AN EVALUATION OF THE EFFECTIVENESS OF FISH SALVAGE OPERATIONS AT THE INTAKE TO THE CALIFORNIA AQUEDUCT, 1979-1993

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We describe the results of the last 14 years of experience gained in operating a large fish protection facility at the intake to the California Aqueduct in the Sacramento-San Joaquin Delta. The Department of Water Resources constructed the behavioral barrier (louver) system in the late 1960s for a maximum flow of about 180 m^3/s. The facilities have since been modified extensively, and the capacity has been increased to about 290 m^3/s. Although more than 40 species of fish have been entrained in the diversion, we focus on the facilities' effectiveness at screening Chinook salmon. Screening efficiency varies with fish length, ranging from 70 to 80 percent for juvenile salmon about 100 mm in length. Significant prescreen losses appear to be caused by subadult striped bass predation in a forebay in front of the fish facility. Small additional losses occur due to handling in the salvage process and when trucking the salvaged fish to Delta release sites about 40 kilometers from the intake. We also briefly describe mitigation measures to offset direct losses of Chinook salmon at the intake as well as actions that might be taken to reduce losses of these and other fish.

California voters authorized the State Water Project in 1960 to provide water from the Feather River, a tributary to the Sacramento River, to urban and agricultural users in the San Francisco Bay area, the San Joaquin Valley, and Southern California. Key project features include Oroville Dam and Reservoir on the Feather River, Harvey O. Banks Delta Pumping Plant in the Sacramento-San Joaquin Delta, the 714-kilometer California Aqueduct, and several storage reservoirs south of the Delta (Fig. 1). The general premise of the State Water Project was to store flows in Oroville Reservoir during the winter and spring months and move water to south-of-Delta storage when flows were naturally high or when water was released from storage in the summer and fall. A more complete description of the State Water Project can be found in DWR 1994.

State Water Project planners included the Feather River Hatchery and a fish protective facility at the intake to the California Aqueduct as the project's two principal fish mitigation and protection features. Our objective is to provide an overview of how the John E. Skinner Fish Protective Facility (Skinner Fish Facility in this report) operates, the species and numbers of fish captured at the facility during 1979 to 1993, major factors contributing to fish losses, and ideas that have been advanced to minimize losses associated with State Water Project diversions from the Delta. (Information on the Feather River Hatchery can be found in Brown & Greene 1994).

Although more than 40 species of fish are captured at the Skinner Fish Facility, in this article we focus on Chinook salmon, *Oncorhynchus tshawytscha*. We

FIGURE 1. Major features of the California State Water Project.

selected this species because more is known about how it fares in the salvage process and because of its widespread abundance and economic, environmental, and cultural importance in California and the Pacific Northwest.

The article briefly describes the Bay/Delta and State Water Project diversions, life history of the Chinook salmon, the salvage process, estimated losses of salmon during each step of the process, and measures taken to minimize or offset these losses. A final section discusses some additional actions being taken or considered to resolve problems associated with State Water Project diversions from the Delta.

During the past 10 to 15 years, several fish species using the estuary have declined in abundance, including striped bass juveniles, delta smelt, and winter-run Chinook salmon. There are several possible reasons for the observed declines, such as: direct and indirect losses at the State, Federal, and agricultural diversions in the Delta; decreases in Delta inflow and outflow resulting from upstream and in-Delta diversions and droughts; effects of toxic materials such as agricultural pesticides; and changes in the estuarine ecosystem caused by accidental and purposeful introductions of non-indigenous fish and invertebrate species.

Although there is no consensus about the relative importance of these and other factors in controlling the distribution and abundance of a particular fish species, almost everyone agrees that losses due to diversions may be contributing or limiting factors for some important species. Attempts to "fix the Delta" almost always include measures designed to minimize or offset fish losses at State Water Project and Central Valley Project diversions. A December 15, 1994, Bay/Delta protection agreement between representatives of agricultural, urban, and environmental water interests and State and Federal agencies provided for seasonally-adjusted pumping limitations (export/inflow ratios) to minimize direct losses of fish at the SWP and CVP Delta intakes. The State Water Resources Control Board adopted these de facto pumping limitations as part of its Water Quality Control Plan for the estuary (SWRCB 1995).

THE DELTA AND STATE WATER PROJECT PUMPING

SWP pumps are located in the southern Delta near the town of Tracy and only about a mile from the intake to the Central Valley Project's Delta-Mendota Canal (Fig. 2). To better understand fish entrainment into the SWP, it is necessary to have a basic appreciation of a few physical, hydrologic, and operational features of the Delta and SWP Delta operations. More complete descriptions are found in Brown and Greene (1992) and DWR (1993).

Most of the water diverted from the Delta by State, Federal, and local interests originates in the Sacramento Valley watershed. Water coming down the Sacramento River to Delta diversions enters the central Delta by way of the CVP's gated Delta Cross Channel and two natural channels, Georgiana Slough and Threemile Slough. Water movement through these channels is dependent on temporal variation in the differences in elevation between the Sacramento and San Joaquin river systems caused by streamflow and tides and is essentially independent of project pumping in the southern Delta (Brown & Greene 1992). When CVP and SWP pumping exceeds flow entering the Delta through these channels plus flow from the San Joaquin River, Sacramento River water can also move into the Delta by going around the tip of Sherman Island and up the lower San Joaquin River. Net upstream flow in the lower San Joaquin River is called "reverse flow."

Fish arrive at the pumps from interior Delta channels, most of them probably from the lower San Joaquin River and central Delta or, in the case of juvenile Chinook salmon, fish that are migrating down the San Joaquin River toward the ocean. A much lower percentage of fish originating in the Sacramento River system is also salvaged at the State and Federal facilities.

