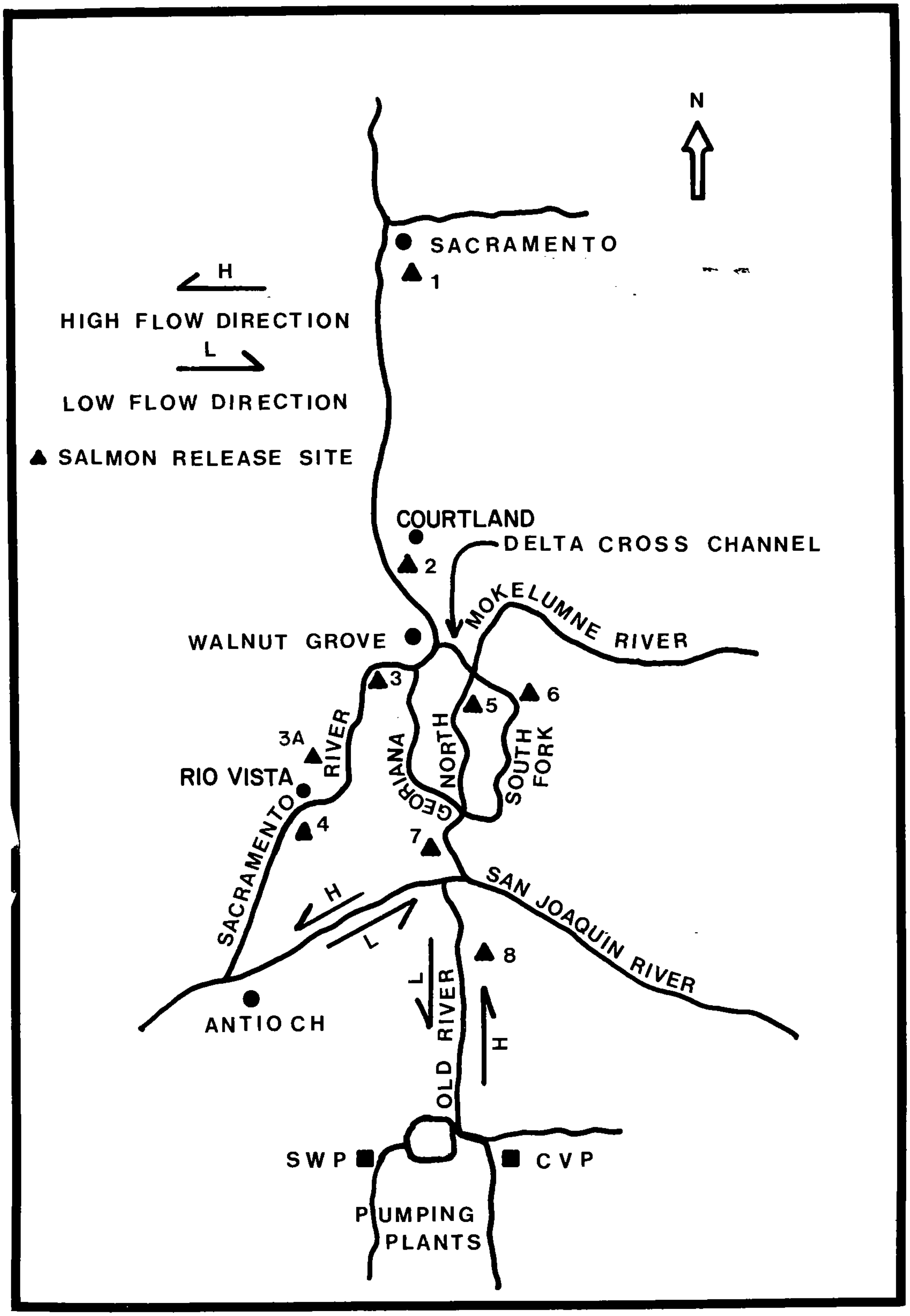

FIG. 3. Detail schematic of the major channels in the Sacramento–San Joaquin Delta including salmon release sites and flow direction in selected channels under high and low runoff conditions.

of port sampling fractions. Tag recovery data and procedures for other years are published by the Pacific Marine Fisheries Commission, 1400 S.W. 5th Ave., Portland, Oregon. We assumed tag groups were distributed equally throughout the fishery and exposed to the same harvest and sampling rates.

Survival Indices

Smolt survival through the Delta was measured using two mark–recovery methods. Our first survival measure, S_o was an estimate based on the tag recoveries of marked fish from the ocean fishery.

$$S_o = \frac{R_1/M_1}{R_2/M_2}, \text{ where:}$$

M_1 = number of tagged fish released in the Sacramento River in the north Delta (Sites 1 or 2)
R_1 = ocean recoveries of M_1
M_2 = number of tagged fish released in western delta or Suisun Bay (Sites 4 or 9)
R_2 = ocean recoveries of M_2

These calculations assume all fish had equal survival probability west of the downstream release points (Sites 4 and 9) and that differences in the tag recovery rates reflect mortality of the upstream groups as they migrated through the delta.

