WILD FISH ENTRAINMENT BY ARCHIMEDES LIFTS AND AN INTERNAL HELICAL PUMP AT THE RED BLUFF RESEARCH PUMPING PLANT, UPPER SACRAMENTO RIVER, CALIFORNIA: FEBRUARY 1997 - MAY 2000

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Abstract-The overall goal of the Red Bluff Research Pumping Plant (RPP) biological evaluation program was to determine whether Archimedes lifts and internal helical pumps could be used to deliver water to the Tehama-Colusa canal without harming fisheries resources in the Sacramento River, with emphasis on chinook salmon. From February 1997 through May 2000, 133 trials were conducted to evaluate species, numbers, and characteristics of fish entrained from the river into the RPP. Trials lasted 24 hours and were segmented into diurnal and nocturnal periods. After passing through a lift or pump, fish were captured in downstream holding tanks, identified, measured (length), and assessed for mortality and injury. The specific objectives addressed in this study were: 1) determine diel and seasonal patterns of entrainment, 2) compare mortality and injury to fish passed through Archimedes lifts and the internal helical pump, 3) estimate the number of chinook salmon entrained annually, and 4) estimate the fraction of juvenile chinook salmon passing Red Bluff Diversion Dam that were entrained into the RPP.

Twenty-eight species of fish were captured during entrainment trials. Juvenile chinook salmon were most frequently entrained followed by prickly sculpin, lamprey, Sacramento sucker, Sacramento pikeminnow, and riffle sculpin. These six species comprised 94% of the 26,220 fish captured. Ninety-four percent of entrained fish were <100 mm in length. Nocturnal entrainment of chinook salmon exceeded diurnal entrainment in 33 of 35 months. Other fish species were also entrained more frequently at night. Seasonal patterns of chinook salmon entrainment followed patterns of abundance in the river, peaking in winter as fall-run juvenile chinook salmon outmigrated.

Mortalities and injuries of fish were compared among pumps during eighty 24-h trials and fifteen 2 to 3-h trials when all three pumps operated simultaneously. In the short-duration trials fish were removed from the tanks every 10-15 minutes. The objective of the short-duration trials was to minimize mortality due to confinement in holding tanks. In both 24-h and short-duration trials, mortalities and injuries were not due solely to pump passage. On their way to the holding tanks, fish traveled past screens with motorized brushes and into concrete channels where dewatering ramps were used to adjust the amount of flow into the tanks. Once in the holding tanks, fish were subject to turbulence and debris. Also, condition of the fish prior to entrainment was unknown. Therefore, frequency of mortality and sub-lethal injury obtained in this study for wild entrained fish are assumed to be overestimates of that due to pump passage alone.

Mean percent mortality of chinook salmon in the short-duration trials was 0.9, 0.6, and 1.2 for Archimedes 1, Archimedes 2, and the internal helical pump, respectively, compared to 2.8, 2.9, and 4.9 in the 24-h trials. Mortality did not differ significantly among the three pumps for the short-duration or the 24-h trials. Percent frequency of chinook salmon with sub-lethal injuries was < 0.3% for each of the three pumps during short-duration trials and <1.8% in the 24-h trials.

The total number of chinook salmon entrained during trials was consistently less than 5,000 each year. The estimated number entrained was calculated weekly for each pump as the product of the number entrained per hour during trials and the hours the pump operated. The estimated total number of chinook salmon entrained was consistently less than 10,000 each year. During this study the RPP was operated for biological evaluations during all seasons. Therefore, the number of fish entrained was higher than would occur if the plant was used solely to meet water needs of the Tehama-Colusa and Corning canals. Forty-nine percent of chinook salmon entrained were collected during trials conducted in December and January, months that the plant typically would not be operated to supply water to the canals.

During this study, 24-h trials were conducted simultaneously with the U. S. Fish and Wildlife Service's rotary screw trap sampling in the Sacramento River to determine the fraction of chinook salmon in the river entrained into the RPP during different seasons of the year. The screw trap sampling provided daily estimates of the total number of juvenile chinook salmon passing Red Bluff Diversion Dam (RBDD). The fraction of fish passing RBDD that were entrained into the RPP was consistently less than the fraction of river discharge diverted. During 84 trials, the fraction of daily passage entrained ranged from 0.00007 to 0.0138 and averaged 0.0022 (0.22%). The highest fraction entrained occurred during the winter outmigration of fall chinook salmon. The fraction of winter chinook salmon entrained averaged 0.0017 and ranged from 0.00008 to 0.0066. The small fraction of salmon entrained likely was due to the position of the pump intakes near the bottom of the river whereas the majority of outmigrating chinook salmon inhabited the upper water column. The small fraction of chinook salmon entrained into the RPP, combined with the low frequency of mortality and sub-lethal injury to all fish passed through the pumps, supports the conclusion that the RPP can be operated with little harm to fishery resources, including chinook salmon, in the Sacramento River at Red Bluff.

Table of Contents

Table of Contents (continued)

List of Tables

List of Tables (continued)

Table **Page**

List of Figures

Figure **Page**

List of Figures (continued)

Figure **Page**

List of Figures (continued)

Figure **Page**

List of Figures (continued)

Figure **Page**

Introduction

Populations of anadromous salmonid fishes in the Pacific Northwest have been reduced by anthropogenic alterations of streams, rivers and their riparian landscapes over the last 150 years. Many consider hydroelectric and water diversion dams to be major factors in the decline of salmonid fishes due to juvenile and adult passage delays, entrainment of juveniles within associated pumping facilities and canals, and loss of habitat (Hallock 1959; Rainey 1985; Pearce and Lee 1991; Liston et al. 1994; Yoshiyama et al. 1998; Black 1998). In California, large water diversions and pumping projects on the upper mainstem of the Sacramento River, including the Glenn-Colusa Irrigation District (GCID), Anderson-Cottonwood Irrigation District (ACID), and Red Bluff Diversion Dam (RBDD) have contributed to the decline of chinook salmon *Oncorhynchus tshawytscha* populations (Ward 1989, Vogel et al. 1988). Winter and spring runs of chinook salmon in the Sacramento River are listed as protected under the *Endangered Species Act of 1973* (59 FR 440; 64 FR 50393, respectively). Steelhead *Oncorhynchus mykiss*, another native salmonid in the Sacramento River, is also federally listed (63 FR 13347).

Prior to installation of the rotary drum screens in 1975, GCID's pumping facility (river km 332; Figure 1) entrained and killed an estimated 800,000 to 9,100,000 juvenile chinook salmon annually (Ward 1989; USA v GCID 1992). Further upstream, ACID's diversion dam (river km 480; Figure 1) also entrained juvenile chinook salmon into its Bonneyview Pump Diversion Facility. According to California Department of Fish and Game (CDFG), ACID's unscreened pumps entrained between 1.23% and 2.45% of the 1991 annual winter-run emergent fry by September of that year (CDFG v. ACID 1992). As a result of these findings, a cylindrical fish screen was installed on this pump facility in 1992.

Completion of Red Bluff Diversion Dam (RBDD; river km 391; Figure 1) in 1964 and lowering of the dam gates in 1966 to supply water to the Tehama-Colusa canal (TCC) posed another threat to outmigrating juvenile chinook salmon in the Sacramento River. From 1982 through 1987 the annual entrainment of outmigrating chinook salmon into the canal headworks varied from 0.2 to 0.6 million (Vogel et al. 1988). The fish louver and bypass system, original components of RBDD, were ineffective at diverting entrained juveniles back to the Sacramento River, and injured 1.6% to 4.1% of the migrants passing through the facility. As a result, in 1990 the louvers and bypass system were replaced with rotary drum screens and a new fish bypass system. The new facilities proved to be successful at returning entrained juveniles to the river unharmed (Bigelow and Johnson 1996).

Since the Federal listing of winter-run chinook salmon as endangered in 1994, the gates on RBDD have been raised each year from September 15th through May 15th to accommodate fish passage. In 1995 the Bureau of Reclamation (Reclamation) completed construction of Red Bluff Research Pumping Plant (RPP) near Red Bluff Diversion Dam (Figure 1; McNabb et al. 1998, Frizell and Atkinson 1999). This project was part of Reclamation's commitment to improve fish passage at the dam and to deliver water to the Tehama-Colusa canal as needed during the eight-month gates-raised period. The plant has two Archimedes lifts and an internal helical pump

(Figure 2a). The lifts and pump were developed to attempt to pass fish with minimal injury or mortality. Because all three pump intakes are unscreened, fish from the Sacramento River are entrained into the plant. Fish pass through a trash rack with 5 cm (2 in) spacings that exclude large debris and most large fish from the pumps. Vertical wedgewire screens designed to contain fish but pass water are located downstream of the pump outfalls (Figure 2b). About 90% of the flow passes through the screens to the TCC while about 10% of the flow, along with entrained fish and debris, continues into an open, curved bypass channel (Figure 2c). Flows in the bypass channel can be diverted into holding tanks (Figure 2d) or returned to the river downstream of RBDD via underground conduits (Figure 3).

If the Archimedes lifts and helical pump at the RPP are to be part of the ultimate solution to fish passage problems at RBDD, they must be able to provide water to the TCC without harming fishery resources in the Sacramento River. To evaluate the plant's ability to do this, Reclamation and interagency cooperators developed a biological evaluation program for the RPP to be conducted over several years (Liston and Johnson 1992). Work presented in this report addresses entrainment of adult and juvenile fish from the Sacramento River into the plant, with an emphasis on juvenile chinook salmon (Objective I). Results of this study will be used to help determine whether Archimedes lifts and internal helical pumps can operate satisfactorily with minimal harm to fish populations in the Sacramento River. If the pumps prove benign, their use would continue to facilitate gates-raised operation of RBDD from mid-September through mid-May with the potential for construction of a larger pumping facility that could deliver water to meet needs year-round.

The overall purpose of this study was to quantify and characterize entrainment of juvenile chinook salmon and other fish species into the RPP during different seasons of the year. The specific study objectives were to:

1. Record diel and seasonal patterns of entrainment for chinook salmon and other fish species entrained into the RPP from the Sacramento River.

2. Estimate the number of individuals in each of the four runs of chinook salmon entrained annually into the RPP.

3. Compare percent frequencies of mortality and sub-lethal injury to fish passed through Archimedes lifts versus the internal helical pump.

4. Estimate the fraction of wild juvenile chinook salmon passing Red Bluff Diversion Dam that are entrained into the RPP during different seasons of the year.

Methods

Plant Operations

The Archimedes lifts, manufactured by Wheelebrator/CPC, consist of 11.5 m (38 ft) long, 3.0 m (10 ft) diameter rotating cylinders with three helical flights continuously welded along the length of the cylinder's inside walls. The lifts are unique in having a rotating, sealed inlet at their lower end allowing them to operate over a wide range of river elevations. During this study each Archimedes lift operated at 26.5 revolutions per minute (rpm), delivering water at an average rate of 2.5 m^3/s (89 to 90 ft^3/s; Table 1). The hydraulic lift ranged from about 3.0 - 4.3 m (10 - 16 ft), depending upon river elevation. The internal helical pump, manufactured by Wemco-Hidrostal, has an inlet diameter of 91 cm (36 in) and is the largest of its type ever constructed (Frizell and Atkinson 1999). It has a single-vane impeller cast with a rotating conical shroud. From February 1997 through April 1998 the internal helical pump operated at 378 rpm and delivered an average of 2.7 m^3/s (96 ft^3/s; Table 1). In September 1998 the speed was reduced to 350 rpm using the variable speed drive. In December 1998 a smaller gear box was installed on the helical pump to permanently reduce the maximum speed to 350 rpm which was used for the remainder of the study. This reduced speed resulted in a decrease in pump discharge to 2.3 m^3/s (82.6 ft^3/s). The hydraulic lift ranged from about 3.8 - 5.5 m (12.5 - 18.5 ft).

The Archimedes lifts operated reliably during this study, and both lifts were operated a similar number of hours (Figure 4). The helical pump operated fewer hours than the Archimedes lifts because of repairs in 1997 and 1998. However, after its speed was reduced in September 1998, the helical pump operated with the same reliability and during the same periods as the Archimedes lifts (Table 1). In some years all three pumps were inoperable in winter and spring due to high river levels.

Fish entrainment was monitored 30% and 32% of the time that Archimedes 1 and Archimedes 2 operated, respectively (Table 1). The number of 24-h trials conducted was 118 and 122, respectively. The helical pump operated for approximately 1500 fewer hours than the Archimedes lifts. Entrainment was monitored 30% of the operating time, and ninety-four 24-h trials were conducted. Eighty 24-h trials were conducted when all three pumps operated simultaneously.

Entrainment Trials

24-h Trials

To address the study objectives, 133 24-h trials were conducted to monitor entrainment of fish from the Sacramento River. During 80 of these trials, all three pumps were operated simultaneously for 24 continuous hours. These trials were termed *complete trials*. Data from these trials were used to compare mortality and sub-lethal injury of fish among pumps since they were operated under similar environmental conditions.

Incomplete trials were those 24-h trials in which mechanical problems or high water levels caused one or more of the pumps to be inoperable or to shut down before the trial was completed. Fifty-three incomplete trials were conducted. Data from all 24-h trials (complete and incomplete) were used to tabulate numbers of fish entrained, to assess species composition and characteristics, to determine diel and seasonal entrainment patterns, and to estimate and project the number of chinook salmon entrained. Data from 84 trials, including complete trials and incomplete trials in which at least two pumps operated continuously for 24 h, were used to assess the fraction of wild chinook salmon entrained based upon data collected simultaneously with the Fish and Wildlife Service's screw trap monitoring.

Wild fish entrained from the river passed through a pump, were discharged into a concrete channel, traveled past vertical wedge-wire screens with motorized brushes and into an open, concrete bypass channel (Figure 3). During trials, wedge-wire screen dewatering ramps on each pump's bypass channel were lowered and the weir beneath the ramp was adjusted to divert approximately 0.02 m^3/s (0.7 ft^3/s) of flow up the ramp and into one of two holding tanks. Fish and debris contained in the bypass flows were also diverted into the holding tanks. The 1.2 m^2 holding tanks contained water to a depth of 0.9 m when full. They operated as a flow-through system with a water replacement rate of 1.2 minutes; discharge flowed into the bypass channel. At these flows, ambient river water quality and relatively non-turbulent conditions were maintained in the holding tanks.

Each 24-h trial began at sunrise and lasted 24 h unless an unscheduled shutdown of the pumps occurred. Fish and debris were removed from the holding tanks twice during these trials; at sunset and the following sunrise. This allowed diel entrainment patterns to be assessed. Times for sunrise and sunset were obtained from the website of the U. S. Naval Observatory in Bethesda, Maryland using the coordinates of latitude and longitude for the pumping plant. Each time tanks were cleared of fish, physiochemical data of water and pumping conditions were recorded, volume of debris in each holding tank was measured, and each fish was identified, measured, and assessed for mortality and injuries. Debris was measured volumetrically (cc) using displacement of water in a graduated 20 L bucket. Fish were returned to the river via the bypass conduits that exit the pumping plant into the Sacramento River or released directly into the river downstream of the pump intakes.