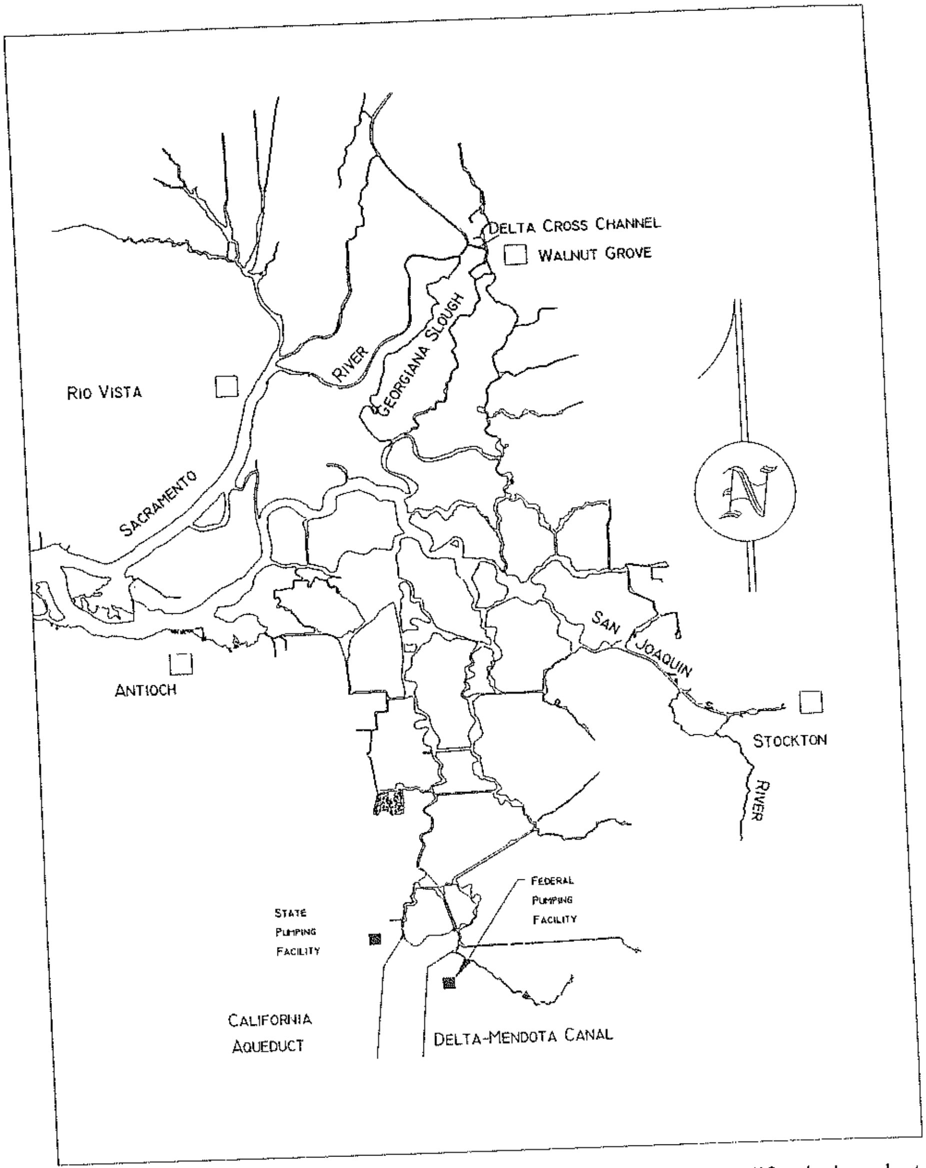
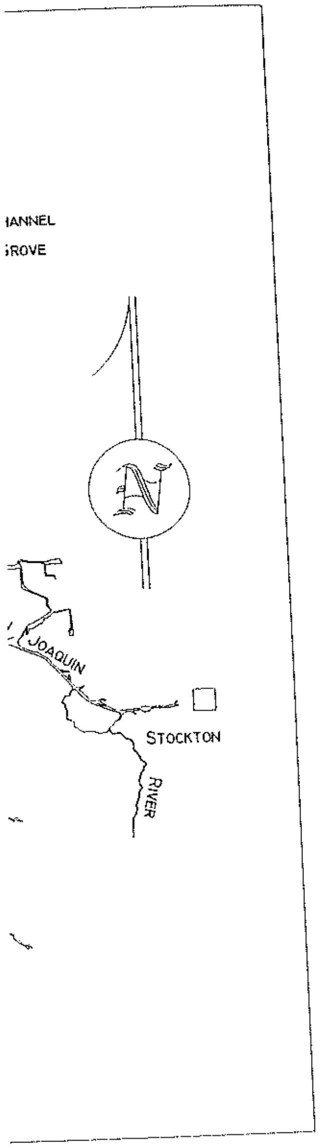


FIGURE 2. The Sacramento/San Joaquin Delta and the intake to the California Aqueduct.

One confounding feature of Delta water movement is the dominance of tidal flows. Reverse flow in the lower San Joaquin River above its confluence with the Sacramento River is often postulated as a fish transport mechanism; however, preliminary results of particle transport modeling indicate that reverse flow (also called "negative Qwest") does not appear to move eggs and larvae from the Sacramento River toward the pumps (Chung & Smith 1993). On the other hand, Wendt (1987) found that salvage of small striped bass at Skinner Fish Facility was



take to the California Aqueduct.

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correlated with calculated net flow in the lower San Joaquin River. A U.S. Fish and Wildlife Service (1992) regression model had Qwest as a statistically significant factor along with temperature, percent water diverted off the Sacramento River, and combined SWP/CVP pumping to explain survival of Sacramento River juvenile salmon through the Delta. Subsequent analyses indicated that the importance of Qwest relative to other factors in the model may have been overstated (Brown & Greene 1992). Whatever the mechanism, and it may even be a stochastic process, some small percentage of juvenile fish in the Sacramento River does move through the Delta and are salvaged by the SWP and CVP pumps.

The pumps have a combined capacity of about 420 cubic meters per second, with the SWP at 290 and the CVP at 130 cubic meters per second. At present, however, U.S. Army Corps of Engineers permits generally allow a maximum of only about 200 cubic meters per second at the SWP pumps.

ASPECTS OF THE LIFE HISTORY OF CENTRAL VALLEY CHINOOK SALMON IMPORTANT TO SCREENING

The following is a summary of some of the important features of Chinook salmon life history that bear on successfully screening juvenile salmon from Delta diversions. Population estimates are included to provide an idea as to why screening and other measures are needed to increase salmon numbers.

Chinook salmon are found in many of the larger streams along the Pacific Rim from California to Japan (Moyle 1976). All Chinook salmon are anadromous in that they spawn in freshwater streams, and the young move to the ocean at an early stage. During their 1-5 years of ocean residence, the salmon grow to adult size, approach sexual maturity and, using the sense of smell and other yet unknown cues, head for streams in which they hatched and reared to repeat the cycle. All Chinook salmon die after spawning.

Life history characteristics within the species and throughout its range vary considerably, with the Central Valley races having some of the greatest variability. Central Valley streams support four Chinook races, or runs — the fall, late-fall, winter, and spring — named after the time the adults move from the ocean into San Francisco Bay en route to their natal spawning grounds.

Following is a short summary of some of the important life history and other features of each race as they relate to Delta diversions. Figure 3 has recent historical escapement (run sizes) for each race. A more complete description of Central Valley salmon life cycles is found in Vogel & Marine (1991).