An arc-sine transformation was made to S_o to remove potential bias due to the constraints of proportions (Zar 1984).

Our second delta survival measure, S_T, is an index of the number of tagged fish passing Chipps Island based on trawl recoveries and corrected for sample effort in time and space.

S_T = R/MT (0.0078) where,
R = number of tagged fish recovered by trawl for each release group
M = number released for each release group
T = fraction of time sampled (10–14 %) when the fish were passing Chipps Island.

The constant 0.0078 = trawl width (9.1 m) divided by mean channel width (1167 m). Channel width is essentially constant at all tides and flows. Variation in trawl width is unknown but we assumed it random and part of variation in S_T. S_T was used to index survival from varied delta release sites to Chipps Island. S_o and S_T were correlated from the same release groups from 1978 to 1984.

Spawner Escapement

Central Valley spawner escapement levels were based on counts of fish entering hatcheries, migrating past dams, carcasses and live fish on spawning grounds, and aerial redd counts (1953–69: Taylor 1973; 1964–81: Reavis 1983; 1970–84: Pacific Fisheries Management Council 1985). Central Valley chinook salmon return to spawn at ages ranging from primarily 2 to 5 yr. Returns of known age (coded wire tagged) spawners indicate that most are 3-yr-old (Reisenbichler 1986). Hence, we used a 2½-yr lag between the time of smolt migration and escapement in correlating flow and escapement.

Results

Survival Indices

Detailed release, recovery, tag code and survival information, as supporting background data for each tagged smolt release group, is available from the authors.

The variability characterizing our two survival measures was based on the available data from replicate tag groups (Table 1). It appears relatively small compared to the variation in the annual survival estimates. Our limited replicates made it difficult to test for differences in annual survivals.

Survival estimate, S_o, was highly correlated with survival index, S_T, with an r=0.90 for survivals between the north delta and Suisun Bay for 1978 to 1984 data. This indicates that two, essentially independent methods yield survivals that are closely related providing support for the validity of both measures.

Bias in our survival estimates associated with differences in water temperature in the truck and release sites appeared minimal (Table 2). In all years the "thermal shock" experienced by the tagged fish was relatively high (4.5–11.1°C) and in 1981 the fish were released in obviously adverse temperatures of 23.9 and 24.5°C that were near lethal (Brett 1952; Orsi 1971). Nevertheless, in the 6 yr evaluated, the temperature differentials were small between the upstream and downstream release sites (0.5 to 5°C, Table 2) suggesting little bias.

Biases associated with differences in tagged fish size at upsteam and downstream release sites also appeared minimal (Table 3). Size differences for 7 of the 11 yr evaluated were very small (0–4 mm) and somewhat higher in other years (8–13 mm). We concluded that such bias did not invalidate the relations between survival and flow, diversion and temperature described below.

Survival: Habitat Relationships

Effects of Flow

Based on ocean tag recoveries, the survival of smolts through the delta from Sacramento to Suisun Bay was

TABLE 1. Summary of the recovery rates of marked fish from both ocean and trawl recoveries and the associated variability around estimates of survival, S_o and, S_T when multiple tag codes were used.

Year	Release site	CWT Code	Recovery rate	Ocean Recovery Estimate: Mean recovery rate	Survival estimate (S_o)	Minimum and maximum estimate of survival	Survival index (S_T)
1980	Sacramento	6-62-8	0.0107	0.0100			0.33
	Sacramento	6-62-11	0.0092				0.35
	Port Chicago	6-62-09	0.0232	0.0243			
	Port Chicago	6-62-12	0.0253				
					0.41	0.36 to 0.46	
1981	Sacramento	6-62-14	0.0003	0.0003			0.02
	Sacramento	6-62-17	0.0003				
	Port Chicago	6-62-15	0.0279				
					0.01	0.0115 to 0.0122	
1982	Sacramento (CNFH)[a]	6-62-18	0.0120	0.0135			1.53
	Sacramento (FRH)[a]	6-62-20	0.0150				1.48
	Port Chicago (CNFH)	6-62-19	0.0091		1.49	1.33 to 1.66	
1984	Courtland	6-62-27	0.0053				NA[b]
	Port Chicago	6-62-31	0.0040	0.0060			
	Port Chicago	6-62-37	0.0080				
					0.89	0.66 to 1.33	
1985	Courtland	6-62-38					0.39
	Courtlant	6-62-39			NA		0.13
	Courtland	6-62-40					0.26
	Courtland	6-62-41					0.41
1987	Courtland (gates closed)	6-62-53			NA		0.60
	Courtland (gates closed)	6-62-54					0.72
	Courtland (gates opened)	6-62-56			NA		0.39
	Courtland (gates opened)	6-62-57					0.42

[a] Fish produced from Coleman National Fish Hatchery and Feather River Hatchery.
[b] NA = Not Available.