To assess seasonal patterns of entrainment, trials were conducted year-round when possible. Trials could not be conducted when river flows exceeded about 991 m^3/s (35,000 ft^3/s) during winter and spring storms. Under such high flows, pumps were shut down and pinch valves in the underground fish bypass conduits were closed to prohibit flooding of the plant. When river levels allowed, at least one 24-h trial was conducted each week throughout the year. From July 1 through March 31 of each year when juvenile winter chinook salmon could be in the river near the RPP, two 24-h trials were conducted each week that the pumps operated continuously (i.e., 24 h each day). This typically occurred in the spring (March) and fall (September 15 - October 31) when the gates on RBDD were raised out of the river yet water was required for agriculture and refuges.

Short-duration Trials

Data from complete 24-h trials were used to compare mortality and sub-lethal injury of fish among the three pumps. However, fish collected during these trials were confined in holding tanks for up to 14 h depending upon when they arrived in the tank in relation to the sunrise or sunset entrainment check. Conditions within the holding tanks could affect fish survival. High debris loads, high water flows into the tanks, long periods of confinement, and presence of other fish in the holding tank all could contribute to fish mortality and injury. Therefore, the 24-h trials included confinement and other effects, and likely over-estimated mortality and injury to fish entrained into the RPP. To obtain better estimates of mortality and injury of wild, entrained fish, 15 *short-duration trials* were conducted in winter and spring 2000 when high numbers of juvenile fall chinook salmon were entrained. During these 2 to 3-h entrainment trials, fish were removed from holding tanks, measured, and assessed for injury and mortality every 10 to 15 minutes. Therefore, mortality was not confounded with long-term confinement or conditions in the holding tanks. However, in both 24-h and short-duration trials, the condition of fish prior to entrainment was unknown. Entrained fish were transported to the river water facility and held for 96 h to assess delayed mortality. Data from the short-duration trials were used to compare mortality and sub-lethal injury among pumps and to evaluate length frequencies of entrained fish; data were not used to assess diel or seasonal entrainment patterns.

Environmental Data

Measurements of river elevation (m;ft), and speed (hz) and discharge (m^3/s; ft^3/s) of each pump were automated and continuously recorded on a computer in the pumping plant's automation facility. Water temperature (°C), dissolved oxygen (ppm, percent saturation), and total gases (% saturation) were measured from river water passing through the holding tanks. Water temperature and dissolved oxygen were measured with a YSI® Model 55 dissolved oxygen meter. Total gases were measured with a Sweeney® Model DS1-A saturometer. An HF Scientific® continuously-monitoring turbidimeter located in the river water fish facility associated with the RPP was used to measure turbidity (NTU).

In 1997 a HydroLab® DataSonde water quality monitoring probe deployed in the Sacramento River on the east side of RBDD provided hourly measurements of water temperature, dissolved oxygen, conductivity, and pH. Each month, data were downloaded, and probes were cleaned and calibrated. In 1998, Reclamation's Northern California Area Office replaced the Hydrolab with a YSI 6820 probe which provided hourly readings of water temperature and dissolved oxygen. These data were accessed through the California Department of Water Resources Data Exchange Center website. Reclamation's Operations and Maintenance personnel provided estimates of daily river discharge (m^3/s; ft^3/s) past RBDD based on data from the U. S. Geological Survey's gaging station near Bend Bridge, approximately 24 km upstream.

Numbers and Characteristics of Entrained Fish

Data from all 24-h trials were used in tabulating and characterizing entrained fish. Fish captured in holding tanks during trials were identified to species, measured (fork length for salmonids, total length for others) to the nearest 1.0 mm, assessed for mortality and injury, and inspected for tags, fin clips, or dyes that designate them as hatchery-released fish or as fish from another study. Injury assessment involved visually inspecting each fish for abnormalities to the integument, eyes, head, and fins. Run designation for chinook salmon was determined from a daily fork-length table generated by Green (1992). When high numbers of juvenile chinook salmon were entrained, the first 100 removed from each holding tank were measured. Additional chinook salmon were counted and recorded as extra dead or extra alive. For other species, the first 30 fish from each holding tank were measured and the remainder counted and recorded as extra dead or extra alive.

Larval fish <30 mm length were frequently observed in the holding tanks, especially during spring trials. These fish were not efficiently retained because of the relatively large mesh-size (3.2 mm, 0.13 in) of nets used to hold fish in the tanks. Therefore, data on fish <30 mm are not reported here. Numbers and patterns of larval fish entrainment were assessed in a separate study under Objective N of the RPP evaluation program (Liston and Johnson 1992; Borthwick and Weber 2001).

Seasonal and Diel Patterns of Entrainment

Data from all 24-h entrainment trials, regardless of the number of pumps operated, were used to determine seasonal and diel patterns of entrainment. However, trials that included only day or only night data were not included in analysis of diel patterns. Start and end times of each diurnal and nocturnal monitoring period were recorded for each trial. Total operating time and pump discharge were used to calculate acre-feet of water pumped during each diel period for each trial. In a 24-h period, approximately 175, 350, and 525 acre-feet of water was pumped when 1, 2, or 3 pumps operated, respectively. The number of fish entrained per acre-foot of water pumped was calculated monthly for each diel period. Monthly comparisons of the number entrained per acre-foot between nocturnal and diurnal periods were made for chinook salmon and other frequently entrained species.

Entrainment trials were conducted in all but five months between February 1997 and May 2000, allowing seasonal patterns of entrainment to be assessed over this three and one-half year period. The number entrained per acre-foot each month was used to assess seasonal patterns of entrainment for chinook salmon and other fish species.

Estimated and Projected Numbers of Chinook Salmon Entrained

Twenty-four hour entrainment trials were used as samples to estimate and project the number of chinook salmon, by run, entrained into the pumps each week. The *estimated* number entrained each week was the product of the number of chinook salmon entrained per hour during trials and the number of hours the pumps operated. The *projected* number entrained each week was the product of the number of chinook salmon entrained per hour during trials and the total hours in a week (i.e., 168). The estimated number was based upon actual operating time and, therefore, provided the best estimate of the number of chinook salmon entrained each week. The projected number was based upon pumps always operating 24 h a day, and therefore was the maximum number that could have been entrained, based upon our sample. Since the estimates and projections were based upon actual weekly entrainment rates, they were only calculated in weeks that trials were conducted. The particular weeks that entrainment trials were conducted, the number of trials that were conducted, and the number of hours pumps operated varied among years. The weekly estimated and projected numbers were summed each year to obtain annual estimates and projections of chinook salmon entrainment.

During trials conducted in 1997 and 1998, juvenile fall chinook salmon released into Battle Creek from Coleman National Fish Hatchery 56 km upstream of the RPP were entrained into the plant. During these years, a total of approximately 26 million juvenile fall chinook salmon were released into Battle Creek. Of these, approximately 2 million were coded-wire tagged and adipose fin-clipped resulting in a ratio of 0.08 marked to unmarked fish. The ratio varied somewhat with each release. The ratio from the most recent release was used to determine the number of hatchery-produced and naturally-produced chinook salmon entrained into the RPP each week. The number of hatchery-produced chinook salmon entrained into the RPP was calculated as the number of adipose-clipped fish entrained divided by the ratio of marked to unmarked fish released from Coleman Hatchery. The number of naturally-produced chinook salmon was calculated as the difference between the total number of chinook salmon entrained and the estimated number of hatchery-produced chinook salmon. Entrainment trials in 1999 and 2000 did not correspond with releases of hatchery-produced chinook salmon. Of the more than 8,000 fall chinook salmon entrained during this study, 3.6% were hatchery-released fish.

Number, Mortality, and Injury of Entrained Fish Compared Among Pumps

Data from the 80 complete, 24-h trials conducted when all three pumps operated concurrently were used to compare number, mortality, and injury of entrained fish among pumps. This ensured that fish collected from the three pumps experienced similar water quality and weather conditions, factors which could affect the number and condition of entrained fish. Each trial included a day and a night sample collected from each of the three pumps. The number and percent mortality of each fish species entrained into each pump was tabulated and calculated for each trial. Due to the non-normal distribution of the data, Kruskal-Wallace tests were used to determine whether %-frequency of mortality differed significantly among pumps for chinook salmon and for all other fish species combined. Percent frequency of injuries, by pump, was calculated for chinook salmon and all other fish species combined. Injuries were also tabulated by type for chinook salmon and all other fish species combined for each of the three pumps. Data from the 15 short-duration trials, which were conducted in an attempt to obtain better estimates of mortality and injury of wild entrained fish, were analyzed similarly. In addition to direct mortality, delayed mortality was assessed in the short-duration trials.

In both 24-h and short-duration trials, frequencies of mortality and sub-lethal injury of wild entrained fish were assumed to be overestimates of pump passage mortality since condition of fish prior to being entrained was unknown. Also, other factors may contribute to mortality. On their way to the holding tanks fish traveled past screens and brushes, in concrete channels, and up a wedge-wire dewatering ramp. In the holding tanks, fish could be subjected to turbulence and debris, especially in the 24-h trials.

Fraction of Riverine Chinook Salmon Entrained

This portion of the study was tightly linked to a companion study entitled *Abundance and seasonal, spatial, and diel distribution patterns of juvenile salmonids passing the Red Bluff Diversion Dam, Sacramento River, California.* This study was conducted by personnel of the U. S. Fish and Wildlife Service (USFWS), Red Bluff Fish and Wildlife Office (Johnson and Martin 1997, Gaines and Martin 2001, draft). From July 1994 through June 2000, up to four rotary screw traps were deployed in the Sacramento River just downstream of RBDD. Data on fish captured in the screw traps were used to estimate abundance and distribution patterns of each of the four runs of juvenile chinook salmon passing RBDD. Population estimates for juvenile salmon were made using the trap efficiency method (Thedinga et al. 1994). Trap efficiency was estimated for each trap by mark and recapture techniques and was calculated as the quotient of the number of recaptures in a trap divided by the number of marked fish released upstream (Martin et al. 2001, draft). Results of the efficiency trials were used to develop a model which predicated daily trap efficiency using percent of river discharge sampled as the primary variate (Martin et al. 2001, draft). Daily passage estimates of the number of juvenile salmon migrating downstream past RBDD on any given day of sampling were then calculated as the number of chinook salmon captured in screw traps divided by trap efficiency. Details on methods used to develop the daily passage estimates are described in Martin et al. (2001, draft).

From fall 1997 through spring 2000, simultaneous data on the number of juvenile chinook salmon captured in rotary screw traps and in holding tanks at the RPP were collected during eighty-four 24-h periods. Three pumps operated on 72 of the dates and two pumps operated on 12 dates. Monitoring was segmented into diurnal and nocturnal periods. Simultaneous monitoring allowed us to estimate the fraction ($\pm$ 90% CI) of the daily total number of juvenile salmonids passing RBDD that were entrained into the RPP on each of the 84 dates. The fraction entrained was calculated for each date as the number entrained into the RPP divided by the estimated number passing RBDD based on screw trap sampling.

Comparisons were made between fractions entrained during the day and night. Relationships were assessed between the fraction of chinook salmon entrained and 1) the percent of river discharge pumped; 2) turbidity; and 3) mean fork length of chinook salmon. Wilcoxan signed-rank tests were used to assess differences in fork length between chinook salmon entrained in the RPP versus those captured in the screw traps for day and night samples. The mean catch per acre-foot of the five most frequently entrained species was calculated and compared between the RPP and screw traps. The Pearson correlation coefficient was calculated to determine how well entrainment rates of chinook salmon into the RPP were correlated with capture rates of chinook salmon in screw traps.

Holding Tank Efficiency Trials

The purpose of these trials was to determine a mean %-efficiency at which holding tanks sample juvenile chinook salmon entrained from the river. Trial results would provide an estimate of the percentage of chinook salmon entrained from the river that were recovered in the holding tanks within a 24-h period. Fish not recovered may have escaped to the river via the bypass channels or may have resided in low velocity zones within the plant.

Hatchery-reared juvenile chinook salmon were used as surrogates for riverine salmonids in these trials. During a trial all three pumps were operated simultaneously. A sample of 32 juvenile chinook salmon was released into the intake of each pump using methods described by McNabb et al. (1998). Fish in each sample were marked with an upper or lower caudal fin-clip to differentiate them from wild entrained chinook salmon.

Eight trials were conducted between March and July, 1999. All trials began about one-half hour after sunrise. Mean fork length of juvenile chinook salmon samples ranged from 48 to 60 mm. Eight trials were also conducted between March and early May, 2000. Four trials began about one-half hour after sunrise and four began about one-half hour after sunset to assess whether %-efficiency was related to diurnal or nocturnal release. A trial started at sunset was followed by a trial started at sunrise the next day so fish in the two trials experienced similar environmental conditions. In 2000, juvenile chinook salmon samples had mean fork lengths ranging from 39 to 68 mm.

Each trial lasted 24 h with holding tanks checked at sunrise and sunset. The percentage of fish recovered during each diel period was calculated for each trial. The mean percent recovered at each diel period was then calculated for all sixteen trials. In addition to being checked at sunset and the following sunrise, holding tanks were checked 0.5, 1, 2, and 6 h after release in six trials conducted in 1999. These trials provided data on travel time of fish between the pump intakes and the holding tanks.

Results

Plant Operations and Environmental Data

In each year of this study, river flows were highest from January through March and lowest from September through November (Figure 5). El Nino storms in 1998 resulted in the highest flows, exceeding 1000 m^3/s (35,340 ft^3/s) from mid-January through February and peaking near 4570 m^3/s (161,000 ft^3/s) on February 3. Intermittent high flows continued through mid-June. Data collected during entrainment trials revealed an inverse relationship between river discharge and the percent of the Sacramento River pumped into the RPP (Figure 6). The percentage pumped ranged from less than 1 to 5.5. The percent of river pumped was lowest in summer, but highest each fall due to low river flows coupled with regular use of all three pumps to meet water needs.

Mean daily water temperatures (°C) and dissolved oxygen concentrations (percent saturation) collected from Sacramento River water flowing through the holding tanks during entrainment trials are shown in Figure 7. Mean water temperature ranged from 8 to 9 °C each winter to between 14 and 15 °C each summer or fall. Mean temperatures also exceeded 14 °C in early

April 2000 which was unusually warm. Mean dissolved oxygen in the holding tanks was consistently greater than 80% and usually exceeded 90% saturation.

On average, mean daily water temperatures collected from the holding tanks and from the multi-parameter probes placed in the Sacramento River were within 1.5% of each other. Mean daily dissolved oxygen concentrations from the two locations were within 1% of each other in 1998, 1999, and 2000. In 1997, however, dissolved oxygen values from the holding tanks averaged 13% higher than those collected from the river. Apparently, the river probe was giving inaccurate readings since the installation of the new probe at that site in 1998 resulted in similar readings between the river and holding tank data. The similarity in temperature and dissolved oxygen values between the holding tanks and the river indicated that fish in the holding tanks were held in ambient river water conditions. Total gas saturation measured in the holding tanks averaged 102%, and ranged from 97% to 107%.