The fall run, presently the most numerous race in the Central Valley, occurs in the mainstem and tributaries of the Sacramento River and in tributaries to the San Joaquin River. Fall-run individuals generally reach the spawning grounds sexually mature and ready to spawn, with most of the spawning occurring at low-elevation stretches of rivers just above the valley floor. Adults mostly spawn in October and November with most of the young salmon, called "smolts," moving downstream and through the estuary in April through mid-June. Fall-run smolts are generally 70-80 mm long and have physiologically adapted to making the osmoregulatory

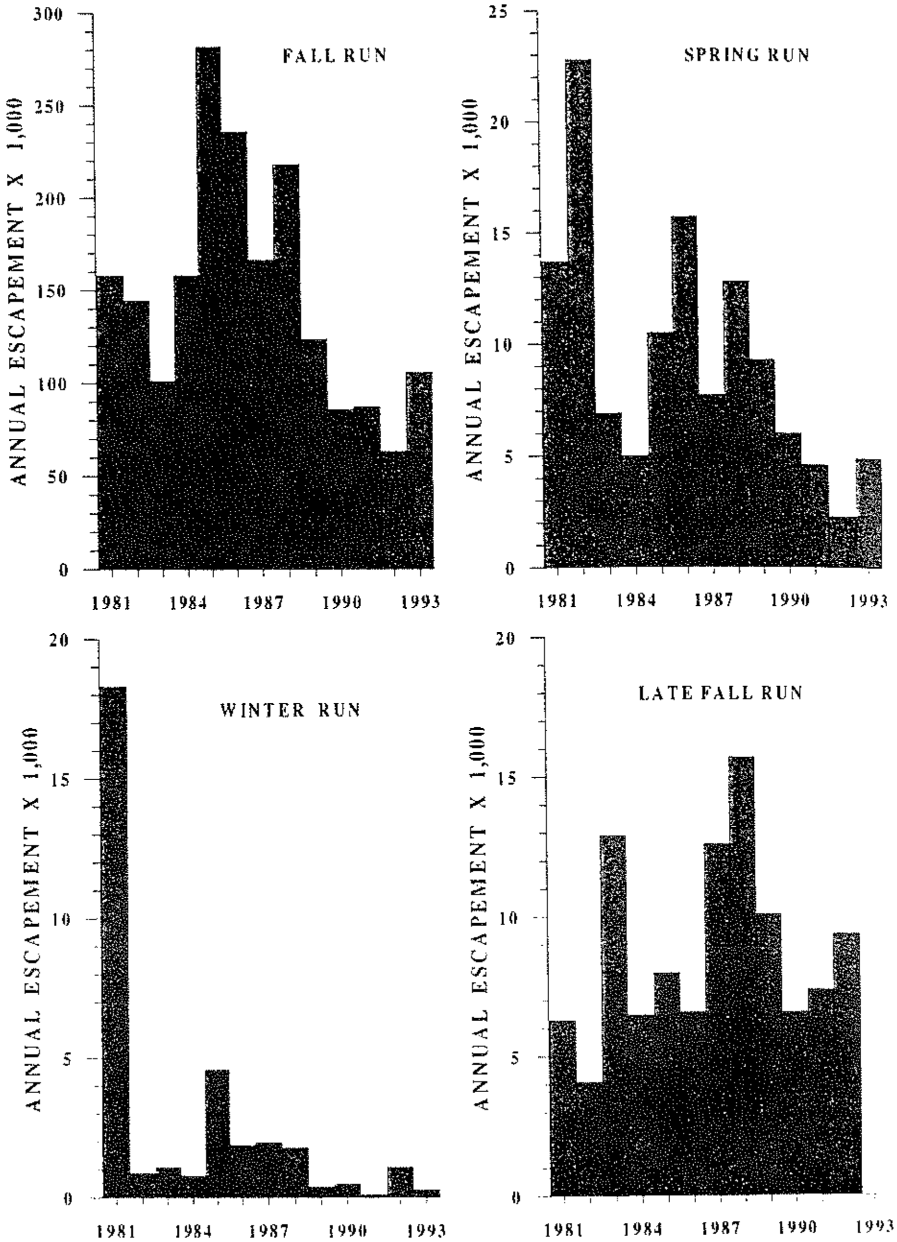
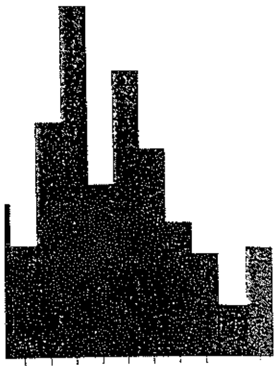


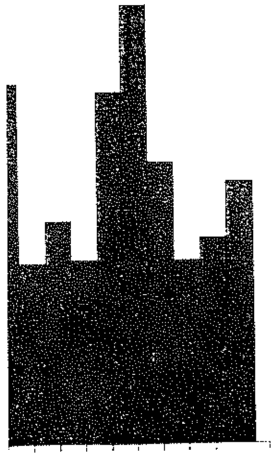
FIGURE 3. Estimated spawning escapement of four races of Central Valley Chinook salmon.

transition from fresh water to the ocean. Some young fall Chinook salmon do enter the estuary in late winter/early spring as fry; others may not leave their home stream until about a year after hatching. The early and late outmigrants can range in size

SPRING RUN



LATE FALL RUN



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from 40 to nearly 200 millimeters. Fall Chinook spawn mostly at 3 years of age, after 2 years in the ocean. Fall-run salmon are artificially propagated at several Central Valley hatcheries: Coleman National Fish Hatchery, Feather River Hatchery, Nimbus Hatchery, and Mokelumne and Merced River Fish Facilities. Smolts from the Coleman, Merced, and Mokelumne facilities are released upriver and migrate through the Delta. The Department of Fish and Game transports smolts from the Feather River and Nimbus hatcheries to San Pablo Bay in 7500 L tank trucks, so these juveniles avoid mortality factors associated with migration through the lower rivers and the Delta.

The late-fall run is relatively small numerically, but the adults achieve the largest average size of the four Central Valley races, mainly because a higher percentage of the adults spawn at 4 and 5 years than in the other three races. Most of the spawning occurs in the mainstem Sacramento River during February and March. Although not much is known about late-fall outmigration, it appears that most juvenile late-fall salmon pass through the estuary in November through January, about a year after hatching. They enter the Delta ranging in size from about 120 to 200 millimeters. There is a small late-fall run artificial propagation program at Coleman National Fish Hatchery, and all of the smolts are released upriver, generally in January.

The winter run is now the smallest of the four Central Valley races in size and abundance and is listed as endangered by both the State of California and the Federal Government. Winter Chinook mostly spawn during May through July in the mainstem Sacramento River, usually in the reach between Red Bluff and Redding. Most juveniles leave the upstream areas by the end of December; peak smolt emigration through the Delta is in late February through mid-April. Smolts are generally in the 80-150 mm length range when moving through the Delta. There is a small winter Chinook artificial propagation program at Coleman National Hatchery with the fish released up river in December and January.

Although perhaps once the most abundant of the four races of Central Valley Chinook, the spring run is now among the least abundant and a petition has been prepared to list the race under the Federal Endangered Species Act. Historically, adult spring run migrated to higher elevation streams, where they held over in cold pools during summer and spawned in late August through September. Dams have blocked access to many of these streams and in some streams, such as the Feather River, eliminated the geographic isolation between fall and spring runs. Due to the present lack of physical isolation, some interbreeding now occurs between the two races. There are still small, genetically distinct spring-run populations on Mill Creek, Deer Creek, and perhaps Butte Creek — all tributaries to the Sacramento River. There is almost no information on fish length and timing of spring run movement through the Delta. Some data indicate that spring run may move into and through the Delta as fry, smolts, and yearlings at about any time of the year except July through September. Spring run are propagated at the Feather River Hatchery, with the production released in San Pablo Bay.