TABLE 2. Temperatures in hatchery truck and receiving waters (in degrees centigrade) experienced by tagged salmon used in survival estimates released above and below diversions and based on ocean tag recoveries.

Year	Release site	Truck temp.	Receiving water temp.	Temperature difference
1969	Sacramento	—	18.6[a]	—
	Rio Vista	—	20.4	—
1970	Sacramento	—	21.4[a]	—
	Rio Vista	—	19.4	—
1971	Sacramento	—	16.4[a]	—
	Rio Vista	—	15.6	—
1978	Sacramento	13.9	22.6	8.7
	Port Chicago	13.9	19.9	6.0
1979	Sacramento	12.2	20.0	
	Port Chicago	—	—	7.8
1980	Sacramento	11.1	16.7	5.6
	Port Chicago	13.9	21.1	7.2
1981	Knights Landing	—	17.8	—
	Port Chicago	12.8	23.9	11.1
1981	Sacramento	13.9	24.5	10.6
	Port Chicago	12.8	23.9	11.1
1982	Sacramento	13.4	20.0	6.6
	Port Chicago	13.9	19.5	5.6
1983	Courtland	11.1	15.6	4.5
	Port Chicago	10.0	19.5	9.5
1984	Courtland	13.9	18.9	5.0
	Port Chicago	15.0	22.3	7.3

[a] Temperatures taken 10 km below Sacramento.

TABLE 3. Mean length and size differences of tagged salmon released above and below diversions and based on ocean tag recoveries.

Year	Release Site	Mean length (mm)	Difference in mean length (mm)
1969	Sacramento	89.7	1.0
	Rio Vista	88.7	
1970	Sacramento	86.5	
	Rio Vista	86.5	0.0
1971	Sacramento	86.0	8.5
	Rio Vista	77.5	
1978	Sacramento	90.9	1.8
	Port Chicago	89.1	
1979	Sacramento	74.5	−8.7
	Port Chicago	83.2	
1980	Sacramento	96.9	9.1
	Port Chicago	87.8	
1981[a]	Knights Landing	77.0	−13.1
	Port Chicago	90.1	
1981	Sacramento	89.7	−0.4
	Port Chicago	90.1	
1982	Sacramento	76	4.0
	Port Chicago	72	
1983	Courtland	79	−3.0
	Port Chicago	82	
1984	Courtland	82	0.0
	Port Chicago	82	

[a] Released in May.

highly correlated to mean daily Sacramento River flow at Rio Vista ($r=+0.85$, Fig. 4). Survival, S_o, increased rapidly with an increase in flow from about 200 to 650 $m^3 \cdot s^{-1}$ where survival appears maximum. Smolt survival remains at about 100% at Rio Vista flows over 650 $m^3 \cdot s^{-1}$. Survival values over the theoretical maximum of 100% for 1982 and 1983 may reflect sampling imprecision or some unknown bias.

The values for 1983 and 1984 probably are biased high relative to other years since they are for fish released about 42 km downstream of Sacramento (at the "Courtland" site) and thus traveled a shorter distance than smolts released in earlier years at Sacramento. Survival indices in 1984 probably are more biased than in 1983, since flows were much lower in 1984.

Our second measure of smolt survival through the delta, that based on tag recoveries from trawling at Chipps Island, also was well correlated with flow ($r=0.83$, 1978 to 1987).

Mechanisms for the Flow: Survival Relationship

Several factors could cause the strong correlations observed between survival and flow. These include

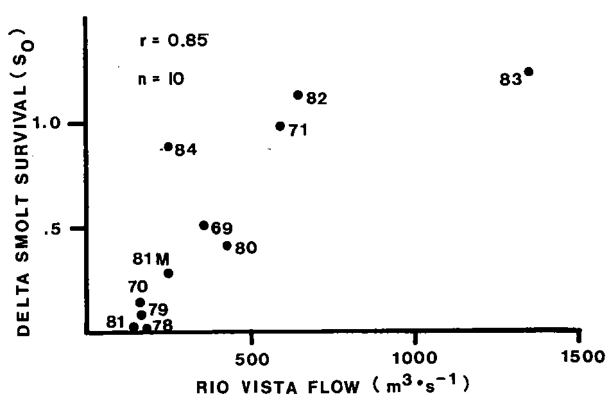

FIG. 4. Relationship between marked chinook smolt survival, (S_o), through the Sacramento–San Joaquin Delta and flow at Rio Vista, California during May or June for 1969–1971, and 1978–1984. May and June releases in 1981 labeled 81M and 81, respectively. 1983 survival data were not included in calculation of the correlation coefficient since survival does not appear to increase over 650 cms. An arc–sine transformation was made to S_o to remove potential bias due to the constraints of proportions (Zar 1984). While r value shown is based on untransformed S_o values, arc–sine transformed S_o yielded an $r=0.87$.