Numbers and Characteristics of Entrained Fish

Twenty-eight species of fish were identified during entrainment trials (Table 2). Sixteen species and 98% of all fish captured were native to the Sacramento River. Chinook salmon was the most frequently entrained species followed by prickly sculpin *Cottus asper*, lamprey ammocoetes *Lampetra* spp., Sacramento sucker *Catostomus occidentalis*, Sacramento pikeminnow *Ptychocheilus grandis*, and riffle sculpin *Cottus gulosus*. These six species comprised 94% of the 26,220 fish captured during entrainment trials. Run composition of chinook salmon was 83.6% fall, 12.1% winter, 2.4% spring, and 1.9% latefall. The period covered in this report included brood years 1996 through 1999 for fall run, 1997 through 2000 for latefall run, and 1997 through 1999 for spring and winter-run chinook salmon.

The lowest mean monthly fork length (mm) for chinook salmon occurred from January through March and from August through October each year, reflecting the outmigration of fall and winter chinook salmon fry, respectively (Figure 8). Mean fork length in these months was typically less than 44 mm. The exception was September 1999 when the mean fork length was 55 mm due to an unusually high proportion (35%) of the chinook salmon entrained being large-sized fall and latefall chinook salmon with mean fork length 93 mm (Figure 9). In September of 1997 and 1998, fall and latefall chinook salmon comprised less than 4% of the chinook salmon entrained. Length distributions of the most frequently entrained species are shown in Figures 9 and 10 for each month of this study.

Ninety-four percent of fish entrained into the plant were <100 mm in length. Length frequency distributions of the four most frequently entrained species are shown in Figure 11. The majority of chinook salmon (81%) entrained were less than 40 mm fork length. Approximately 70% of the lamprey ammocoetes ranged from 70 to 119 mm in total length. Of the 273 metamorphosed Pacific lamprey entrained, 74% were greater than 300 mm total length; the remainder ranged from 100 - 139 mm. Interestingly, there were no Pacific lamprey in the >150 to 299 mm range (Figure 10). Five of the six river lamprey entrained, however, were in that size range. Total length of prickly sculpin was approximately normally distributed with over 80% in the 40 to 90 mm range. Sacramento sucker were represented in all size classes from 30 mm to >200 mm. The majority, however, were less than 60 mm total length, and the size class with the highest %-frequency was 30 to 39 mm. Six and eight percent of the lamprey and Sacramento suckers, respectively, were greater than 200 mm total length. The species most frequently entrained with individuals greater than 100 mm in length were lamprey, Sacramento suckers, prickly sculpin, and Sacramento pikeminnow.

Seasonal and Diel Patterns of Entrainment

Sampling effort was measured in terms of acre-foot of water pumped during entrainment trials (Figure 12). This effort was most intensive each fall (mid-September into October) when typically all three pumps were used to supply water to the canals, and estimates of winter chinook salmon take into the RPP were required (National Marine Fisheries Service 1993). During each week that pumps operated for 24 h a day, on each of the seven days, two 24-h entrainment trials were conducted to provide a sample for estimating the weekly take of winter chinook salmon. By mid-to-late October, the demand for water decreased, and pumping and entrainment monitoring was reduced.

The number of juvenile chinook salmon entrained per acre-foot of water pumped exhibited a seasonal trend being lowest in summer, highest in winter, and intermediate in spring and fall (Figure 12). This pattern was consistent each year, although summer entrainment rates were higher in 1999 and were similar to fall entrainment rates. The number of chinook salmon entrained was less than 0.3 per acre-foot pumped in every month except December, January, and February when it usually exceeded 0.3 and ranged up to 3.5 salmon per acre-foot pumped in January 1998. These winter peaks in entrainment corresponded with the outmigration of fall chinook salmon fry. Figure 13 shows the number of chinook salmon entrained per 24 h of pump operation during 24-h entrainment trials conducted each month.

Generally, entrainment for all other fish species combined was lowest in fall and winter, and highest in spring and summer (Figure 12). The high spring and summer entrainment was due to high numbers of prickly sculpin entrained (Figure 14). An exception to the low fall entrainment occurred in November 1997 when more than 1 fish per acre-foot was entrained. Most of those were lamprey ammocoetes apparently dislodged from the sediment as a result of high river flows following a storm (Figure 14). The only other month that entrainment exceeded 1 fish per acre-foot was June 1998 due to unusually high numbers of Sacramento suckers and lake species such as bluegill and largemouth bass (Figure 14). High river flows in late May required that gates on RBDD be raised causing fish residing in Lake Red Bluff to move downstream. Consequently, an entrainment trial conducted on June 3 and 4 entrained more lentic species and individuals than typical for that time of year.

The relationships between chinook salmon entrainment, river discharge, and turbidity are shown in Figure 15. River discharge and turbidity influenced entrainment during winter months when juvenile chinook salmon were abundant in the Sacramento River near the RPP. At other times of the year, however, increases in discharge or turbidity did not result in an increase in number entrained per acre-foot because few juvenile chinook salmon were in the river.

Nocturnal entrainment of juvenile chinook salmon exceeded diurnal entrainment in 33 of the 35 months that entrainment was monitored (Figure 16). In the two months when diurnal entrainment was higher, sample sizes were small (3 and 15 fish). There was no apparent seasonal pattern in the degree of differences between nocturnal and diurnal entrainment. Greater entrainment at night also held true for other species (Table 3). The mean monthly nocturnal entrainment of juvenile chinook salmon was nearly five times greater than the mean monthly diurnal entrainment. Fall chinook salmon had the lowest nocturnal to diurnal entrainment ratio (2.7) while winter run had the highest (16.5). For fish other than chinook salmon, nocturnal entrainment was eight times greater than diurnal entrainment.

Estimated and Projected Numbers of Chinook Salmon Entrained

An objective of this study was to estimate the number of individuals in each of the four runs of chinook salmon entrained into the RPP annually. The estimated number entrained was calculated weekly based upon the entrainment rate (i.e., number per hour), derived from the week's entrainment trial(s), and the hours of pump operation. The number of chinook salmon that would be entrained annually if the pumps operated continuously each week that entrainment was monitored was projected (Figure 17). Actual and projected numbers of chinook salmon decreased each year while estimated numbers varied with hours of pump operation (Figure 17). Estimated numbers were lowest in 1998 and 2000 due to low pump hours. High river flows made pumps inoperable during much of spring and early summer of 1998, while the 2000 data only extends through May. The highest actual and projected numbers entrained were 4,535 and 28,312, respectively in 1997. The highest estimated number entrained was 9,520 in 1999.

The actual, estimated, and projected numbers of chinook salmon entrained varied among brood years for each run (Figure 18). Typically, the number of hours the pumps operated was much greater than the number of hours entrainment was monitored, resulting in large differences between the actual and estimated numbers of chinook salmon entrained. An exception to this occurred in brood year 1997 for spring and fall run chinook when actual and estimated numbers were similar. During the winter of 1997-1998, one 24-h entrainment trial was conducted each week. Because the pumps only operated each week to conduct these entrainment trials, the actual and estimated numbers entrained were similar. High numbers of chinook salmon were entrained during those 24-h trials, resulting in the projected number entrained being several times greater than the actual number entrained for both fall and spring run.

Number, Mortality, and Injury of Entrained Fish Compared Among Pumps

24-h Trials

Eighty 24-h trials were conducted with all three pumps operating simultaneously allowing comparisons among pumps to be made. Most juvenile chinook salmon were entrained into Archimedes 2 (50%) followed by Archimedes 1 (30%) and the internal helical pump (20%; Table 4). This was consistent with the entrainment pattern among pumps reported by McNabb et al. (1998) and Borthwick et al. (1999). The tendency for more chinook salmon to be entrained into Archimedes 2 was fairly consistent occurring in 61% of the trials. For all other fish combined, Archimedes 1 entrained the greatest percentage (40%) followed by Archimedes 2 and the internal helical pump each with 30%.

Mortality of juvenile chinook salmon entrained into Archimedes 1 and Archimedes 2 and collected in the holding tanks was 2.8% and 2.9%, respectively (Table 4). Mortality of chinook salmon collected from the internal helical pump's holding tank was higher at 4.9%. Results of Kruskal-Wallis tests revealed no significant difference among the three pumps in mortality of juvenile chinook salmon collected from pump holding tanks (P=0.07). Considering all three pumps combined, overall mortality of chinook salmon entrained into the RPP was 3.3%

The percent mortality of all fish except chinook salmon combined was 4.5% for Archimedes 1, 4.9% for Archimedes 2, and 5.1% for the internal helical pump. Percent frequency of mortality for the ten most commonly entrained species is shown in Table 4. Mortality was relatively high for Sacramento suckers. Nearly 50% of those entrained were small (<50mm; Figure 11). Other species with high frequencies of mortality tended to have relatively small sample sizes. Considering all three pumps combined, overall mortality of fish other than chinook salmon was 4.8%.

While in the holding tanks fish survival may be affected by volume and type of debris, amount of water flowing into the holding tank, amount of time confined in the tank, and presence of other fish (Figure 19). Regression analysis was conducted for each pump to assess the relationship between volume of debris and mortality of chinook salmon recovered from the holding tanks (Figure 20). Although these variables were poorly correlated for each pump ($r^2 < 0.15$), the regressions were highly significant (P<0.001) suggesting that mortality may be affected by a combination of factors including debris.

The percentage of injured chinook salmon (dead and alive) removed from the holding tanks servicing Archimedes 1 and Archimedes 2 was 3.1 for each of the lifts (Table 5). The percentage injured was higher for chinook salmon removed from the internal helical pump's holding tank (4.9). The percentage of live chinook salmon removed from the holding tanks with sub-lethal injuries was 1.2, 0.8, and 1.7 for Archimedes 1, Archimedes 2, and the internal helical pump, respectively. Fish other than chinook salmon followed a similar pattern with the highest frequency of injuries in fish removed from the internal helical pump's holding tanks (5.7%) followed by the Archimedes lifts (5.0 for each; Table 5). For each pump, the frequency of injuries was lower for chinook salmon than for other fish combined. For all three pumps combined, the percent frequency of sub-lethal injuries to chinook salmon was 1.2%. The most frequent injuries to chinook salmon and other fish occurred on the skin (Tables 6 and 7). Open wounds, abrasions, and bruises were the most common skin injuries. Bulging eyes were commonly observed on dead fish but rarely on live fish. Damage to fins was less frequent on chinook salmon than on other fish. Head injuries were relatively infrequent for all fish.

Short-duration Trials

Mortality of juvenile chinook salmon and all other fish combined was much lower in the 2 to 3-h entrainment trials than in the 24-h trials (Table 8). Mortality of chinook salmon ranged from 0.6 to 1.2% in the short-duration trials compared to 2.8 to 4.9% in the 24-h trials. Similarly, mortality of all other fish combined was 0 to 0.9% in the short-duration trials compared to 4.5 to 5.1% in the 24-h trials. As in the 24-h trials, there were no significant differences among pumps in percent mortality of chinook salmon (Kruskal-Wallace test, $P = 0.23$) or of all other species combined ($P = 0.21$). The percent frequency of chinook salmon with sub-lethal injuries was 0.2 for each of the Archimedes lifts and 0.1 for the helical pump. For all other fish combined, the frequency of fish with sub-lethal injuries was 0.5% for Archimedes 1, 1.2% for Archimedes 2, and 1.1% for the helical pump. Considering the RPP as a whole, percent frequency of mortality and sub-lethal injuries for chinook salmon was 0.8 and 0.2, respectively. For all other species combined percent frequency of mortality and sub-lethal injuries was 0.6 and 0.9, respectively.

Chinook salmon removed alive from the holding tanks during these trials were held in the river water laboratory for 96 h to assess delayed mortality. The percentage of fish that died during the 96-h observation period was 2.2, 0.9 and 2.7 for Archimedes 1, Archimedes 2, and the internal helical pump, respectively.

Mortality of Large Fish (>200 mm)

There is interest in knowing if Archimedes lifts and internal helical pumps can pass large fish unharmed. During entrainment trials 1.9% of all fish collected exceeded 200 mm in length. The four most commonly entrained large fish, in decreasing order, were Pacific lamprey *Lampetra tridentata*, Sacramento sucker, Sacramento pikeminnow, and hardhead *Mylopharodon concephalus* (Table 9). Large fish frequently slid across the fish separator bars at the end of the dewatering ramp and were captured in a metal box at the end of the bars rather than in the holding tanks (Figure 3). The metal box was 89 cm long, 38 cm wide, and 76 cm deep (35 in x 15 in x 30 in) and contained river water. Unlike the holding tanks, the box was not a flow-through system. Conditions within the box were not always amenable to fish survival, particularly during periods with high debris and flow, and may have contributed to fish mortality and injury.

Archimedes 1 entrained the most large fish (226) followed by Archimedes 2 (179) and the internal helical pump (96). None of the large fish passed through Archimedes 2 died, while 2.2% and 4.2% of the large fish passed through Archimedes 1 and the internal helical pump, respectively, were dead when collected from the holding tank or the metal box. Because not all of these trials were conducted when the three pumps operated simultaneously under similar environmental conditions, mortality among the three pumps was not directly comparable. Overall mortality of the 501 large fish entrained into the plant and collected in a holding tank or a metal box was 1.8%. Of the 492 large fish entrained alive, 3.6% were injured. Percentage injured by pump was 4.5, 1.7, and 3.3 for Archimedes 1, Archimedes 2, and the internal helical pump, respectively. Most of the injuries were abrasions or open wounds on the skin.

Fraction of Riverine Chinook Salmon Entrained
Between September 1997 and May 2000, 24-h samples were collected simultaneously from the RPP and the rotary screw traps on 84 dates. Based on screw trap estimates of daily total numbers of chinook salmon passing the dam, the fraction entrained from the river into the RPP on the 84 dates ranged from <0.0001 (<0.01%) to 0.0138 (1.38%, Figure 21) with an average of 0.0022 (0.22%). The fraction entrained was less than 0.005 in 89% of the samples and was consistently less than the fraction of river discharge pumped (Figure 21). The fraction of river discharge pumped represented the expected fraction of salmon entrained if the fish were uniformly distributed and entrained in proportion to density. The upper 90% confidence interval of the fraction entrained exceeded the fraction of river discharge pumped on only one sampling date. The Pearson correlation between the fraction of river discharge pumped and the fraction of chinook salmon entrained was 0.287 indicating factors other than the fraction of river pumped were responsible for changes in entrainment patterns.

The chinook salmon run that experienced the highest fraction entrained was the fall run averaging 0.0036 and ranging from 0.0002 to 0.0138. The fraction of winter chinook salmon entrained averaged 0.0017 and ranged from 0.00008 to 0.0066. Spring and latefall chinook salmon were only entrained in combination with salmon from other runs. Therefore, their fractions entrained could not be determined. However, the fraction of chinook salmon entrained was consistently less than 0.002 in samples that contained spring and latefall chinook salmon.

For each of the three pumps, about 30% of the samples collected during simultaneous trials with the screw traps contained no chinook salmon (Figure 22a). Disregarding the large number of samples with no chinook salmon, the histogram of the natural log of the fraction of chinook salmon entrained was approximately normally distributed for each of the three pumps. For both Archimedes lifts, the most frequent fraction of chinook salmon entrained was 0.0009 to 0.0014 (0.09% to 0.14%). For the helical pump, it was 0.0015 to 0.0022 (0.15% to 0.22%).