Fish protection at the State Water Project Delta intakes depends on the timing of juvenile outmigration through the upper Delta as well as the size of the fish. The bulk of the outmigration, in terms of total numbers, is in April, May, and June when fall-run smolts move to the ocean. Although accurate estimates are not available, it appears that during this spring period the numbers of annual juvenile outmigrants from the Sacramento Valley are in the low tens of millions and from the San Joaquin Basin are in the low hundreds of thousands. However, other fall-run life stages and life stages of the other three races may be present at almost any time and size. This variation in size and timing makes it difficult to eliminate, reduce, or offset salmon losses at the State Water Project intake. The overall screening operation is further complicated by timing, size, and physiological makeup of the other 40 or so fish species that may encounter the screens.

Juvenile Chinook salmon all look alike and in the Delta cannot be accurately sorted by race. The 1992 and 1993 biological opinions issued by the National Marine Fisheries Service contained incidental take statements that required an estimate of the numbers of winter-run juveniles taken (killed) at the SWP/CVP Delta intakes. The opinions called for adoption of a length criteria system developed by Department of Fish and Game staff; a system that uses spawning time and growth rates to predict the range of size that fish of each race might have on a given date.

Department of Water Resources staff converted this size criteria system to a graphical representation of the length intervals on which individual fish can be plotted to determine their race. As shown in a plot of untagged salmon collected at a rotary screw trap near the intake to the Glenn-Colusa Irrigation District (Fig. 4), this size by date classification system is not completely reliable in that there are not discrete groups of fish within the size band for each race. The large overlap between the races, especially late-fall and winter, is due to the natural variation in spawning time, emergence and growth among the races and even within each race among spawning and rearing locations. It does, however, provide a qualitative estimate of run timing and has proven to be a useful tool in sorting winter run from the other races. The Department of Water Resources has contracted with a geneticist at the University of California at Davis' Bodega Marine Laboratory for a 3-year study to determine if micro-satellites in the nuclear DNA can be used to provide a more quantitative race identification system.

FISH SCREENS AND THE FISH SALVAGE PROCESS

The State Water Project Delta screening system, illustrated in Fig. 5, was patterned after a system developed for the Central Valley Project Delta intake in the early 1950s. The screens are based on the ability of fish to avoid being entrained (a behavioral barrier) as compared to a more typical screen designed to physically exclude fish (a positive barrier). The system works as follows.

Clifton Court Forebay (not shown on Fig. 5), a 37 million-cubic-meter regulating reservoir, is located between the canal intake (and the screens) and the Delta. Inflow of water and entrained fish from the Delta is controlled by three radial gates, which are opened at higher tidal elevations to fill the reservoir. The presence of the forebay helps regulate water level and allows project operators to control water

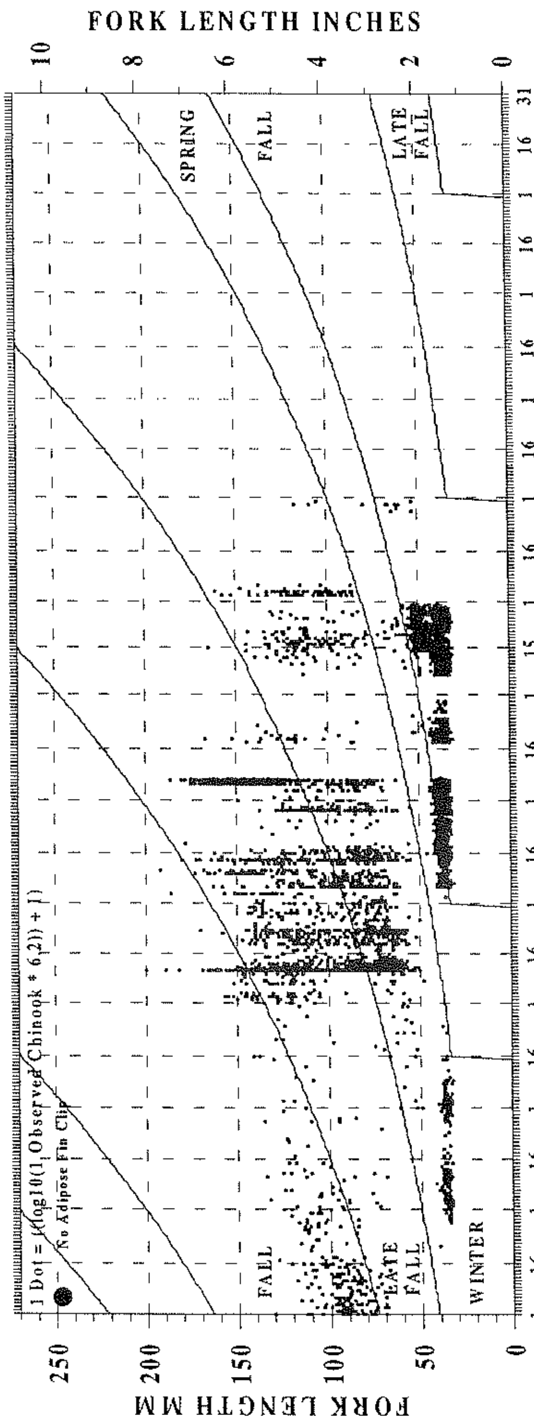

FIGURE 4. Classification by race of juvenile Chinook salmon collected at the Glenn-Colusa Irrigation District by rotary screw trap, August 1994-March 1995.

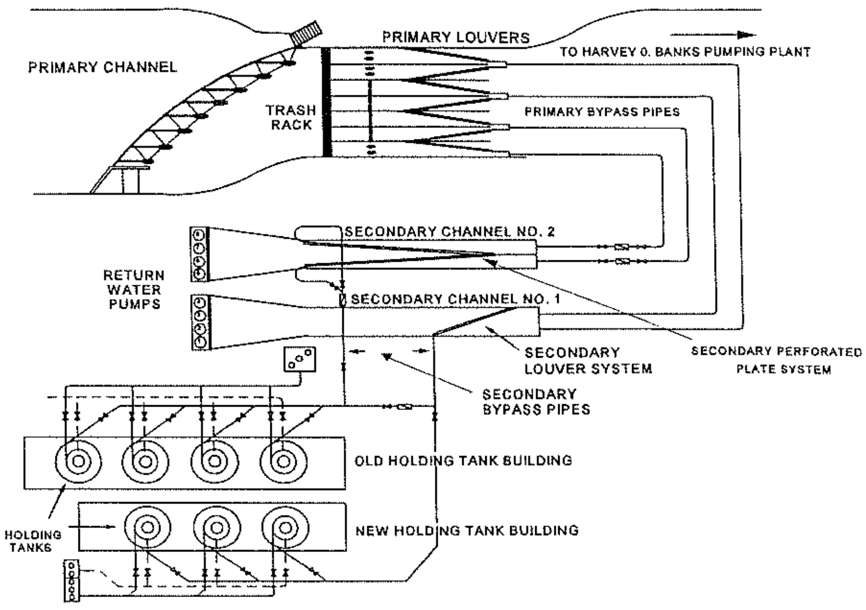

FIGURE 5. Schematic diagram of the John E. Skinner Fish Protective Facility.

velocity at the screens. Water velocity is an important determinant of screen efficiency.