diversion, temperature, turbidity, and toxicity. High flows would dilute pollutants while the increase turbidity associated with greater flows would lessen predation. Both could potentially increase smolt survival but we could not evaluate these hypotheses due to lack of data.

Our emphasis has been to evaluate the independent effects of diversion and temperature on survival since flow, diversion and temperature are all strongly correlated with each other (absolute r = 0.74–0.79) making it difficult to use correlation techniques to separate the relative roles of these three factors on survival. Quantifying the independent effects of each factor requires experimental approaches and will help to identify the most effective restoration measures.

Effects of Diversion — Smolt survival, S_0, in the delta was negatively correlated (r=-0.63) with the percentage of water diverted from the Sacramento River at Walnut Grove via the cross channel and Georgiana Slough (Fig. 5 and 3).

We also found that in all four years (1984, 1985, 1986, and 1987), under high diversion rates (>60 %) with the delta cross channel gates open, the survival of smolts (S_T) released above the diversion was about 50 % less than for those released below the diversion (Table 4). When the cross channel gates were closed, preventing diversion through that channel, there was no difference in survival of these two groups during the high flow year of 1983, and about a 25 % difference in the very low flow year of 1987 presumably due to the effect of diversion via Georgiana Slough.

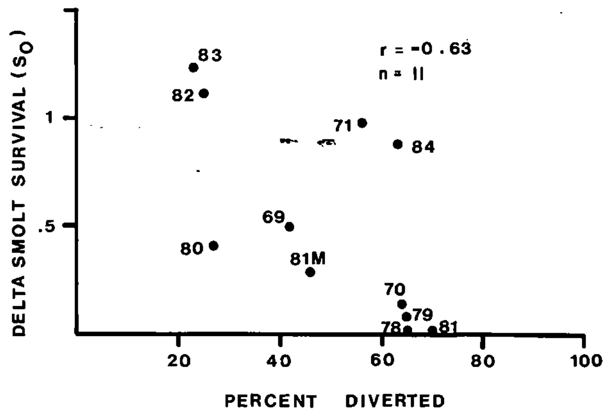

FIG. 5. Relationships between marked chinook smolt survival, S_0, through the Sacramento-San Joaquin Delta and thepercent diverted from the Sacramento River at Walnut Grove, California during May or June 1969–1971 and 1978–1984. An arc-sine transformation was made to S_0 to remove potential bias due to the constraints of proportions (Zar 1984). While the r value shown is based on untransformed S_0 values, arc-sine transformed S_0 yielded an r=-0.63.

TABLE 4. Survival indices of coded wire tagged (CWT) chinook smolts released at several locations in the Sacramento-San Joaquin Delta from 1983 to 1987 and recovered by trawl at Chipps Island.

Release Site	1983	1984	1985	1986	1987
Above Diversion[a] gates opened	—	0.61	0.34	0.35	0.40
Above Diversion gates closed	1.06	—	—	—	0.67
Below Diversion[b] gates opened	—	1.05	0.77	0.68	0.88
Below Diversion gates closed	1.33[c]	—	—	—	0.85[b]
North Fork Mokelumne R.[d]	NR	0.51	0.28	0.36	NR
South Fork Mokelumne R.[d]	NR	0.86	0.23	0.26	NR
Lower Mokelumne R.[e]	1.13	NR	NR	NR	NR
Lower Old River R.[f]	0.33	0.16	0.21	0.23	NR

[a] Release Site 2 on Fig. 3.
[b] Release Site 3 on Fig. 3.
[c] Release Site 3A on Fig. 3.
[d] Release Sites 5 and 6 on Fig. 3.
[e] Release Site 7 on Fig. 3.
[f] Release Site 8 on Fig. 3.
NR = No Release.

TABLE 5. Diversion and flow conditions in the north, central and southern Sacramento–San Joaquin Delta from the period that marked fish released at Courtland (Site 2 on Fig. 3) were travelling to Chipps Island (1983 to 1987).