The Delta distribution, which adjusts estimates for the probability of catching no fish, was used to compare the fraction of fish entrained in day versus night samples for each of the three pumps (Figure 22b). The fraction entrained was higher during the day for Archimedes 1. For Archimedes 2 and the internal helical pump the fractions entrained day and night were very similar. Among the three pumps, the internal helical pump had the lowest fraction of fish entrained in both day and night samples.

There was no relationship between fraction of chinook salmon entrained into the RPP and river turbidity ($r^2 = 0.001$, $P = 0.770$, n = 317). Similarly, there was no relationship between fraction of chinook salmon entrained and mean fork length of entrained salmon ($r^2 = 0.006$, $P = 0.098$, n = 314). When comparing the mean fork length of chinook salmon captured in screw traps and the RPP, lengths of fish captured in screw traps were significantly greater in night samples (Wilcoxan signed-rank test, $P<0.001$, n=203) and in day samples (Wilcoxan signed-rank test, $P = 0.016$, n = 109; Figure 23).

The number of fish captured per acre-foot in the screw traps and the RPP is shown in Table 10 for the five species most frequently entrained into the pumps. Chinook salmon were captured in higher densities in the traps with a pump to trap ratio of 0.22. There was a strong, positive correlation between the number of chinook salmon captured per acre-foot in the rotary screw traps and in the RPP on the 84 dates when simultaneous samples were collected (Pearson correlation coefficient = 0.824). The correlation was stronger for day samples (0.855) than for night samples (0.640) when typically more fish were captured in both traps and the RPP.

Sacramento pikeminnow and Sacramento sucker were entrained in higher densities in the RPP with ratios of 4 and 3, respectively. Lamprey ammocoetes and prickly sculpin, both benthic species, were entrained in much higher densities in the RPP than in the screw traps (ratios of 202 and 114, respectively). It should be noted that these ratios are somewhat conservative since fish <30 mm (excluding salmonids) were not tabulated from RPP samples, however, they were tabulated in screw trap samples.

Holding Tank Efficiency Trials

Results from all sixteen trials combined revealed that on average 10 to12% of the juvenile chinook salmon released into the pump intakes were not recovered in the holding tanks within 24 h of release (Table 11). There were no significant differences among the three pumps in the percentage of fish recovered at 24 h (ANOVA; P=0.80). There also were no significant differences between the percentage of sunrise and sunset released fish recovered for any of the pumps although sample size was small (n=4; $P \geq 0.05$; two-sample t-tests). In 1999 six trials were conducted in which travel time was monitored at 0.5, 1, 2, 6, 14, and 24 h after release. All trials began at sunrise. Table 12 shows time-in-travel during these trials for juvenile chinook salmon released into each of the three pumps. The pump with the highest mean percentage recovered varied by hours post-release.

Discussion

Plant Operations

The Biological Opinion for the RPP predicted that during the juvenile winter chinook salmon outmigration period, 2.0% of the Sacramento River discharge would be pumped into the RPP (National Marine Fisheries Service 1993). The actual average percent pumped during the winter run outmigration period was 3.5%, with a high of about 5.5% occurring in fall 1997. During the mid-September through October portion of the winter-run outmigration, gates at RBDD were raised yet TCC water demands were high requiring frequent use all three pumps. Also, during this period river discharges were typically at their yearly minimum. While the percentage of the river pumped was highest in the fall, it was lowest in the summer when flows were relatively high and use of the pumps was low. Overall, during this studies' entrainment trials, the average percent of river discharge pumped into the RPP was 2.6.

Numbers and Characteristics of Entrained Fish

Twenty-eight fish species were identified during entrainment trials. All twenty-eight species were previously reported entrained in similar proportions during February 1997 through June 1998 (Borthwick et al. 1999). Gaines and Martin (2001, draft) reported capturing thirty-nine species in rotary screw traps deployed near the RPP from July 1994 to June 2000. Twelve species collected in rotary screw traps but not entrained in the RPP during our trials were spotted bass *Micropterus punctulatus*, redear sunfish *Lepomis microlophus*, black crappie *Pomoxis nigomaculatus*, white crappie *Pomoxis annularis*, Kokanee/sockeye *Oncorhynchus nerka*, brown trout *Salmo trutta*, American shad *Alosa sapidissma*, striped bass *Morone saxatilis*, fathead minnow *Pimephales promelas*, Sacramento splittail *Pogonichthys macrolepidotus*, black bullhead *Ictalurus melas*, and Sacramento blackfish *Orthodon microlepidotus*. The greater diversity of species captured in the screw traps compared to the RPP was likely due to a much more intensive screw trap sampling effort. While entrainment of fish into the RPP was monitored for one or two 24-h periods each week, screw traps were typically monitored for four to seven 24-h periods each week. Another plausible reason for differences in the diversity of species captured is that the RPP and screw traps sampled different portions of the river's water column.

Juvenile chinook salmon comprised 87% of the fish captured in the rotary screw traps (Gaines and Martin 2001, draft) but only 40% of the fish captured in the RPP during entrainment trials. This difference is likely due to the traps and the RPP sampling a different strata of the water column. Rotary screw traps sample the top 1.2 m of the water column whereas the 1.2 m diameter intakes on the RPP pumps are located near the bottom of the water column at a depth of approximately 3.6 - 4.8 m (12 - 16 ft). Studies conducted from 1950 - 1952 by the USFWS in the Sacramento River near Red Bluff assessed the vertical distribution of downstream migrating chinook salmon using a push net to sample at 0.6 m intervals from the surface to a depth of 1.8 m (Azevedo and Parkhurst 1957). Their sampling revealed that juvenile chinook salmon migrated at all depths, however, numbers were greatest 0.6 to 1.2 m below the surface and fewest at 1.2 to 1.8 m below the surface. Other studies on outmigrating juvenile Pacific salmon indicate that they generally utilize the entire water column. However, their abundance at different depths within the water column can vary by diel period (McDonald 1960, Edmundson et al. 1968, Wickwire and Stevens 1971), by spatial zone across a river (Dauble et al.1989), by fish size (Wickwire and Stevens 1971), and by water depth (Mains and Smith 1964). Also, results from one river are not necessarily applicable to another (Mains and Smith 1964).

Other evidence that the rotary screw traps and the RPP sampled different strata of the river's water column was in the relative percentage of benthic species captured. Prickly sculpin and lamprey ammocoetes comprised 28% and 18% of the fish entrained into the RPP, respectively, but 1% or less of the fish captured by rotary screw traps (Gaines and Martin 2001, draft). Sacramento sucker and Sacramento pikeminnow comprised similar proportions in the RPP (6% and 2%, respectively) and in the rotary screw traps (4% for each species; Gaines and Martin 2001, draft).

Eighty-one percent of entrained chinook salmon were less than 40 mm fork length which was also the most abundant size class sampled in rotary screw traps (Gaines and Martin 2001, draft). The mean monthly fork length of chinook salmon captured during entrainment trials was consistently less than 40 mm in December, January, and February reflecting the outmigration of fall chinook salmon fry (Vogel et al. 1988). Mean fork lengths were <45 mm during August, September, and October when winter-run chinook salmon were outmigrating. The largest fork lengths occurred in May, June, and July. The number of chinook salmon entrained in the summer, however, was low (<22 each month), except in 1999 when relatively high numbers of large fall and late-fall chinook salmon continued to be entrained through September. Lower river flows in winter and spring 1999 than in the previous two years may explain why larger chinook salmon remained in the river through September (Vogel et al. 1988).

Nearly 50% of Sacramento suckers entrained into the plant were less than 50 mm total length. Length frequencies of Sacramento suckers captured in rotary screw traps were similarly skewed to the small size classes (Gaines and Martin 2001, draft). The percent frequency of sucker entrainment into the RPP gradually decreased with increasing length, leveling off near 2% for each of the 10 mm size classes between 100 mm and 200 mm. Percent frequency increased to 8% for suckers >200mm in length. Similarly, most lamprey (including ammocoetes) were less than 140 mm, however, a rise in percent frequency to 6% occurred in the >200 mm size class due to entrainment of adult Pacific lamprey.

Prickly sculpin exhibited an approximately normal length frequency distribution, most ranging from 50 to 70 mm. Percent frequency gradually decreased for size classes less than 50 mm and greater than 70 mm. The largest size class was 120-129 mm. Prickly sculpin captured in rotary screw traps exhibited a very similar size frequency distribution (Gaines and Martin 2001, draft) Many prickly sculpin and Sacramento suckers less then 30 mm in length were entrained during our trials. Because they were not efficiently retained by the relatively large mesh-size (3.2 mm, 1/8 in) of nets used to hold fish in the tanks, these small fish were not enumerated. However, they were abundant, particularly during the spring. In a separate study addressing entrainment of larval fish, prickly sculpin and Sacramento sucker comprised 87.5% and 11.5% of the larval fish entrained into the plant, respectively (Borthwick and Weber 2001).

The trash racks proved effective at excluding most large fish from the RPP. Only 1.9% of the fish captured during entrainment trials were ≥200 mm in length. Occasionally, fish that appeared too large in girth to pass through the 5.1 cm (2 in) openings between the bars of the trash racks were entrained into the plant. These fish may have entered the sump area during high flows when openings between the trash rack and walkway were submerged, or they may have increased in size while residing in the sump area.

Seasonal and Diel Patterns of Entrainment

For juvenile chinook salmon, entrainment was consistently highest in the winter months of December, January, and February coinciding with the outmigration of post-emergent fall chinook salmon near Red Bluff (Vogel et al.1988; Gaines and Martin 2001, draft). The highest density of fish entrained was 3.5 per acre-foot in January 1997. Typically, if the plant was functioning only to deliver water, it would not be operated in these winter months. High river levels often preclude use of the RPP during winter when water demands generally are low. Excluding winter months, entrainment of chinook salmon consistently was less than 0.3 fish per acre-foot, or less than 60 fish per 24 pump hours.

Patterns of entrainment were similar in 1997 and 1998 with the highest number entrained per acre-foot pumped in winter and spring, decreasing in summer, then increasing again in fall as juvenile winter-run chinook salmon outmigrated. In 1999, summer entrainment was greater than in the previous two years, and similar to fall entrainment. River flows in the winter of 1997 and winter and spring of 1998 were higher than in 1999 possibly resulting in earlier outmigration of fall chinook salmon at a small size (<50 mm). This pattern is consistent with data on chinook salmon abundance at Red Bluff during a wet winter (Vogel et al. 1988). The relatively low river flows in the winter of 1999 may have encouraged fry to remain longer in the upper Sacramento River. Based upon Vogel et al. (1988), it can be predicated that in wet years such as 1998, most juvenile fall chinook salmon will migrate past the RPP before pumping begins in the spring. In contrast, in drier years such as 1999 when the annual peak outmigration of fall chinook salmon was delayed until April through June (Vogel et al. 1988), more salmon would be vulnerable to entrainment into the RPP when pumping begins in the spring. These fish would pass the RPP at a larger size (Gaines and Martin 2001, draft) so may not be entrained as easily as smaller fish that pass in the winter.

There was no consistent seasonal entrainment pattern among years for all other fish combined. Entrainment was less than 1.0 fish per acre-foot pumped in every month except November 1997 and June 1998. Most fish entrained in November 1997 were lamprey ammocoetes, which may have been dislodged from the substrate during high river flows making them vulnerable to entrainment. In rotary screw traps, the number of ammocoetes captured per acre-foot of water sampled was also highest in November 1997 (Gaines and Martin 2001, draft). Sacramento suckers and prickly sculpin composed most of the fish entrained in June 1998. Prickly sculpin entrainment was consistently high in June of each year. Sucker entrainment was unusually high in June 1998 due to atypical gate operations at RBDD prompted by high river flows. Each year gates were lowered from May 15 through September 15. In 1998 gates were lowered on May 15th, but high river flows required that they be raised on May 28th. When the gates were raised, suckers residing in Lake Red Bluff appeared to move downstream in unusually high numbers resulting in high numbers being entrained during a single trial conducted in early June. The number captured per acre-foot of water sampled in rotary screw traps that month was also the highest in the 5.5 years of sampling (Gaines and Martin 2001, draft). Capture was near 0.5 suckers per acre-foot in both screw traps and the RPP. In all other months, entrainment of Sacramento suckers into the RPP was less than 0.1 fish per acre-foot pumped.

Prickly sculpin exhibited a seasonal pattern of entrainment with rates consistently highest in late spring and summer each year. Although the number captured per acre-foot was much lower in rotary screw traps, the seasonal pattern was very similar (Gaines and Martin 2001, draft).

Sacramento suckers and prickly sculpin less than 30 mm were not enumerated in this study, but were addressed in a separate study on larval fish entrainment (Borthwick and Weber 2001). Seasonal entrainment patterns of larval suckers and prickly sculpin (i.e., those < 30 mm) were similar to that of juvenile and adults, however, the number of larval fish entrained per acre-foot pumped was dramatically higher. For prickly sculpin, entrainment of larval fish ranged from about 26 to 220 fish per acre-foot pumped in the late spring and summer period. In contrast, entrainment of juveniles and adults was consistently less than 0.6 fish per acre-foot pumped. Similarly, for Sacramento suckers entrainment of larval fish ranged from 0 to 65 fish per acre-foot during the study period while entrainment of juveniles and adults ranged from 0 to 0.5 fish per acre-foot.

Seasonal entrainment patterns of juvenile chinook salmon appeared to be due to a combination of seasonal abundance patterns and river conditions (Figure 15). Entrainment consistently peaked in the winter when the abundance of outmigrating juvenile chinook salmon was typically the greatest (Gaines and Martin 2001, draft). In 1999 and 2000, these peaks in entrainment corresponded with peaks in river discharge and slight rises in turbidity. In 1998, peak entrainment preceded peak river flows and turbidity which occurred in the spring and early summer. A spike in river turbidity and discharge in November 1997 did not result in increased entrainment because few juvenile chinook salmon were present in the river. Similarly, the spike in river discharge in February 1997 occurred without a corresponding peak in juvenile chinook salmon entrainment, presumably because few chinook were present in the river. River discharges exceeded 2266 m^3/s (80,000 ft^3/s) from 12/31/96 through 1/5/1997, with a peak of over 3398 m^3/s (120,000 ft^3/s) on January 1, 1997 (Figure 5). These high flows likely pushed most of the chinook salmon fry out of the upper Sacramento River by February when entrainment monitoring began.

The diel pattern of entrainment was similar to earlier findings (McNabb et al.1998, Borthwick et al. 1999) with mean monthly nocturnal entrainment of chinook salmon on average nearly five times greater than diurnal entrainment. This is consistent with findings from rotary screw traps where catch per acre-foot of juvenile chinook salmon emigrating past RBDD showed distinct diel patterns of abundance, being greatest at night (Johnson and Martin 1997, Gaines and Martin 2001, draft). A study conducted from 1982 through 1987 revealed that entrainment of juvenile chinook salmon through the Tehama-Colusa canal headwork louvers was also consistently greater at night than during the day (Vogel et al. 1988). Results from the Sacramento River are consistent with studies conducted elsewhere on migration patterns of juvenile Pacific salmon (McDonald 1960, Mains and Smith 1964, Dauble et al. 1989). McDonald (1960) found that fry of coho, sockeye, pink, and chum salmon initiated downstream movements shortly after dark and terminated those movements as daylight approached. In experiments conducted with sockeye and coho salmon fry, artificial light prevented their normal downstream movement at night.