A trashrack in front of the screens collects much of the floating debris before it encounters the screens themselves.

The primary bays contain louver screens (about 6 m high by 25 m long) on each side of the "V" and a solid wall in the middle, which ends just before the apex of the "V." The louver screens themselves are similar to large vertical venetian blinds, with 2.5 cm openings along the face, which is at a 15 degree angle with the flow. The operating principle is that fish will sense the turbulence along the screen face and avoid entering the spaces between each slat in the louver. The ability to avoid entering the slot depends on fish size and water velocity. In the mid-1980s, at the request of the Department of Fish and Game, the Department of Water Resources installed center walls in all bays to improve fish salvage efficiency, especially for striped bass.

Fish going through the primary louvers wind up in the California Aqueduct and may be killed in one of the pumping plants along the aqueduct. Many of the non-salmonids apparently survive the process, since there are extensive fisheries for catfish and striped bass in the aqueduct itself and in reservoirs from the Delta to Silverwood, near Riverside.

Fish making it to the apex of the "V" enter a bypass pipe leading to the secondary screening system. The purpose of the secondary screens is to further concentrate the fish before they enter the holding tank buildings. The original secondary was a louver system similar to the primary. In the mid-1980s, the Department of Water

Resources constructed another parallel, secondary system but with a positive barrier, flat-plate screen with about 6-mm openings. At the end of the secondaries, bypasses lead to holding tanks.

The five holding tanks, in two separate buildings, are about 6m diameter by 6 m deep and contain about 80 cubic meters of water at nominal operating depth of 2.75 meters. Fish enter the holding tanks from the secondary bypasses. Originally there was only one series of holding tanks but in the early 1990s, at the request of the Department of Fish and Game, the Department of Water Resources added a second series so in-tank velocities could be maintained at acceptable levels when pumping at full capacity.

Every 2 hours when the facility is operating, the bypass flow (and fish) are diverted to a counting tank, typically for 10 to 30 minutes. All fish in the counting tanks during the sampling period are collected, enumerated, and identified. Department of Fish and Game staff, who conduct the collection, counting, and transport process, convert the sampling data to estimates of total daily salvage by species. If the counting interval is at least 10 minutes of 120 minutes and the fish are reasonably abundant, the estimates are probably accurate to ± 20%. The sample counts are extrapolated to daily totals, by species, and the data (including fish length) are found on the Interagency Ecological Program's Home Page (http://wwiep.water.ca.gov). The database is updated weekly.

Periodically during the day, Department of Fish and Game staff loads all fish from the holding tanks into a 7500-liter tank truck and hauls them about 40 kilometers to release sites near the confluence of the Sacramento and San Joaquin rivers. Salt (sodium chloride) is added to reduce stress, and pure oxygen is injected to maintain acceptable dissolved oxygen levels. Hauling frequency is based on fish density and any controlling reasonable and prudent measures in the delta smelt or winter Chinook biological opinions.

HISTORICAL SALVAGE OF ALL FISH SPECIES

During the 1979-1993 period, 47 species of fish were salvaged at Skinner Fish Facility (Table 1). (We selected 1979-1993 because this represents the most reliable historical salvage database. Data actually go back to 1968, but quality control on data collection and storage was not rigorous until 1979.) Six additional species, including white bass and yellow perch, although listed in the database in small numbers, are not included because their identifications have not been confirmed. More than half (26 out of 47) of the species salvaged have been purposefully or accidentally introduced into California. Most are fresh or brackish water species, although salvage of Pacific herring and staghorn sculpin indicates that typical Bay species sometimes move into the Delta.

Not all of the 47 species are abundant in the salvage. Five introduced species accounted for more than 90 percent of the salvage (Table 2). One species alone, striped bass, dominated the salvage for the reporting period, with about 70 percent of the total. (These numbers represent fish longer than about 20 mm; larval striped bass and other fish less than about 20 mm total length are not salvaged or counted very effectively with the present system.)

TABLE 1. Fish species collected at Skinner Fish Facility, 1979-1993.

Common Name	*Scientific Name*	*Introduced* (I) *or Native* (N)
Chinook salmon	*Oncorhynchus tshawytscha*	N
Steelhead rainbow trout	*Oncorhynchus mykiss*	I
Striped bass	*Morone saxatilis*	I
White catfish	*Ameiurus catus*	I
Brown bullhead	*Ameiurus nebulosus*	I
Yellow bullhead	*Ameiurus natalis*	I
Black bullhead	*Ameiurus melas*	I
Channel catfish	*Ictalurus punctatus*	I
Blue catfish	*Ictalurus furcatus*	I
Black crappie	*Pomoxis nigromaculatus*	I
White crappie	*Pomoxis annularis*	I
Green sunfish	*Lepomis cyanellus*	I
Bluegill	*Lepomis macrochirus*	I
Largemouth bass	*Micropterus salmoides*	I
Smallmouth bass	*Micropterus dolomieu*	I
Warmouth	*Lepomis gulosus*	I
Redear sunfish	*Lepomis microlophus*	N
Tule perch	*Hysterocarpus traski*	N
Sacramento perch	*Archoplites interruptus*	N
American shad	*Alosa sapidissima*	I
Threadfin shad	*Dorosoma petenense*	I
Splittail	*Pogonichthys macrolepidotus*	N
Sacramento squawfish	*Ptychocheilus grandis*	N
Hardhead	*Mylopharodon conocephalus*	N
Golden shiner	*Notemigonus crysoleucas*	I
Carp	*Cyprinus carpio*	I
Hitch	*Lavinia exilicauda*	N
Sacramento blackfish	*Orthodon microlepidotus*	N
Goldfish	*Carassius auratus*	I
Sacramento sucker	*Catostomus occidentalis*	N
Threespine stickleback	*Gasterosteus aculaetus*	N
Longfin smelt	*Spirinchus thaleichthys*	N
Delta smelt	*Hypomesus transpacificus*	N
Wakasagi[1]	*Hypomesus nipponensis*	I
White sturgeon	*Acipenser transmontanus*	N
Green sturgeon	*Acipenser medirostris*	N
Inland silverside[2]	*Menidia beryllina*	I
Yellowfin goby	*Acanthogobius flavimanus*	I
Chameleon goby[3]	*Tridentiger trigonocephalus*	I
Prickly sculpin	*Cottus asper*	N
Staghorn sculpin	*Leptocottus armatus*	N
Riffle sculpin	*Cottus gulosus*	N
Bigscale logperch	*Percina macrolepida*	I
Starry flounder	*Platichthys stellatus*	N
Lamprey	Various Species	N
Mosquitofish	*Gambusia affinis*	I
Pacific herring	*Clupea pallasii*	N

[1] Identified by Johnson Wang. Electrophoretic confirmation pending.
[2] Also called Mississippi silverside.
[3] According to Scott Matern, University of California at Davis, two species are actually present: *T trigonocephalus* and *T. bifasciatus*.