	1983	1984	1985	1986	1987-O[f]	1987-C[f]
Percent Diverted[a]	23	62	65	64	69	29
Sacramento R. Flow[b]	1352	256	203	219	149	270
San Joaquin Flow[c]	1013	19	17	135	−23[h]	-58[h]
Temperature[d] above Diversion	15.6	18.9	17.8	22.8	19.2	19.2
Temperature[d] below Diversion	16.1	18.9	18.9	23.4	17.8	19.5
Temperature[e], Mokelumne R.	16.7	21.1	17.8	21.1	NR[g]	NR
Temperature[d], Lower Old R.	17.2	23.9	20.0	23.4	NR	NR

[a] from Sacramento River at Walnut Grove.
[b] at Rio Vista ($m^3 \bullet s^{-1}$).
[c] at Jersey Point ($m^3 \bullet s^{-1}$).
[d] °C at release site.
[e] mean at North Fork and South Fork Mokelumne River.
[f] O = Cross channel gates opened; C = Cross channel gates closed, reflects conditions during 3 day gate closure.
[g] NR = No Release.
[h] Upstream flows.

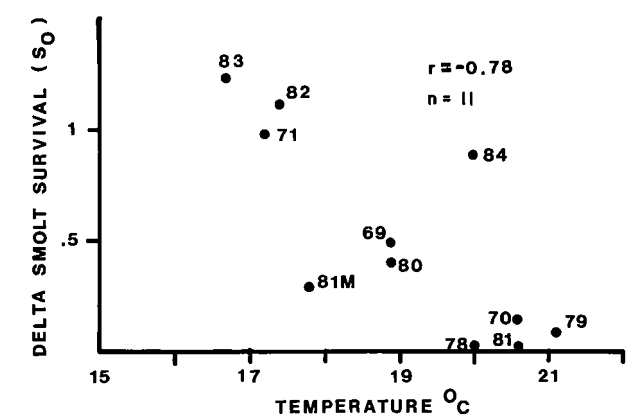

FIG. 6. Relationship between marked chinook smolt survival, S_o, through the Sacramento-San Joaquin Delta and mean temperature between Sacramento and Suisun Bay during May or June, 1969–71 and 1978–84. An arc-sine transformation was made to S_o to remove potential bias due to the constraints of proportions (Zar 1984). While r value shown is based on untransformed S_o values, arc-sine transformed S_o yielded an r=-0.80.

Release temperatures at the sites above and below the diversion point in a given year were nearly identical indicating that the survival differences were due to the diversion process and not to temperature differences in the Sacramento River (Table 5). The 1987 data indicate that closing the cross channel even during low flow years can yield a major increase in delta smolt survival. These results indicate that diversions account for a part of the flow: survival relationship.

Tagged smolts released in the central delta had survivals slightly lower than those released above the point of diversion at Site 2 during 1985 and 1986 while data from 1984 indicated survivals were similar (Table 4). The group of tagged smolts released in lower Old River (Site 8, Fig. 3) had the lowest survival indices of all release groups for all years (Table 4).

Effect of Temperature — We found that smolt survival in the delta also was correlated to mean water temperature between Sacramento and Suisun Bay (r=-0.78, Fig. 6). The highest temperatures experienced by smolts are in late May and June. We have not been able to quantify the effects of temperature alone on survival but have plans to attempt this as discussed later.

Estimated Historical Survival — To evaluate how water development has affected smolt survival over the past 70 plus years we regressed smolt survival estimates (S_o) on Sacramento River flow at Sacramento. From this regression, estimates of the average smolt migration pattern by month (Table 6), and estimates of historic monthly flows at Sacramento, we calculated average survivals under four water development scenarios. These are: no development, 1920 level, 1940 level and 1990 level.

The results indicate that reduced inflow to the delta caused by water development in the Sacramento Valley

TABLE 6. Distribution in (percent) of total midwater trawl catch (April through June) of unmarked fall run smolts by month at Chipps Island in 1978—1986.

	Percent of Catch		
Year	April	May	June
1978	27	40	33
1979	19	52	29
1980	14	34	52
1981	34	50	16
1982	18	49	33
1983	19	49	32
1984	11	66	23
1985	26	63	11
1986	37	55	8
mean (1978-86)	22	51	17

has reduced smolt survival (Table 7). The greatest difference, as expected, are in the dry and critical years. The estimated maximum decrease in survival associated with the 1990 level of water development is about 40% (no development versus 1990). We estimated that survival decreased about 30% between 1940 and 1990. These are minimal estimates of decreases in survival as they do not account for the greater survival per unit flow that would have occurred before the delta cross channel began diverting a significant portion of the Sacramento River flow in the 1950's.