Our holding tank efficiency trials and other studies at the RPP (Borthwick et al. 2000, McNabb et al. 2000) revealed that a fraction (about 1 to 12%) of chinook salmon passed through the pumps resided in the plant for several hours or days before moving downstream to the holding tanks. The percentage of fish holding up was consistently greater for fish released through the pumps during the day than for those released at night. Because all our 24-h entrainment trials began at sunrise, it's likely that some fraction of fish entrained during the day did not move into the holding tanks until night. Therefore, day entrained fish would be counted as night entrained fish resulting in a bias in our night to day entrainment ratios. However, due to the relatively small number of chinook salmon passing RBDD during the day compared to night (Johnson and Martin 1997), this bias is likely small.

On average, the monthly nocturnal entrainment of all species other than chinook salmon combined was eight times greater than diurnal entrainment. For the five most frequently entrained species, prickly sculpin had the greatest propensity for night entrainment while Sacramento pikeminnow had the lowest. Entrainment of larval fish also was significantly greater at night than during the day or crepuscular periods for prickly sculpin, Sacramento sucker, and all species combined (Borthwick and Weber 2001). These findings on greater nocturnal entrainment of fish into the RPP have important implications for plant operations. If it becomes desirable or necessary to reduce the number of fish entrained, pumping could be restricted to daylight hours.

Estimated and Projected Numbers of Chinook Salmon Entrained

The actual number of chinook salmon entrained into the RPP during entrainment trials decreased each year from 1997 through 2000. This was due to a decrease in sampling effort (i.e., fewer entrainment trials) and/or sampling during periods of lower fish density in the river. In 1998, after exceptionally high entrainment in early January, high river levels precluded use of the plant from mid-January through early March, in late March, and in late May. Therefore, during much of the fall chinook salmon outmigration period, entrainment monitoring was not conducted. Actual numbers entrained decreased slightly more in 1999. Entrainment was monitored for more hours in 1999 than in 1998, however, fewer fish were entrained per acre-foot. Actual number entrained was lowest in 2000 because only data from January through May was included.

The estimated number entrained is the number entrained extrapolated to include fish entrained while the pumps were running but entrainment was not monitored. It is based upon the entrainment rate (number entrained per hour) and the number of hours the pumps operated. The estimated number was highest in 1997 and in 1999, about 9,500 chinook salmon. Low pump hours resulted in low estimated numbers entrained in 1998 and 2000 (nearly 4500 to 4800). There also was interest in projecting the number of chinook salmon that would be entrained if the pumps ran continuously, 24 hours a day. Because a constant multiplier (i.e., 168 hours) was used with the actual number entrained per hour each week, the projected numbers followed a pattern similar to the actual numbers, being highest in 1997 (near 28,000) and lowest in 2000 (near 6,500). Therefore, the estimated number provided the best assessment of the number of chinook salmon entrained into the RPP during actual pump operations. The projected number provided an assessment of the maximum number of chinook salmon that could have been entrained into the plant had it operated continuously during the weeks that entrainment trials were conducted.

Brood year 1997 had the highest actual and projected numbers entrained for fall and spring-run chinook salmon due to high entrainment in the winter of 1997 - 1998. Because the pumps were not operational in December of 1998 or 1999, the actual and projected number of fall and spring chinook salmon entrained was considerably less for brood years 1998 and 1999. When the pumps did operate in December and January, it was for the sole purpose of conducting biological evaluations. The plant typically would not be operated in these months if functioning solely to deliver water to the Tehama Colusa and Corning canals. Therefore, the high actual and projected numbers of fall and spring-run chinook salmon entrained would be far fewer than determined during this study. Of the more than ten thousand chinook salmon entrained during trials, 49% were entrained in December and January.

Brood year 1998 had the highest actual, estimated, and projected numbers of latefall and winter-run chinook salmon entrained. Actual, estimated, and projected numbers of winter chinook salmon were near 500, 1500, and 3000, respectively.

This study and others have revealed that about 1 to 15% of chinook salmon entrained into the RPP are not recovered in the holding tanks within a 24-h period. Therefore, the actual, estimated, and projected numbers entrained based upon our 24-h entrainment trials were conservative.

Mortality and Injury of Entrained Fish Compared Among Pumps

24-h Trials

Consistent with previous studies at the RPP (McNabb et al.1998, Borthwick et al. 1999), each of the Archimedes lifts entrained more chinook salmon and had lower frequency of mortalities and sub-lethal injuries than the internal helical pump. The difference in mortality between the two pump types however, was not statistically significant. Besides pump configuration, two important differences between these pump types that may affect fish mortality are their speed and the characteristics of the pump's outfall. The helical pump is designed to operate at a much higher speed (350 rpm) than the Archimedes lift (26.5 rpm). The faster pump speed may contribute to the higher frequency of mortalities. Prior to May of 1998 the helical pump operated even faster, at 378 rpm. Although we have entrainment data to compare mortality of entrained chinook salmon when the pump operated at 378 versus 350 rpm, other variables such as debris loads, water quality and size of entrained fish confound these comparisons. Systematic trials under similar environmental conditions with similar sized fish would need to be conducted to accurately assess whether this difference in pump speed affected fish survival. Trials conducted by Helfrich et al. (2000) using a 41 cm diameter internal helical pump revealed that survival of both Sacramento splittail and chinook salmon was unrelated to pump speed over the range of 461 to 601 rpm tested ($R^2 = 0.01$, $p = 0.867$)

Engineering evaluations have not been made on the pump outfalls, however, there are obvious differences between the discharges of the two pump types (Frizell and Atkinson 1999). The Archimedes lifts discharge water in pulses associated with the dumping of water from each flight of the pump. Discharges are centered over the 1.5 m deep channel. Water from the internal helical pump is discharged from a height of approximately 1.0 m above the water surface into the 1.5 m deep channel. The helical pump's discharge structure is off-center reducing the depth of water that the discharge plunges into to less than 0.5 m on the off-center side. This increases the likelihood that a fish discharged from the pump could strike the channel's concrete substrate. The off-center installation also causes water to slosh from side to side as it travels downstream causing velocity fluctuations along the vertical screens (Frizell and Atkinson 1999).

Experiments using hatchery-reared juvenile chinook salmon were conducted in winter and early spring of 2000 to evaluate the effect on mortality of the plunge fish experience when discharged from the internal helical pump (McNabb et al. 2000). Experiments compared mortality of fish released through a port in the top of the pump's discharge structure with mortality of fish released downstream of the pump's discharge. Both groups of fish were collected in the holding tanks. Results showed no significant difference in mortality between the two release groups indicating that plunging from helical pump's discharge structure into the channel did not contribute significantly to mortality. However, as stated in McNabb et al. (2000), these experiments did not answer the question of whether fish passed through the pump travel safely through the discharge structure and into the channel in the same manner as those that were inserted in the port at the top of the pump's discharge structure.

During our study, the frequency of mortality and sub-lethal injury of fish collected from holding tanks was low for each of the three pumps considering that the condition of fish prior to being entrained was unknown. Also, in addition to passing through a pump, fish traveled the lengthy flow stream from the pump's discharge to the holding tanks (Figure 3). Once in the holding tank, fish were confined for up to 14 h depending upon when they entered the tank in relation to the sunset or sunrise check. While in the holding tank fish mortality could be affected by type and amount of debris, amount of water flowing into the tank, length of time confined in the tank, and presence of other fish. Therefore, our frequencies of mortality and injury to wild fish passed through the Archimedes lifts and helical pump are assumed to be overestimates.

Our data did not show a correlation between debris and chinook salmon mortality in holding tanks for any of the pumps (Figure 20). Whether a given amount of debris affects survival was likely confounded with the type of debris, the amount of time the fish was exposed to the debris, and the amount of water flowing into the holding tank. High flows caused turbulent conditions that increased the likelihood of debris striking a fish. Although each entrainment trial began with low flows into the holding tanks, debris impinged on the dewatering ramp decreased the volume of water passing through the ramp thereby increasing the volume of water going to the holding tanks (Figure 19). Due to the relatively small operating volume of the holding tanks (about 1370 L; 360 gal), high flows into the tanks created turbulent conditions which may have contributed to mortality and injury, especially when coupled with debris and long periods of confinement. Confinement time of individual fish and duration of high flows into the holding tanks were two variables that could not be measured.

Sub-lethal injuries to fish also may be affected by conditions in the holding tanks. Strikes from debris or predators may account for some of the integument injuries observed. Small-sized suckers tended to be less hardy than similar-sized chinook salmon to tolerating turbulence and debris in the holding tanks. Compared to all other fish, chinook salmon had a higher incidence of bulging eyes, exophthalmia. This condition has a variety of possible causes including several infectious agents (bacterial and viral) and parasites, nutritional deficiencies, gas supersaturation, kidney functions (increased pressure in the choroid gland), and trauma (Kim True, USFWS, California-Nevada Fish Health Center, personal communication.). Gas supersaturation was unlikely since total gas saturation values measured in holding tanks were below levels found detrimental to fish (Weitkamp and Katz 1980). Bulging eyes also are a symptom of IHN (infectious hematopoietic necrosis), a disease frequently found in fall chinook smolts released from Coleman National Fish Hatchery. To avoid handling and adding stress to these diseased fish, entrainment monitoring was generally not conducted when diseased smolts were released. Therefore, less than 0.1% of chinook entrained with bulging eyes were collected during times when IHN infected smolts were released from Coleman National Fish Hatchery.

Considering all three pumps, overall mortality of chinook salmon entrained into the RPP and recovered from holding tanks was 3.3%. The overall percentage of chinook salmon recovered from the holding tanks with sub-lethal injuries was 1.2. The Biological Opinion for the pumping plant (National Marine Fisheries Service 1993) expected a "substantially higher rate of injury or mortality" to entrained fish passed through the internal helical pump compared to the Archimedes lift. Although frequency of mortality and sub-lethal injury to entrained chinook salmon was greater with the internal helical pump, levels were considerably less than expected and not statistically different from the Archimedes lifts.

Short-duration Trials

Experiments conducted under Objective B of the RPP evaluation program (McNabb et al. 1998, 2000) provided a better estimate of chinook salmon mortality from pump passage than did entrainment trials. The condition and history of each treatment group of fish used in the experiments was known. Also, during experiments fish were immediately removed from the holding tanks and therefore were not subjected to mortality from debris, other fish, or stress of confinement. However, the experiments used hatchery-reared chinook salmon. The short-duration entrainment trials conducted during our study were intended to provide an estimate of mortality of wild chinook salmon entrained from the Sacramento River. The intent was to avoid the confounding mortality factors previously mentioned in our 24-h entrainment trials. While the condition of the fish prior to entrainment was unknown, fish were removed from holding tanks every 10 to15 minutes as in experiments. Percent mortality in the short-duration trials was similar to that reported by McNabb et al. (2000) in the pump passage experiments. Direct mortality of chinook salmon passed through the Archimedes lifts ranged from 0.4 to 0.8% in the passage experiments and 0.6 to 0.9% in the short-duration trials. For the helical pump, percent mortality was lower for chinook salmon in the short-duration trials (1.2%) than for salmon from the passage experiments (2.8%). The low frequencies of mortalities are consistent with low levels of stress found in fish passed through the lifts and pumps (Weber and Borthwick 2000).

Compared to the 24-h entrainment trials, mortality of entrained chinook salmon and all other fish combined was less in the short-duration trials for each of the pumps. Although the lower mortality could be attributed to many things including smaller sample size, different sized fish, and different environmental conditions, the lack of confinement in the holding tanks with debris and high flows likely contributed a great deal towards the lower mortality.

Mortality of chinook salmon held for 96 h was greater in the short-duration trials (0.9% - 2.7%) compared to experiments (0.7% - 1.0%; McNabb et al. 2000) and compared to previous trials in which entrained juvenile chinook salmon were held for 96 h (0.5 - 0.8%; Borthwick et al. 1999). In the short-duration trial with the greatest number of chinook salmon entrained, fish were inadvertently held at high densities in 20 L buckets for a long period before being transferred to the river water laboratory. This was suspected of contributing to the relatively high delayed mortality.

Mortality of Large Fish

Entrainment of large fish (≥200 mm) during trials suggested that both pump types, but particularly the Archimedes lifts, were capable of passing large fish with low incidence of mortality and injury. Mortality among more than 400 large fish passed through the Archimedes lifts was lower than mortality of small fish (1.2% and 3.0%, respectively). Mortality of nearly 100 large fish passed through the helical pump was slightly higher (4.2%) than mortality of small fish (3.8%). However, the sample size for large fish passed through each pump was much less than for small fish. The largest fish passed through each type of pump was a 730 mm (24 in) Pacific lamprey which was collected alive from the holding tanks. Excluding Pacific lamprey, the largest fish passed through an Archimedes lift during entrainment trials was a 480 mm (19 in) Sacramento pikeminnow. The largest passed through the internal helical pump was a 432 mm (17 in) Sacramento sucker. Both were collected alive.

Fraction of Riverine Chinook Salmon Entrained

The biological opinion for the RPP (National Marine Fisheries Service 1993) assumed that juvenile chinook salmon would be uniformly distributed in the Sacramento River and entrained in proportion to the fraction of river discharge pumped into the plant. Our data do not support this assumption with a low correlation between the fraction of chinook salmon entrained and the fraction of river pumped (Pearson correlation = 0.287). The fraction of salmon entrained was consistently less than the fraction of discharge pumped. The upper 90% confidence interval (CI) for fraction entrained only exceeded the fraction of river discharge pumped on one of 84 sampling dates (1/7/98). Rotary screw trap sampling also revealed that chinook salmon were not uniformly distributed in the Sacramento River (Gaines and Martin 2001, draft).

The highest fraction of daily chinook salmon passage that was entrained into the RPP occurred on 12/24/97 with 0.0138 (1.38%) and an upper 90% CI of 0.0339 (3.99%). Half of the fourteen sample dates with a 90% CI exceeding 0.01 were collected in winter (Dec - early Feb) when the plant typically was not used to provide water to the TCC. Winter samples were collected specifically for our study. The highest entrainment rates corresponded with the outmigration of fall chinook salmon.

Most winter chinook salmon outmigrated past RBDD during August through November (Martin et al. 2001, draft). During those months, the fraction of chinook salmon passing RBDD that were entrained into the RPP on each date sampled averaged 0.0017 and ranged from 0.00007 to 0.0066. The fraction entrained was much less than the fraction of river discharge pumped on each sampling date (Figure 21).