HISTORICAL SALVAGE OF CHINOOK SALMON

As shown in Table 2, about 1.9 million juvenile Chinook salmon were salvaged at Skinner Fish Facility during 1979 through 1993. This total is broken down by year in Table 3, which also includes total annual pumping for the period. Although there is considerable variability in the numbers, the totals after 1989 are generally lower than in previous years, reflecting the general lower abundance of Central Valley Chinook. The high salvage in 1986 probably reflects fry washed out during high February/March flows, as well as good fry-to-smolt survival as a result of high streamflows during the rearing period.

Chinook salmon juveniles can be present in the Delta during all months of the year, but they are most abundant during April, May, and June (Table 4). The April-June salvage consists mainly of wild fall-run smolts, with a few hatchery fish included. The fall fish are yearlings, which may be wild fall- or spring-run and probably some Merced River Hatchery fish.

TABLE 2. Estimated salvage of 20 most common fish species at State Water Project Intakes, 1979-1993.
(*All estimates are rounded*)

Common Name	*Total Salvage*	*Maximum Annual Salvage*	*Year Maximum Occurred*
Striped bass	71,887,000	13,038,000	1986
Threadfin shad	15,408,311	7,184,000	1993
American shad	7,852,000	900,000	1981
White catfish	3,630,000	811,000	1984
Yellowfin goby	2,963,000	1,610,000	1984
Splittail	2,186,000	1,160,000	1986
Chinook salmon	1,913,840	435,000	1986
Channel catfish	1,184,709	359,000	1986
Prickly sculpin	685,000	376,000	1986
Inland silverside	684,000	74,102	1987
Longfin smelt	328,000	140,000	1988
Delta smelt	319,000	56,110	1988
Bigscale logperch	155,000	41,000	1988
Chameleon goby	127,000	65,000	1993
Steelhead	92,000	17,000	1982
Bluegill	84,000	31,000	1988
Largemouth bass	67,000	31,000	1993
Riffle sculpin	60,598	45,962	1985
Black crappie	56,000	12,000	1991
Staghorn sculpin	37,000	28,000	1990

SOURCES OF SALMON MORTALITY IN THE SALVAGE PROCESS

The Chinook salmon salvage numbers are estimates of the numbers of juvenile salmon that wound up in the holding tanks. Some salmon (and other salvaged fish) die or are lost between the time they enter Clifton Court Forebay to the time they are discharged from the hauling trucks at the release sites. For Chinook salmon, sufficient experimental work has been done to provide a good idea of where the mortalities occur. In most cases, we have empirically-derived loss estimates at each step, but not everyone agrees as to the reliability of these loss estimates. Following

TABLE 3. Annual salvage of Chinook salmon at Skinner Fish Facility and SWP Delta Pumping, 1979-1993.

Year	*Salvage (All Races)*	*Pumping (km^3)*
1979	122,439	2.669
1980	80,133	3.104
1981	101,605	2.626
1982	278,419	3.250
1983	68,942	2.322
1984	145,041	2.032
1985	140,713	3.327
1986	435,233	3.301
1987	177,880	2.819
1988	151,908	3.338
1989	106,259	3.822
1990	35,296	3.825
1991	39,170	2.193
1992	22,190	1.940
1993	8,641	3.146

TABLE 4. Typical annual pattern of Chinook salmon salvage at State Water Project Intake (*data are for 1984*).

Month	*Total Number Salvaged*	*Number per 1000 Cubic Meters*	*Average Length (mm)*
January	—	—	—
February	79	0.001	101
March	1,659	0.01	161
April	27,259	0.10	103
May	40,077	0.20	100
June	46,131	0.21	94
July	2	—	115
August	575	0.002	136
September	—	—	—
October	10,515	0.08	195
November	8,856	0.03	179
December	9,884	0.03	192

is a summary of the loss estimates, how they were derived, and some suggestions on how losses might be reduced.

Pre-screen Losses

Artificial environments such as occur near structures in water (*e.g.*, bridge piers and fish screens) often act to concentrate predators. The predatory fish use the structures for concealment and can remain in backwater areas, which reduces their energy expenditure while waiting for prey to appear. The intake to the California Aqueduct appears to provide predator habitat, and the density of striped bass and other piscivores is generally higher than in adjacent Delta channels.

At the SWP intake, prescreen losses are synonymous with Clifton Court Forebay predation losses. The forebay contains a wide variety of fish (Table 5). More than 80 percent of the fish collected in a 1-month beach seining effort were striped bass,

TABLE 5. Numbers and sizes of 12 most abundant fish species captured by beach seining in Clifton Court Forebay, November 16 to December 21, 1992.

Common Name	*Total Catch*	*Mean Length (mm)*	*Length Range (mm)*
Striped bass*	10,852	321	53 - 1105
White catfish*	655	359	215 - 520
Channel catfish*	517	489	236 - 628
American shad	475	280	178 - 405
Carp	374	587	420 - 758
White sturgeon	72	1,091	811 - 1643
Goldfish	66	405	372 - 425
Green sturgeon	32	657	416 - 1632
Largemouth bass[1]	28	361	282 - 497
Splittail	24	327	282 - 376
Sacramento blackfish	24	433	295 - 471
Chinook salmon	10	686	510 - 887

[1] Potential predator on Chinook salmon.

most of which were large enough to prey on juvenile Chinook salmon. As part of the Interagency Ecological Program studies, the Department of Fish and Game has estimated that in March 1993 the total striped bass population in the forebay was about 200,000, even after almost 29,000 stripers had been removed in a pilot predator removal program. Other estimates have indicated similar levels of abundance, although there may be seasonal variation.

Juvenile salmon enter Clifton Court Forebay through the radial gates and, even by the most direct route, must traverse a few kilometers of open water before entering the salvage facilities. Interagency Ecological Program staff have made several attempts to determine losses of juvenile Chinook between the radial gates and the trashracks. The experimental design for each test to estimate predation losses consists of releasing two groups of marked (spray-dyed) hatchery salmon smolts — one group near the radial gates and the other in front of the trashracks immediately in front of the screens. Marked fish are recovered in the holding tanks, and the difference in recovery between the two release groups provides an estimate of predation in Clifton Court Forebay. Losses of marked hatchery salmon across the forebay are significant (Table 6).