Discussion

Survival Methodology

Feasibility and Validity

The preceeding description of studies in the Sacramento—San Joaquin delta of California indicate that given appropriate funding and personnel, juvenile salmonid survival estimates are attainable. Costs associated with this approach, however, are high relative to abundance surveys when fish production, tagging and tag retrieval and decoding are considered. Each step in the mark/recapture process involved complex logistics. Extensive coordination between hatchery personnel, biologists, sampling crews and boat operators was essential to meet experimental design criteria. Recovering tagged smolts by trawling has the advantage of obtaining results without having to wait for the fish to enter the ocean fishery. It also provides an opportunity to estimate survival using two methods which forms a basis for evaluating the validity of our survival estimates.

The use of tagged hatchery smolts to investigate factors affecting wild fish seems appropriate. Ideally, we would have tagged wild smolts but found great difficulty in collecting sufficient numbers that were in good health. As noted earlier, both of our approaches to estimate survival provided essentially identical results lending validity to our conclusions relative to the factors affecting survival.

In an attempt to address this concern, we have plans

TABLE 7. Average estimated Delta survival indices of fall-run chinook smolt by water year type at different levels of development: unimpaired (no development), and at 1920, 1940, and 1990 levels of development.[a]

Water year types	(Sample size)	Unimpaired no development	1920 level of development	1940 level of development	1990 level of development
Wet	(19)	0.97	0.92	0.91	0.83
Above normal	(10)	0.91	0.85	0.83	0.61
Below normal	(10)	0.84	0.69	0.66	0.41
Dry	(10)	0.76	0.57	0.55	0.33
Critical	(8)	0.33	0.17	0.21	0.12
Mean		0.76	0.64	0.63	0.46

[a] Annual survivals were estimated by weighting monthly survival indices by the average percent from 1978 to 1986 of total outmigrants going to sea (Table 6). Monthly survival indices were estimated from monthly flows using the linear relationship between salmon survival and flow at Sacramento where $y = 0.00005X - 0.465$ when y = survival and x = mean monthly Sacramento River flow. Data from 1969–71 and 1978–81 was used to derive the equation. Monthly flows for the four different levels of development was obtained from California Department of Water Resources planning simulation model studies (personal communication, 1416 Ninth Street, Sacramento, CA).

TABLE 8. Mean catch of chinook salmon smolts per 20 min tow with the midwater trawl at Chipps Island during April, May and June from 1978 to 1986.

Year	April	May	June	Flow (mean April, May, June at Rio Vista)	Annual mean[a]	Mean temp.[b]	Percent Diverted[c]
1978	23.1	34.0	27.6	541	28	63	45
1979	14.9	41.6	23.2	257	25	63	55
1980	5.6	14.0	21.1	394	17	62	38
1981	17.3	25.3	8.3	249	15	67	55
1982	18.9	51.7	34.6	1490	38	60	27
1983	24.8	65.0	42.8	1566	48	57	23
1984	3.2	20.0	7.0	302	10	64	50
1985	10.3	24.7	4.1	203	20	66	61
1986	22.5	32.9	4.7	356	24	65	44

[a] Total catch divided by the total number of tows for April through June.
[b] Degrees Fahrenheit, Sacramento River at Freeport (mean April through June).
[c] Percent of the Sacrament River diverted at Walnut Grove (mean April through June).

to measure survival of unmarked, wild smolts in the delta. The general approach would sample wild smolts by midwater trawl at both Sacramento (Site 1, Fig. 3) and at Chipps Island throughout the April–June migration period and to use the catch per unit effort ratios of the Sacramento site divided by the Chipps Island site to provide a survival index. A lag factor of about one week applied to the Chipps Island data would be used to correct for migration time. Results could be very useful in evaluating past survival: habitat relationships and the method would yield numerous measures of survival as environmental conditions change between April and June.

Our evaluations suggest that the survival measures are not influenced unduly by extraneous procedural factors. Potential bias associated with "temperature shock" at release sites and differences in fish size appeared only minimal. Hence we believe our survivals and correlations between survival and flow, temperature, and diversion are sound.

Habitat Alteration Effects

Survival: Habitat Relationships

Relatively high coefficients of correlation (absolute r=0.52–0.85) between smolt survival and flow, temperature and diversion for both S_o and S_T provides evidence that one or a combination of two or more of these factors working together has a major influence on smolt survival in the Sacramento River delta. Even after arcsine transformation, highest survivals were observed when flows were high and temperatures and diversions were low. The relationships between wild smolt abundance at Chipps Island and flow (r=0.89). Temperature (r=-0.83) and diversion (r=-0.77) for the years 1978 to 1986 are added support for the above conclusions ($P<0.05$ in all cases) (Table 8). The three sets of correlations between S_o, S_T and smolt abundance and flow, temperature and diverison were consistent and are in the directions one would expect, lending validity to our conclusions.