The low ratio of chinook salmon per acre-foot captured in the RPP versus the rotary screw traps (0.22) is another indication that relatively few riverine salmon were entrained into the RPP. As suggested previously, this low frequency of entrainment may be due to the location of the pump intakes in relation to the vertical distribution of outmigrating juvenile chinook salmon. Another possible explanation is that sweeping velocities along the trash racks in front of the pump intakes deter fish from entering the sump area. The plant was designed to provide a sweeping velocity component in front of the trash racks to exclude sediment, debris, and fish. During measurements taken with an acoustic Doppler current profiler in March 1996, sweeping velocities along the trash racks ranged from 0.6 to 0.9 m/s (2 to3 ft/s) when the two Archimedes lifts were each pumping 2.6 m^3/s (93 ft^3/s; Tracy Vermeyen travel report, April 15, 1997).

Because the number of juvenile chinook salmon passing Red Bluff was greatest at night (Gaines and Martin 2001, draft), more salmon were entrained into the RPP at night than during the day. The fraction of riverine chinook salmon entrained into the RPP, however, was very similar between day and night samples for each of the three pumps. This suggests that the vulnerability of chinook salmon to entrainment was similar day and night. Turbidity also did not influence the fraction of fish entrained into the RPP. Due to their position at about 3.6 m (12 ft) below the water surface, low light conditions likely exist near the pump intakes at all times. This may explain why the fraction entrained was similar day versus night and was not influenced by turbidity.

There was no relationship between fork length and fraction of chinook salmon entrained. However, mean fork lengths of chinook salmon captured in traps were significantly greater than mean fork lengths of chinook salmon captured in the RPP. The RPP, located along the river margin, may have sampled younger fish which used the margins as rearing habitat. Rotary screw traps located in the main channel may have sampled older fish that were actively migrating downstream.

During the eighty-four dates when 24-h samples were collected simultaneously from the screw traps and the RPP, there was a strong, positive correlation between the number of chinook salmon captured per acre-foot in the traps and in the RPP. Although they likely have different efficiencies, a positive correlation between the RPP and traps was expected since they are fixed sampling methods located in the same general vicinity. The high correlation indicates that the number captured per acre-foot in the traps was a good predictor of the number entrained per acre-foot into the RPP, and vice versa.

Densities of two benthic inhabitants, prickly sculpin and lamprey ammocoetes, captured in the RPP were more than 100 and 200 times greater than in the screw traps, respectively. As with chinook salmon, this skewed ratio is thought to be related to the vertical distribution of these species in relation to the portion of the water column that the RPP and screw traps sample. Densities of juvenile Sacramento suckers and Sacramento pikeminnow captured in the RPP were 3 and 4 times greater than in the screw traps, respectively. In large streams juvenile Sacramento suckers and pikeminnow occupy areas along the stream margins which may make them more vulnerable to capture in the RPP than in the screw traps (McGinnis 1984).

Holding Tank Efficiency Trials

The purpose of these trials was to determine how effective our method of tabulating the number of fish collected in the holding tanks during a 24-h period was at evaluating the number of riverine chinook salmon entrained into the RPP. Our results suggest that on average, 10 - 12% of the chinook salmon entrained into the RPP were not captured in holding tanks within 24 h. Therefore, our actual, estimated, and projected numbers of chinook salmon entrained based upon our 24-h trials likely are conservative. Also, because fish may reside in the plant for several hours before moving downstream to the holding tanks, our diel patterns of entrainment may be skewed towards greater night entrainment. Another consideration when interpreting this data is that 81% of chinook salmon entrained into the plant were < 40 mm fork length, while only about 18% those used in our efficiency trials were <40 mm fork length. Size of fish may be an important consideration when assessing holding tank efficiencies.

The 10 to 12% of the chinook salmon not recovered within 24 h in our study was higher than reported by McNabb et al. (2000). During their study, chinook salmon released for pump passage experiments were frequently captured after a trial was completed, either during another trial the same night or while collecting fish at a subsequent sunrise or sunset check of the holding tanks for a 24-h entrainment trial. Occasionally, these fish were never recovered and were designated as *holdouts*. Investigations indicated that holdouts resided near pump outfalls or in the screening facilities. The percentage of fish released into the pump intakes that were holdouts ranged from 7 to 8 in 1998 and 1999 when velocities in the screening facilities were similar to conditions during our trials. In trials conducted to evaluate travel time of chinook salmon through the plant, 3% to 12% of fish released into pump intakes were not recovered in holding tanks within 24 h (Borthwick et al. 2000). Travel time and the percentage recovered were influenced by light conditions (i.e., day or night release) and turbidity of the water at release. Work during this study also revealed that fish not captured were holding up near pump outfalls or in the screening facilities. The difference in the results among various studies is likely a function of size of chinook salmon, water quality conditions, and velocities within the screening facility.

Frizell and Atkinson (1999) suggest that passage delays in the screening facility are due to the ramp located at the downstream end creating a recirculating eddy preventing flow from accelerating into the open bypass channel. The ramp created a zone of deceleration with sweeping velocities near the bottom very low, ranging from approximately 0.12 to 0.61 m/s (0.4 to 2.0 ft/s) for a distance of 2.4 m (8 ft) upstream of the bypass entrance (Frizell and Atkinson 1999). Juvenile salmon of the size used in our holding tank efficiency trials can maintain their position in these velocities (Bell 1991). Therefore, the screening facility can provide a refuge for chinook salmon. Also, juvenile salmonids can sense changes in velocity, and may avoid moving from one gradient to another, especially from a lower to a higher gradient (Bell 1991). Therefore, chinook salmon that encounter low velocity zones in the screening facility likely resist moving back into high velocity waters.

Summary

- The fish most frequently entrained into the RPP, in decreasing order, were chinook salmon, prickly sculpin, lamprey ammocoetes, Sacramento sucker, Sacramento pikeminnow, and riffle sculpin. These six species comprised 94% of the fish entrained. Ninety-four percent of entrained fish were <100 mm in length.

- Seasonal patterns of chinook salmon entrainment followed patterns of abundance in the river, peaking in winter when fall chinook salmon were outmigrating.

- Mean percent mortality of chinook salmon in the short-duration (2 to 3-h) trials was 0.9, 0.6, and 1.2 for Archimedes 1, Archimedes 2, and the internal helical pump, respectively, compared to 2.8, 2.9, and 4.9 in the 24-h trials. Mortality did not differ significantly among the three pumps for the short-duration or the 24-h trials.

- In both 24-h and short-duration trials, frequencies of mortality and sub-lethal injury of wild entrained fish were assumed to be overestimates of pump passage mortality since other factors may have contributed to mortality. Fish traveled past screens and brushes, in concrete channels, and up a wedge-wire dewatering ramp on their way to the holding tanks. In the holding tanks, fish were subjected to turbulence and debris, especially during 24-h trials. Also, condition of fish prior to entrainment was unknown.

- The fraction of the estimated daily total number of juvenile chinook salmon passing RBDD that were entrained into the RPP on 84 trial dates averaged 0.0022 (0.22%) and ranged from 0.00007 to 0.0138. The fraction entrained was consistently less than the fraction of river discharge pumped into the RPP.

- The greatest number and fraction of chinook salmon entrained during 24-h trials occurred in winter months (December through early February) when fall chinook salmon were outmigrating. During this winter period the plant typically would not be operated if used solely to deliver water to the Tehama-Colusa canal.

- The fraction of the estimated daily total number of winter chinook salmon passing RBDD that were entrained into the RPP averaged 0.0017 and ranged from 0.00008 to 0.0066.

- There was a positive correlation (Pearson correlation coefficient = 0.824) between the number of chinook salmon captured per acre-foot in the screw traps and in the RPP on the 84 dates when simultaneous samples were collected.

- The number of chinook salmon entrained per acre-foot into the RPP was greater at night than during the day in 33 of the 35 months that entrainment was monitored. However, the fraction of riverine chinook salmon entrained was similar between day and night suggesting that vulnerability to entrainment during those two diel periods was similar.

- Trials conducted with hatchery-reared chinook salmon revealed that 10 to 12% of fish released into the pumps were not collected in the holding tanks within 24 h of release. This suggests that entrainment trials underestimated the actual number of chinook salmon entrained into the RPP.

- The number captured per acre-foot of prickly sculpin and lamprey ammocoetes, both benthic species, was much higher (100-200 times) in the RPP than in rotary screw traps. This large difference was likely due to the RPP sampling the bottom of the water column while screw traps sampled the upper 1.2 m of the water column. Catch per acre-foot of chinook salmon, which migrate in the upper water column, was higher in the screw traps than in the RPP.

- In conclusion, the low fraction of chinook salmon entrained into the RPP, combined with the low frequency of mortality and sub-lethal injury to all fish passed through the pumps, supports the conclusion that the RPP can be operated with minimal harm to Sacramento River fishery resources near Red Bluff, including chinook salmon.

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Table 1. Summary of pump operations and fish entrainment monitoring at Red Bluff Research Pumping Plant, February 1997 - May 2000.

PARAMETER	ARCHIMEDES-1	ARCHIMEDES-2	HELICAL
Pump Speed (rpm)	26.5	26.5	378 and 350[1]
Average Discharge (m^3/s) (Range)	2.5 (2.1 - 2.7)	2.5 (2.0 - 2.8)	@378: 2.7 (2.3 - 2.9) @350: 2.3 (2.1 - 2.7)
Period of Pump Operation	1997: Feb - Dec 1998: Jan, Mar - Dec 1999: Feb - Oct 2000: Feb - May	1997: Feb - Dec 1998: Jan, Mar - Dec 1999: Feb - Oct 2000: Feb - May	1997: Feb - mid July Sep - Dec 1998: Jan, Mar - Apr Sep - mid-Nov 1999: Feb - Oct 2000: Feb - May
Total Hrs. Pump Operated	9922	9647	8145
Total Hrs. Entrainment Monitored	2974	3045	2461
% of Time Entrainment Monitored	30	32	30
Number of 24-h Trials Conducted	118	122	94

[1] Pump speed was 378 rpm from Feb 1997 - Apr 1998. Thereafter, pump speed was 350 rpm.

Table 2. Fish species entrained from the Sacramento River and captured in holding tanks at Red Bluff Research Pumping Plant during 24-h entrainment trials, February 1997 through May 2000.[1]

SPECIES	NUMBER ENTRAINED	PERCENT OF TOTAL
Chinook salmon (*Oncorhynchus tshawytscha*)[2]	10,412	40
Fall run	(8,704)	(83.6)
Winter run	(1,255)	(12.1)
Spring run	(252)	(2.4)
Latefall run	(201)	(1.9)
Prickly sculpin (*Cottus asper*)[2]	7,305	28
Lamprey ammocoetes (*Lampetra spp.*)[2]	4,580	18
Sacramento sucker (*Catostomus occidentalis*)[2]	1,497	6
Sacramento pikeminnow (*Ptychocheilus grandis*)[2]	511	2
Riffle sculpin (*Cottus gulosus*)[2]	357	1
Pacific lamprey (*Lampetra tridentata*)[2]	273	1
Threespine stickleback (*Gasterosteus aculeatus*)[2]	228	<1
Bluegill (*Lepomis macrochirus*)	220	<1
Tule perch (*Hysterocarpus traski*)[2]	172	<1
White catfish (*Ictalurus catus*)	144	<1
Steelhead/Rainbow trout (*Oncorhynchus mykiss*)[2]	114	<1
Hardhead (*Mylopharodon concephalus*)[2]	86	<1
California roach (*Lavinia symmetricus*)[2]	86	<1
Mosquitofish (*Gambusia affinis*)	31	<1
Common carp (*Cyprinus carpio*)	40	<1
Largemouth bass (*Micropterus salmoides*)	18	<1
Speckled dace (*Rhinichthys osculus*)[2]	25	<1
Unidentified adult lamprey (*Lampetra spp.*)[2]	25	<1
Threadfin shad (*Dorosoma petenense*)	24	<1
Green sunfish (*Lepomis cyanellus*)	15	<1
Unidentified sunfish (Centrarchidae)	14	<1
Channel catfish (*Ictalurus punctatus*)	9	<1
Brown bullhead (*Ictalurus nebulosus*)	7	<1
River lamprey (*Lampetra ayresi*)[2]	6	<1
Smallmouth bass (*Micropterus dolomieui*)	6	<1
Sturgeon (*Acipenser spp.*)[2]	4	<1
Golden shiner (*Notemigonus crysoleucas*)	2	<1
Hitch (*Lavinia exilicauda*)[2]	2	<1
Bass sp. (*Micropterus spp.*)	3	<1

Table 2.-Continued.

Bullhead sp. *(Ictalurus spp)*	1	<1
Western brook lamprey *(Lampetra richardsoni)* [2]	1	<1
Goldfish (*Carassius auratus*)	1	<1
Minnow sp. (Cyprinidae)	1	<1
TOTAL	26,220	

[1] Includes all chinook salmon, steelhead/rainbow trout, and sturgeon entrained. For other species, includes individuals $\geq$ 30 mm total length.
[2] Species native to the Sacramento River.

Table 3. Mean monthly number of fish entrained per acre-foot of water pumped for nocturnal and diurnal periods. Includes the five most frequently entrained fish species, and all fish species except chinook salmon combined. Trials were conducted at the Red Bluff Research Pumping Plant from February 1997 through May 2000.

Species	Mean Monthly Number Entrained per Acre-foot Pumped		Nocturnal:Diurnal
	Nocturnal	Diurnal	
Chinook salmon			
Fall	0.388	0.146	2.7
Latefall	0.003	0.001	3.3
Spring	0.021	0.003	7.0
Winter	0.028	0.002	16.5
All Salmon	**0.428**	**0.090**	**4.8**
Prickly sculpin	0.352	0.029	12.1
Lamprey ammocoetes	0.135	0.017	7.9
Sacramento sucker	0.078	0.008	9.8
Sacramento pikeminnow	0.014	0.005	2.8
All fish except salmon	0.642	0.080	8.0

Table 4. Total number and percent mortality of fish species most frequently entrained into experimental pumps at Red Bluff Research Pumping Plant during 24-h entrainment trials (N=80) conducted when all three pumps ran simultaneously; February 1997 through May 2000. Each entrainment trial started at sunrise and continued for 24 h.

	ARCHIMEDES 1		ARCHIMEDES 2		INTERNAL HELICAL	
SPECIES	Number	% Mortality[1]	Number	%Mortality [1]	Number	% Mortality[1]
Chinook salmon[2]						
Fall run	1730	2.4	2929	2.4	1243	5.0
Winter run	267	3.7	458	4.6	97	1.0
Spring run	43	11.6	89	5.6	24	12.5
Late-fall run	40	2.5	50	12.0	42	7.1
All chinook salmon	**2080**	**2.8**	**3526**	**2.9**	**1406**	**4.9**
Prickly sculpin	1657	1.7	1076	1.4	1153	3.9
Lamprey ammocoetes	367	0.5	348	0.9	498	1.2
Sacramento sucker	204	17.2	174	23.6	125	15.2
Sacramento pikeminnow	62	4.8	84	1.2	25	16.0
Riffle sculpin	102	0.0	81	1.1	78	0.0
Threespine stickleback	78	30.8	45	31.1	39	33.3
Pacific lamprey	95	3.2	66	1.5	53	1.9
Bluegill	21	19.0	30	20.0	12	16.7
White catfish	45	17.8	18	33.3	32	6.3
All fish except chinook	**2744**	**4.5**	**2048**	**4.9**	**2094**	**5.1**
ALL FISH SPECIES	**4824**	**3.8**	**5574**	**3.6**	**3500**	**5.0**

1 Mortality should not be interpreted strictly as pump passage mortality. This table represents mortality of fish that passed through a pump, then traveled by a screening facility, around curved bypass channels, up a dewatering ramp and into a holding tank. Fish could reside in a holding tank for up to 14 h depending upon when they arrived in relation to the time of collection at sunrise or sunset. Mortality of fish collected from the holding tanks could be affected by the duration it was confined to the tank, the amount of water flowing into the tank, the type and/or volume of debris in the tank, or by other fish in the tank. Also, the condition of fish in the river prior to being entrained was unknown.