Models to determine predation losses of juvenile salmon due to Clifton Court Forebay predation use a 75 percent prescreen loss factor, which is an average of the 1978, 1984, and 1985 estimates (*i.e.*, of 100 juveniles entering the forebay, only 25 are calculated to reach the salvage facility). The National Marine Fisheries Service specifies this factor in its winter Chinook biological opinion. The 75 percent factor was also adopted in 1986 as part of a Department of Fish and Game/Department of Water Resources mitigation agreement to offset direct losses of fish at the salvage facility.

The high estimates of losses to predators and the finding that striped bass are likely the major predators have caused considerable interest in a possible program

TABLE 6. Losses of juvenile hatchery-reared fall Chinook salmon crossing Clifton Court Forebay. (*Estimated from mark/recapture studies.*)

Month and Year of Study	*Average Size of Test Fish (mm)*	*Estimated Predation Rate (%)*
October 1976	115	97
October 1978	88	88
April 1984	79	63
April 1985	45	75
June 1992	77	98
December 1992	121	77
April 1993	66	94
November 1993	117	99

to reduce losses by catching striped bass with nets and hauling them for release in San Pablo Bay or other locations far from Clifton Court Forebay. A major predator removal program was planned for fall 1994, but opposition by angler organizations caused it to be postponed. In the meantime, results of a limited acoustic tagging program indicated that sublegal striped bass in the forebay move freely through the radial gates to the open Delta, so removal may have only limited effectiveness.

Future studies by Department of Water Resources and Department of Fish and Game personnel will refine the loss estimates and confirm preliminary indications that striped bass move between Clifton Court Forebay and the Delta more or less at will.

Screen Efficiency

Because the bars in the louver system are 2.5 cm apart, the State Water Project primary and secondary louver screening systems are not 100 percent efficient for Chinook salmon and other fish whose bodies can fit through the gaps. In 1970 and 1971, the Department of Fish and Game and Department of Water Resources evaluated the efficiency of the screening facility for several species of fish, including Chinook salmon. Several variables were tested, such as fish length, approach velocity, bypass ratio, and the presence of a solid center wall in the V-shaped screens.

The average screening efficiency derived from all salmon tests for the primary and secondary louver screens is summarized in Fig. 6 (DWR/DFG 1973). For the primary screens, efficiency ranged between about 70 and 85 percent with no apparent relationship with fish length. Efficiency of the secondary screens ranged from about 70 to 95 percent and, as would be expected, increased with fish length. The lack of a similar relationship in the primary system is probably an artifact of the testing process.

The Department of Fish and Game has combined the data to obtain an overall (combined primary and secondary) screen efficiency, which is calculated from the following equations based on fish length:

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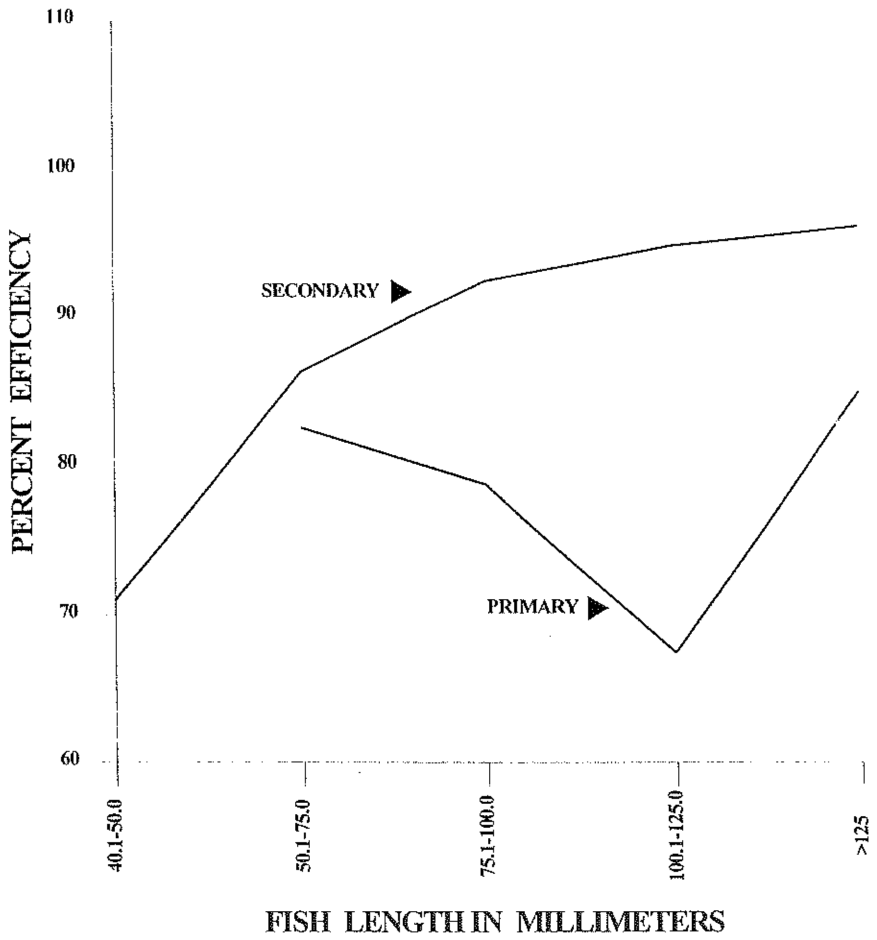

FIGURE 6. Relation between Chinook salmon length and screening efficiency, average of all test data. (Modified DWR/DFG 1973)

Length	*Efficiency* (E)
1-100 mm	E = 0.630 ÷ (0.0494) (Approach velocity)
>100 mm	E = 0.568 ÷ (0.0579) (Approach velocity)

where velocity is expressed in feet per second. During the designated salmon outmigration season, October through May 15, water project operators attempt to maintain the approach velocity near 1 m sec^{-1}, which optimizes screening efficiency for Chinook salmon. Overall, calculated screen efficiencies are typically in the range of 70-80 percent (*i.e.,* 70 to 80 of 100 salmon encountering the screens end up being salvaged).

A variable and unknown portion of the losses at the screens is probably due to predation by striped bass in the primary and secondary screen channels. For example, on March 10, 1992, Department of Fish and Game staff removed 74 striped bass (average size of 289 mm) upstream of the secondary channel louvers. Periodic removal of piscivores appeared to reduce the population, and this is included in routine maintenance activities at the screens.

Handling and Trucking

The salvage process requires that fish be removed from the holding tank, loaded into a tank truck, and hauled to a release site about 40 km from the facility. In 1984 and 1985, Department of Fish and Game staff evaluated losses of Chinook salmon from handling and trucking. The procedures involved handling or trucking the salvaged fish similarly to normal operations, then placing the fish in a small pool, and recording latent mortality for the next 24 hours. In 12 of 15 tests with Chinook salmon, survival after handling and trucking averaged 99 percent. Two tests, conducted in June, had low survival due to high water temperatures. The other test, in November, had 87.5 percent survival. Based on results of the handling and trucking studies, Fish and Game has established criteria for holding tank flows and fish density in the hauling trucks.

Post-release Mortality

There are no data available to determine if the salvage process causes Chinook salmon and other fish to be particularly vulnerable to predation at the release sites.