Diversion — Schaffter (1980) found densities of salmon in the Sacramento River above the diversion channels at Walnut Grove were similar to those in the delta cross channel suggesting that fish were diverted in proportion to the flow split at that location. Smolts diverted into the central delta must travel a longer route and are exposed to increased predation. The higher temperatures of the central delta, more agricultural diversions and more complex channel configurations, also may reduce their ability to survive. In addition, upon reaching the mouth of the Mokelumne on the lower San Joaquin River they are often exposed to upstream (reverse) flows moving to the south via Old River toward the project pumping plants and sometimes to reverse flow in the San Joaquin River itself (Table 5, Fig. 3).

Tagged smolts released in the southern delta (Site 8) had the lowest survival of all release groups for all years which probably reflects more harsh conditions in the southern delta. Higher water temperatures and reverse flows (Table 5), predation near the south Delta Project fish screens (Hall 1980; R. Kano, DFG, pers. comm., same address as Kjelson/Brandes) and smolt mortality associated with the fish screen salvage process (Menchen 1980; P. Raquel, DFG, pers. comm., same address as Kjelson/Brandes) all may contribute to these high mortalities.

Temperature — High temperatures in the delta that approach lethal levels in June of low runoff years also play some yet unquantified role in smolt mortalities. Chinook salmon are stressed as temperatures rise and temperatures over 18°C are usually considered undesirable for juvenile chinook (Brett et al. 1982; Banks et al. 1971). Temperatures acutely lethal to chinook salmon smolts are about 24°C (Brett et al. 1982; Orsi 1971). Energy needs also increase as temperatures rise (Brett et al. 1982) thus food may be more limiting as temperatures increase. Chinook smolts consume both insects and zooplankton during their estuarine migration (Kjelson et al. 1982). We do not have sufficient data to evaluate if food densities of either type are limiting to smolts during their week long migration through the delta but it is possible.

Since many of our CWT smolt releases were made from mid-May to early June when temperatures were often high, it is possible that the flow: survival relationship in Fig. 4 does not apply to April and early May when temperatures are lower. If high temperatures are a major cause of the lower survival at low flows then the smolt survival for April and early May would be expected to be somewhat higher at low flows than our results indicate.

We plan to initiate cooperative efforts with the State (SWP) and Federal (CVP) water project operators so we can release tagged smolts in April and June under identical flow and diverison conditions. This will be possible in drier years when the river flows in April and June are under the control of project operations through reservoir releases. The temperature differences between April and June will thus enable us to quantify the changes in survival attributed to temperature alone.

Spawner: Flow Relationships — Relationships between salmon spawner escapements and flow during the smolt outmigration period reflect the importance of flow on smolt survival. Positive correlations between longterm escapements of Central Valley fall-run chinook and flow during the smolt migration period were observed (Table 9, Fig. 7 and 8).

The correlation between escapement and flow in the upper Sacramento appears to have declined in recent years (1968–81) due to recent water development changes (see Reisenbichler 1989). The relationships for Feather and American river stocks were strengthened when the portion of the escapement attributed to

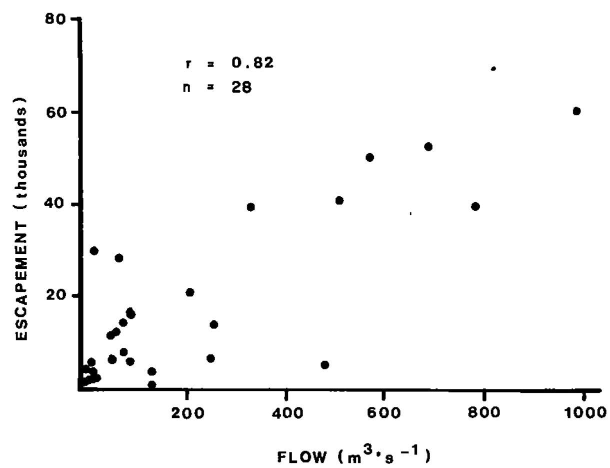

FIG. 7. Spring flows at Vernalis, California (mean April through June) experienced by the smolt outmigrants from 1956 to 1984 and the resulting San Joaquin fall-run chinook salmon escapement in 1958–86 (2$^1/_2$ yr lag).

TABLE 9. Correlations between fall-run chinook spawner escapement and flow during smolt outmigration for various stocks in California.