2 Run membership was determined from a daily fork-length table generated by Sheila Greene, California Department of Water Resources, Environmental Services Office, Sacramento (8 May 1992) from data by Frank Fisher, California Department of Fish and Game, Inland Fisheries Branch, Red Bluff (revised 2 February 1992).

Table 5. Percentage of juvenile chinook salmon and other fish entrained into experimental pumps at Red Bluff Research Pumping Plant that exhibited injuries when collected from holding tanks during 24-h entrainment trials (N=80) conducted when all three pumps operated simultaneously; February 1997 through May 2000.

Groups of Fish	Percent Injured		
	Archimedes 1	Archimedes 2	Helical
All Chinook[1]	3.1	3.1	4.9
Surviving Chinook	1.2	0.8	1.7
Other Fish[1]	5.0	5.0	5.7
Other Surviving Fish	2.9	2.8	2.6

[1] Includes all fish with injuries, whether individuals were alive or dead at the time of collection.

Table 6. Percentage of alive and dead juvenile chinook salmon with specified injuries. Chinook salmon were collected in holding tanks at Red Bluff Research Pumping Plant during 24-h entrainment trials (N=80) conducted when all three pumps operated simultaneously; February 1997 through May 2000.

Type of Injury[1]	Archimedes 1		Archimedes 2		Helical	
	Alive	Dead	Alive	Dead	Alive	Dead
Fins						
Eroded >30%	0	1.7	0	3.3	0	4.3
Eroded to base	0	0	0	1.1	0	1.4
Hemorrhage or Bruise	0.07	0	0	1.1	0	1.4
Missing	0	0	0	0	0	1.4
Skin						
Bruise	0.20	3.4	0.19	3.3	0.17	8.7
Partially Deskinned	0	1.7	0.14	4.3	0	1.4
Split or Open Wound	0.48	8.6	0.09	8.7	0.33	13.0
Abrasion	0.14	5.3	0.28	18.5	0.42	20.3
Hemorrhage	0.14	3.4	0.09	0	0.08	1.4
Eyes						
Bulging	0.07	20.7	0	21.7	0.25	18.8
One Missing	0	1.7	0	4.3	0.17	5.8
Both Missing	0	0	0	1.1	0	4.3
Hemorrhage	0	3.4	0	5.4	0.42	8.7
Head						
One operculum missing	0	0	0	3.3	0	0
Open wound or abrasion	0.14	1.7	0	3.3	0	2.9
Decapitated	0	0	0	0	0	5.8
Bruise or hemorrhage	0	3.4	0.05	4.3	0.08	4.3

[1] A fish may have more than one type of injury.

Table 7. Percentage of alive and dead fish other than juvenile chinook salmon with specified injuries. Fish were collected in holding tanks at Red Bluff Research Pumping Plant during 24-h entrainment trials (N=80) conducted when all three pumps operated simultaneously; February 1997 through May 2000.

Type of Injury[1]	Archimedes 1		Archimedes 2		Helical	
	Alive	Dead	Alive	Dead	Alive	Dead
Fins						
Eroded >30%	0.30	6.6	0.06	12.0	0.24	8.5
Eroded to base	0.25	3.3	0.28	8.0	0.18	3.8
Hemorrhage or Bruise	0.40	0.8	0.11	1.0	0.30	0
Missing	0.05	0.8	0.11	0	0.24	0.9
Skin						
Bruise	0.60	1.6	0.74	2.0	0.54	1.9
Partially Deskinned	0.05	6.6	0.11	4.0	0.12	1.9
Split or Open Wound	0.40	8.9	0.40	13.0	0.18	11.3
Abrasion	0.20	10.6	0.23	7.0	0.24	2.8
Hemorrhage	0.60	4.9	0.91	5.0	0.71	6.6
Eyes						
Bulging	0.05	1.6	0.06	11.0	0	7.5
One Missing	0	3.3	0	3.0	0	0.9
Both Missing	0	0.8	0	1.0	0	0.9
Hemorrhage	0.05	0.8	0	0	0	0.9
Head						
One operculum missing	0	0	0	0	0	2.8
Open wound or abrasion	0.05	1.6	0.06	0	0	2.8
Decapitated	0	1.6	0	2.0	0	1.9
Bruise or hemorrhage	0.05	4.1	0.06	3.0	0.06	2.8

[1] A fish may have more than one type of injury.

Table 8. Results of short-duration (2 to 3-h) entrainment trials (N=15) conducted from January through March, 2000. Entrained fish were removed from holding tanks every 10-15 minutes. The objective of these trials was to obtain a better estimate of mortality of entrained fish by minimizing mortality due to confinement in tanks and interactions with debris and other fish. Mean fork length of chinook salmon entrained during these trials was 38 mm.

	ARCHIMEDES 1		ARCHIMEDES 2		INTERNAL HELICAL	
SPECIES	Number	% Mortality	Number	% Mortality	Number	% Mortality
Chinook salmon[1]	468	0.9	1045	0.6	782	1.2
Lamprey ammocoetes	319	0	253	0.4	198	0
Prickly sculpin	27	0	33	0	47	0
Pacific lamprey	18	0	12	0	16	0
Sacramento sucker	8	0	11	0	3	0
Steelhead/Rainbow trout	7	0	7	0	5	0
Threespine stickleback	6	50	5	20.0	0	--
White catfish	2	0	0	--	0	--
Sacramento pikeminnow	3	0	9	0	4	0
Riffle sculpin	4	0	6	0	4	0
Mosquito fish	0	--	3	33.3	0	--
Bluegill	0	--	2	0	0	--
California roach	0	--	1	0	0	--
Hardhead	0	--	1	0	4	0
All fish except salmon	394	0.8	343	0.9	281	0
All fish combined	**862**	**0.8**	**1388**	**0.6**	**1063**	**0.8**

[1] Surviving chinook salmon were held in the river water lab for 96 h to assess delayed morality. Despite high handling mortality which occurred during counting and measuring fish in one trial with high numbers entrained (>300/pump), percent mortality at 96 hours for fish passed through Archimedes 1, 2, and the helical pump was 2.2, 0.9 and 2.7, respectively.

Table 9. Mortality of large fish ($\geq$200 mm) entrained into experimental pumps at Red Bluff Research Pumping Plant during 24-h and short-duration entrainment trials conducted from February 1997 through May 2000. Pumps were not always operated simultaneously.

SPECIES (avg; min-max total length in mm)	ARCHIMEDES 1		ARCHIMEDES 2		HELICAL	
	Number	% Mortality	Number	% Mortality	Number	% Mortality
Pacific lamprey (566; 307 - 732)	109	2.8	58	0	42	2.4
Sacramento pikeminnow (249; 202 - 480)	32	3.1	26	0	20	5.0
Sacramento sucker (251; 201 - 432)	47	0	51	0	12	8.3
Hardhead (235; 203 - 338)	29	3.4	26	0	10	0
White catfish (271; 232 - 345)	3	0	6	0	1	0
Steelhead\Rainbow trout (250; 205 - 375)	4	0	6	0	7	14.3
Channel catfish (271; 211 - 334)	0	-	3	0	1	0
Bass (275; 210 - 380)	1	0	2	0	2	0
River lamprey (246; 216 - 275)	1	0	0	--	1	0
Common carp (255; 255 - 255)	0	--	1	0	0	--
ALL LARGE FISH	**226**	**2.2**	**179**	**0**	**96**	**4.2**

Table 10. Results from simultaneous collections of fish passed through pumps at the Red Bluff Research Pumping Plant and from rotary screw traps placed in the Sacramento River near the pumping plant from September 1997 through May 2000. N is the number of samples collected.

Species	Mean Number (SD) Captured Per Acre-foot of Water Sampled		Capture ratio pumps/traps
	Pumps (N = 467)	Rotary Screw Traps (N = 168)	
Chinook salmon	0.1708 (0.5671)	0.7690 (1.2989)	0.22
Lamprey ammocoetes	0.0404 (0.4034)	0.0002 (0.0011)	202
Prickly sculpin	0.0228 (0.1357)	0.0002 (0.0005)	114
Sacramento pikeminnow	0.0016 (0.0041)	0.0004 (0.0015)	4
Sacramento sucker	0.0042 (0.0058)	0.0015 (0.0084)	3

Table 11. Results of 16 holding tank efficiency trials conducted at Red Bluff Research Pumping Plant in 1999 and 2000. All three pumps were operated during each trial.

Pump	No. Fish per Trial	Mean (SD) % of Fish Recovered 24 h After Release[1]		
		All Trials (N=16)	Sunrise Release Trials (N=4)	Sunset Release Trials (N=4)
Archimedes 1	30 - 32	88 (8)	84 (11)	90 (8)
Archimedes 2	31 - 32	90 (6)	94 (4)	88 (15)
Internal Helical	31 - 32	88 (12)	82 (13)	85 (14)

[1]Mean trial duration was 23.6 h. In 1999, all samples were released at sunrise. In 2000, samples were released at sunset on day one and at sunrise the next day to assess if release time affected percent of fish recovered.

Table 12. Time-in-travel for chinook salmon (52 mm mean fork length) released in pump intakes and collected from holding tanks. Six trials were conducted, and all three pumps were used in each trial. Experimental fish were released at sunrise.

Hours Post-Release	Mean Percent Recovered (SD)		
	Archimedes 1	Archimedes 2	Internal Helical
0.5	38 (19)	40 (20)	32 (24)
1.0	46 (16)	53 (29)	40 (25)
2.0	67 (16)	59 (26)	55 (23)
6.0	78 (13)	72 (24)	75 (28)
14.0	87 (6)	76 (20)	82 (25)
24.0	90 (5)	88 (7)	98 (7)

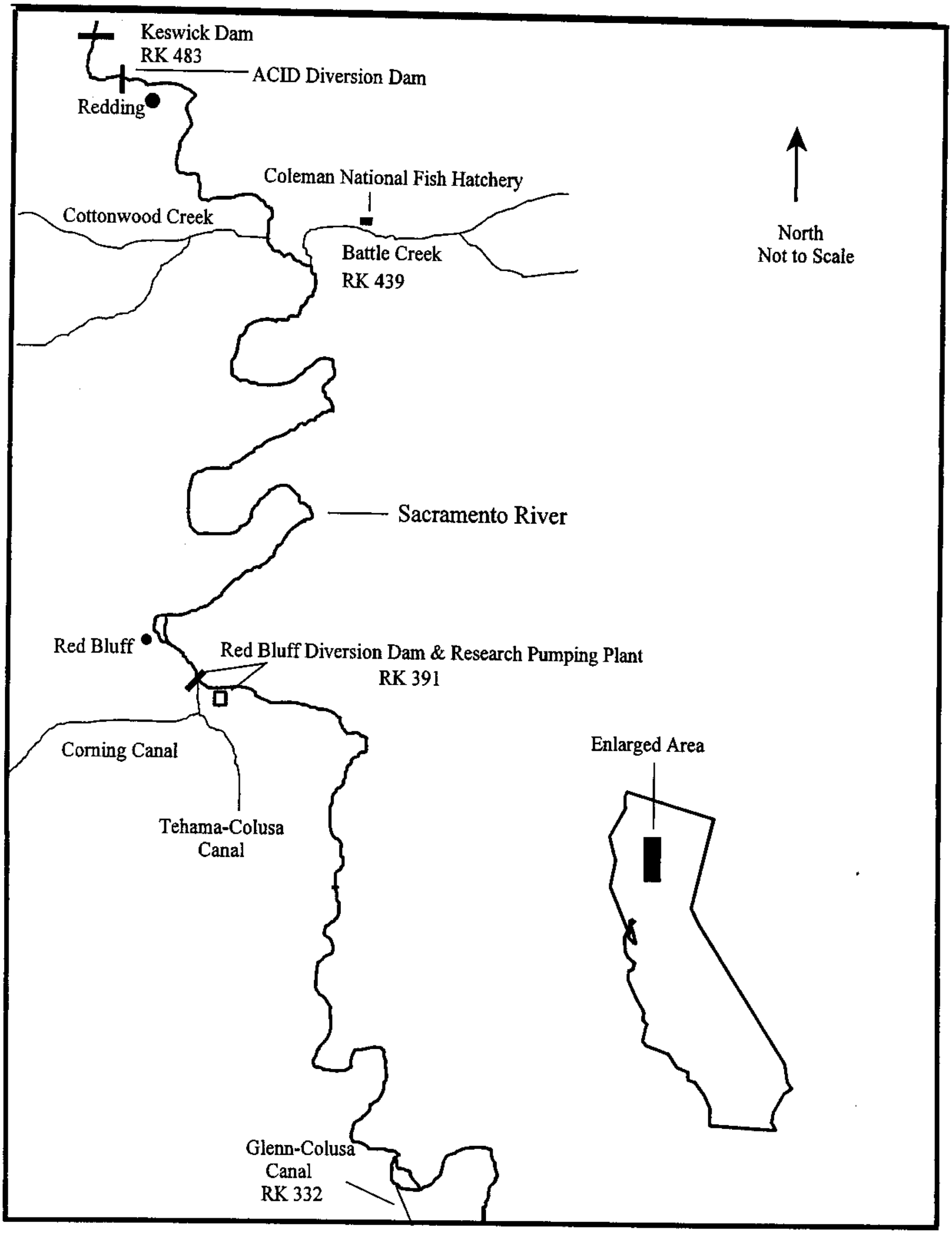


Figure 1. Location of Red Bluff Research Pumping Plant on the Sacramento River at river kilometer 391 (river mile 243).