Aquatic Weeds

In the past 2 years, there has been a buildup of aquatic weeds in Clifton Court Forebay. The main problems have been due to an introduced pondweed, the Brazilian elodea (*Egeria densa*) and, to a lesser extent, hornwort (*Ceratophyllum demersum*).

Weeds are dislodged by wind, and some move toward the California Aqueduct, where they clog the screens, and fragments enter the holding tanks and fish transport trucks. Salvaged fish become entangled in the weed mass, both in the holding tanks and in the truck. The stress associated with the entanglement increases the direct and latent mortality of the salvaged fish.

The Department of Water Resources attempted to control the weed problem by a spring 1995 application of a selective herbicide (Komeen) over a 150-hectare section of Clifton Court Forebay where they are most dense. The first application appeared successful, and a second treatment will follow later in the year. Department of Fish and Game and Department of Water Resources staff did not observe any direct toxicological effects of the herbicide on fish in the forebay.

DISCUSSION

As is apparent from the information presented above, the fish protective facilities at the intake to the California Aqueduct salvage large numbers of fish but do not provide complete protection for juvenile Chinook salmon and other fish entrained into the California Aqueduct by way of Clifton Court Forebay. For example, calculations using procedures specified in the 4-Pumps Agreement and the winter-run biological opinion show that for every salmon salvaged more than three have been lost to predators in the forebay or through the fish screens. Even though the calculations may overestimate the losses, they do demonstrate a serious problem.

Suggested technical solutions have taken several forms, some of which have been implemented. The most commonly advanced suggestions are described below. Solutions that decrease water demand are beyond the scope of this article and are not included.

Improve Existing Facilities

During the past 10 years, the Department of Water Resources has spent several million dollars to improve Skinner Fish Facility. Improvements have ranged from major changes in the screens themselves (including a new, positive-barrier secondary system), a new holding tank building, rescreening the old holding tanks, a new tank truck and improved hauling procedures, and contracting with the Department of Fish and Game to conduct the counting and salvage operations. Also, Water Resources has invested additional millions in support studies to better understand the sources of mortality at the intake/salvage system and find ways to minimize these losses. It is doubtful that significant improvements to the existing system can be found that will substantially reduce losses, except perhaps reduction in losses to predators.

Mitigate for the Losses

In 1986, the Department of Fish and Game and Department of Water Resources signed an agreement, known as the 4-Pumps Agreement, in which Water Resources was to mitigate or offset direct fish losses at the intake. For Chinook salmon, the agreement specified that Fish and Game would calculate the annual losses and both departments, with the help of a fish advisory committee, and would propose, approve, and fund projects to increase salmon production. The general principals were that efforts should be geared toward natural production, as compared to hatcheries, and the emphasis should be on San Joaquin Valley streams. Typical projects have included gravel restoration, conjunctive use (installing pumps that allow farmers to use well water and leave streamflows in place), predator isolation (isolate large backwater ponds created by mining gravel in valley salmon streams), and improvements to the Merced Fish Hatchery. The goal is to have enough projects to offset the annual losses; however, because of the recent low run sizes in the San Joaquin system, there has not been sufficient production to offset salmon losses accumulated since 1986.

The 4-Pumps Agreement also included a $15 million lump-sum account for projects that appear to have significant benefits but that are difficult to quantify. For example, this fund was used to place about 76,500 cubic meters of spawning gravel in the upper Sacramento River near Redding. Additional approved allocations from this fund to benefit salmon include a conservation hatchery on the Tuolumne River, fish screens in Suisun Marsh and predator isolation projects on the lower tributaries.

Replace Existing Screens

Most modern fish screens are positive-barrier flat plates with openings as small as 3-4 mm to exclude fish while allowing water to pass through. To prevent fish from being impinged on the screens, the velocity of water approaching the screen face is low; for example, existing Department of Fish and Game criteria call for an approach velocity of about 0.1 m/sec. Because of space limitations, it would be physically very difficult to install the amount of screen area necessary to achieve the required approach velocity at the existing intake and maintain present export capacity.

New passive-barrier screens could be moved to the forebay intake, perhaps in a series of V-shaped screens at the present location of the radial gates. Bypasses at the narrow end of the Vs would lead the fish to a collection facility, possibly a barge to transport the fish to release sites away from the screens. A major problem with this alternative is that the fish would continue to be salvaged at the southwest corner of the Delta — not a location on their usual migratory path. In addition the screens would be designed for the maximum instantaneous flow (the flow when the gates are just opened), thus dramatically increasing the required screen area and cost. The small screen openings and the amount of aquatic plant and peat fibers in the water would also make cleaning difficult.

Reduce the Number of Salmon Entering the Forebay and Encountering the Screens

Since Chinook salmon move from the spawning grounds to the ocean in fairly well-known migration corridors and times, measures can be taken to limit the number of fish arriving at the intake. Measures underway or being considered include:

(1) Close the Delta Cross Channel from February 1 through May 20 each year. This measure is part of the December 15, 1994, Delta Agreement and is now in effect. Closing the cross channel reduces the number of salmon that leave the Sacramento River.

(2) Install an acoustical barrier at the head of Georgiana Slough during the outmigration period. Recent studies have indicated that Georgiana Slough is a natural migration path for some Sacramento Valley Chinook, that their survival when going this route is lower than if they had stayed in the main river, and that an acoustical barrier can keep at least a portion of the fish in the Sacramento River (U.S. Fish & Wildlife Service 1992; Hanson 1995). This barrier is now in the third year of testing at Georgiana Slough.

(3) Install a physical barrier at the head of Old River in the spring to help keep San Joaquin Basin smolts from leaving the river and winding up at the State Water Project and Central Valley Project pumps. The barrier has been tested with positive results, but it is not clear when or if it will be installed on a permanent basis.

(4) Pump in accordance with export/inflow ratios in the Delta Agreement and the 1995 water quality control plan for the estuary.

(5) Continue to truck much of hatchery production to San Pablo Bay.

Move the Intake to the California Aqueduct

One solution is to move the intake from the southern Delta to the Sacramento River near Hood. Two variations of this solution are to isolate the conveyance channel from Hood just downstream of Sacramento to the California Aqueduct (a peripheral canal) or to have a canal from Hood to some location in the Delta (a through-Delta system). Several technical issues remain to be resolved about screening a large intake on the Sacramento River (Odenweller & Brown 1982), as well as issues related to the size of the diversion and the amount of flow to be bypassed. The Interagency Ecological Program is addressing the fish screening technical issues associated with a possible diversion at Hood.

The next few years will see a serious examination of Delta issues from both fish and water supply viewpoints. A group of stakeholders representing agricultural, environmental, and urban water interests will be working with the recently appointed Bay/Delta Advisory Council and State and Federal agencies to review the issues and recommend actions that have the general goals of improving conditions for fish and their associated estuarine habitat as well as improving water supply reliability for the 20 million Californians who receive at least part of their water supply from the Delta.

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