Stock	Flow period	Years	r	Reference
Upper Sacramento River	May[b]	1952–81	0.59[a]	Dettman et al. (1987)
	May[b]	1952–67	0.59[a]	"
	May[b]	1968–81	0.15	"
Feather River	June[b]	1952–81	0.31[a]	Dettman et al. (1987)
Feather River[e]	June[c]	1964–81	0.48[a]	Dettman & Kelley (1987)
American River	June[b]	1952–81	0.03	Dettman et al. (1987)
American River[e]	June[c]	1967–81	0.49	Dettman & Kelley (1987)
San Joaquin Tributaries	April–June[d]	1956–84	0.82[a]	Figure 7
Total Central Valley	May[b]	1960–86	0.47[a]	Figure 8

[a] Correlation significant at $P<0.05$ or less.
[b] Flow measured at Chipps Island.
[c] Flow measured in the northern delta.
[d] Flow measured at Vernalis.
[e] Estimates of hatchery contribution released below Walnut Grove diversion based on coded wire tag recoveries were omitted from escapement.

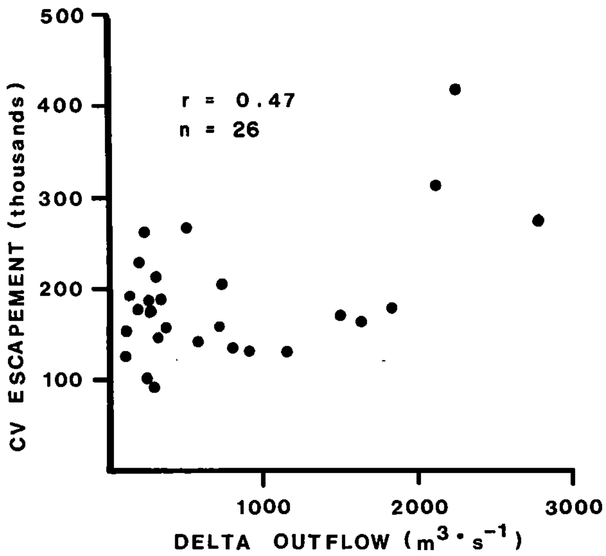

FIG. 8. The relationship between Central Valley fall-run chinook salmon escapement in 1960–86 versus May Delta outflow experienced $2^1/2$ yr earlier (1958–84) by smolt outmigrants.

hatchery fish that was not exposed to the delta diversion at Walnut Grove was omitted.

The best long term correlation observed was for the San Joaquin tributaries (Fig. 7), a system that is highly developed with little hatchery contribution and where large escapements are only seen after high runoff during the smolt migration $2^1/2$ yr earlier. Work by the California Department of Fish and Game (Bill Loudermilk, Region 4, 1234 E. Shaw Avenue, Fresno, CA, pers. comm.) indicates that salmon escapement in the Tuolumne River (Fig. 2) per unit of spring river flow during smolt migration has decreased over time (1939–86). This suggests that the increased habitat alterations both upstream and in the estuary over that period has decreased adult stocks. The correlation for total Central Valley stocks is surprisingly good considering the multitude of inland factors influencing adult production. In addition, the relationships are further impacted by imprecise and biased escapement estimates and variation in ocean survivals.

Management Applications

Our smolt survival results have been the basis for formal testimony presented to the State Water Resources Control Board during ongoing hearings to evaluate and revise present water quality and flow standards designed to protect salmon and other beneficial uses in the estuary.

The results also are being used to evaluate potential operational and structural protective measures such as flow pulses, decreased diversion rates, temperature controls, fish screens and channel barriers. Smolt survival information has encouraged a diverse cooperative effort between biologists, engineers, water managers and regulators to evaluate the cost and benefits to both fishery and water interests of varied management options. The planned studies described earlier to evaluate the relative importance of temperature and diversion are a result of this cooperation. This also has led to new evaluations of salmon restoration opportunities in upstream areas in the Sacramento and San Joaquin Valleys, in an attempt to gain a comprehensive Central Valley salmon restoration plan.

Use of survival data has also been made in varied modeling efforts on Central Valley salmon designed to evaluate the long-term stock benefits of increased flows, lesser diversion levels and other restoration measures in the delta and upstream drainages.

Results of our estimations of historical survivals reflecting alterations in flow can potentially be used to set goals for stock restoration although major philosophical/management questions arise relative to the level of restoration desired. Potential salmon management goals in the delta include specified smolt survival levels to be met by various protective measures.

Acknowledgments

We thank the many seasonal aids, boat operators, and hatchery personnel for their assistance. General encouragement and advice in analysis and data interpretation by P. Chadwick, D. Dettman, Dr. R. Brown, D. Kelley, D. Kohlhorst, Dr. R. Reisenbichler, and K. Urquhart was most helpful. We are indebted to D. Stevens for his critical review of the manuscript and continued advice. Support by S. Herrgesell and A. Eden in typing the manuscript and by K. Odenweller who drew the figures is greatly appreciated. This research was supported by the Interagency Ecological Study Program for the Sacramento–San Joaquin Estuary.

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