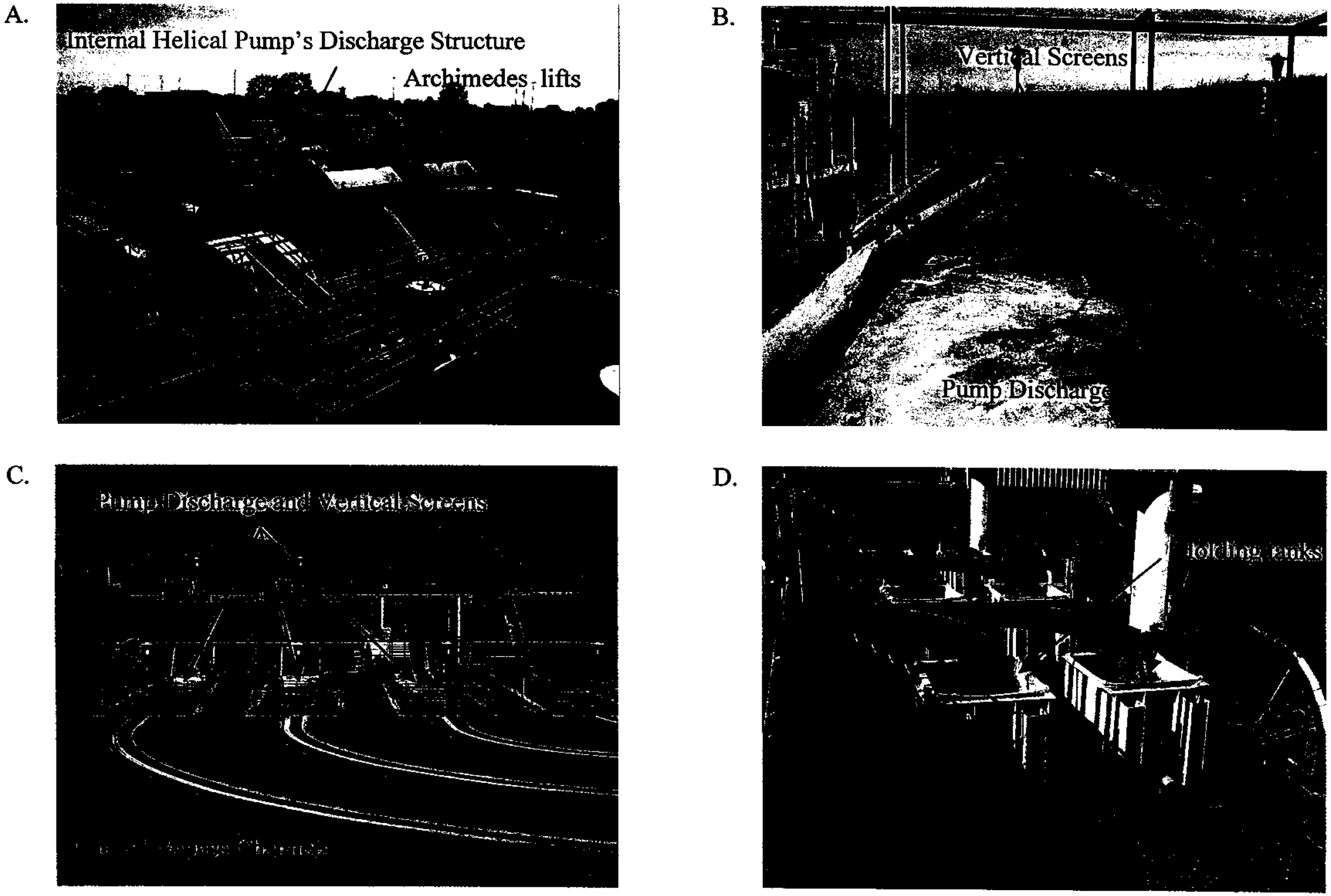


Figure 2. Features of Red Bluff Research Pumping Plant. (A) The two Archimedes lifts and the discharge structure of the internal helical pump. (B) Vertical wedge-wire screens downstream of the pump discharge. (C) Curved open bypass channels downstream of the vertical screens. (D) Holding tanks downstream of the curved bypass channels.

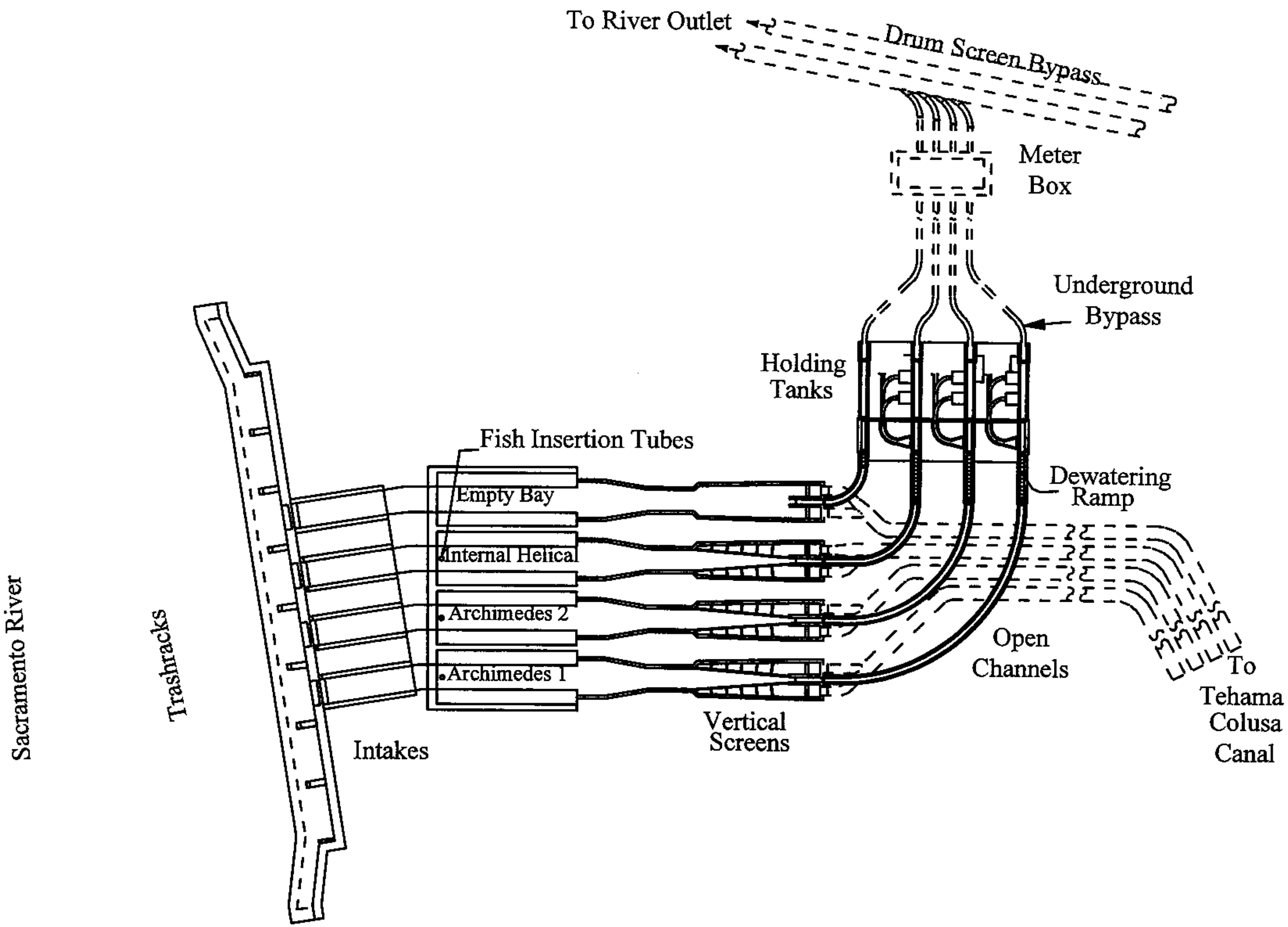


Figure 3. Schematic of Red Bluff Research Pumping Plant showing pathways of movement for fish entrained from the Sacramento River. During trials fish were collected in holding tanks.

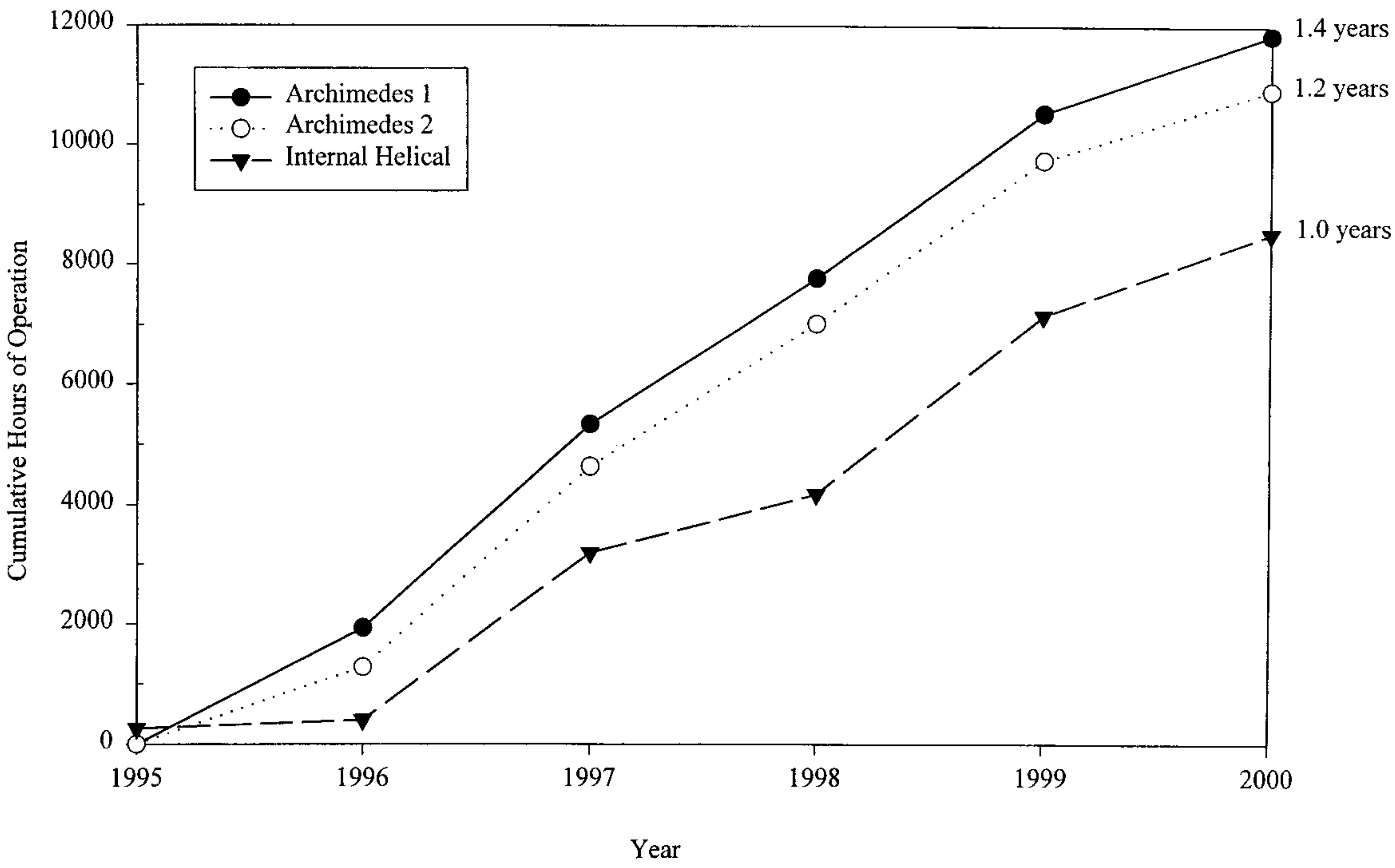


Figure 4. Cumulative hours of operation, by year, for the Archimedes lifts and the internal helical pump at Red Bluff Research Pumping Plant from May 1995 through May 2000.

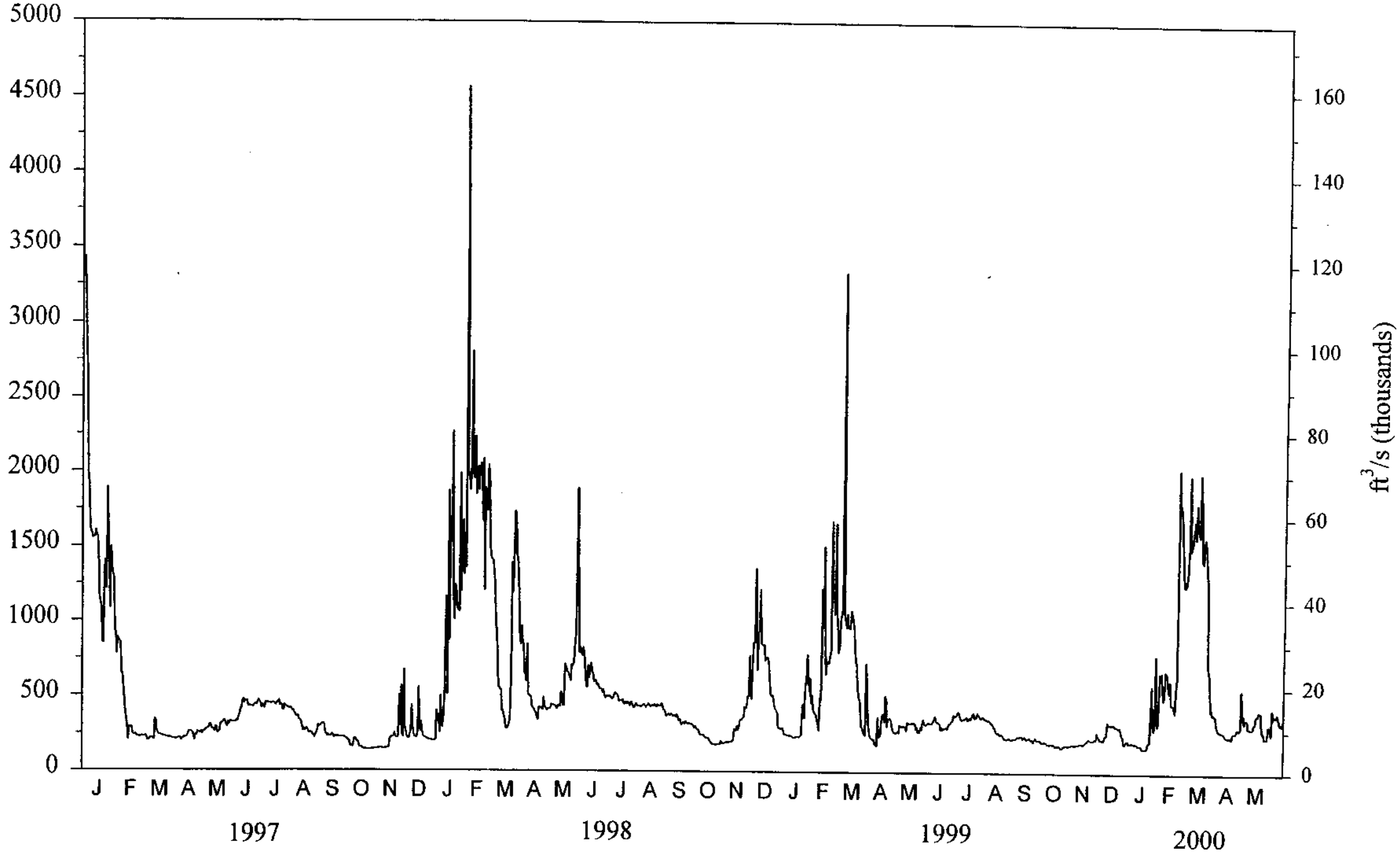


Figure 5. Daily Sacramento River flows past Red Bluff Diversion Dam (RBDD) from January 1997 through May 2000. Flows were estimated by Bureau of Reclamation personnel based upon U. S. Geological Survey flow data collected at Bend Bridge approximately 24 river km upstream of RBDD.

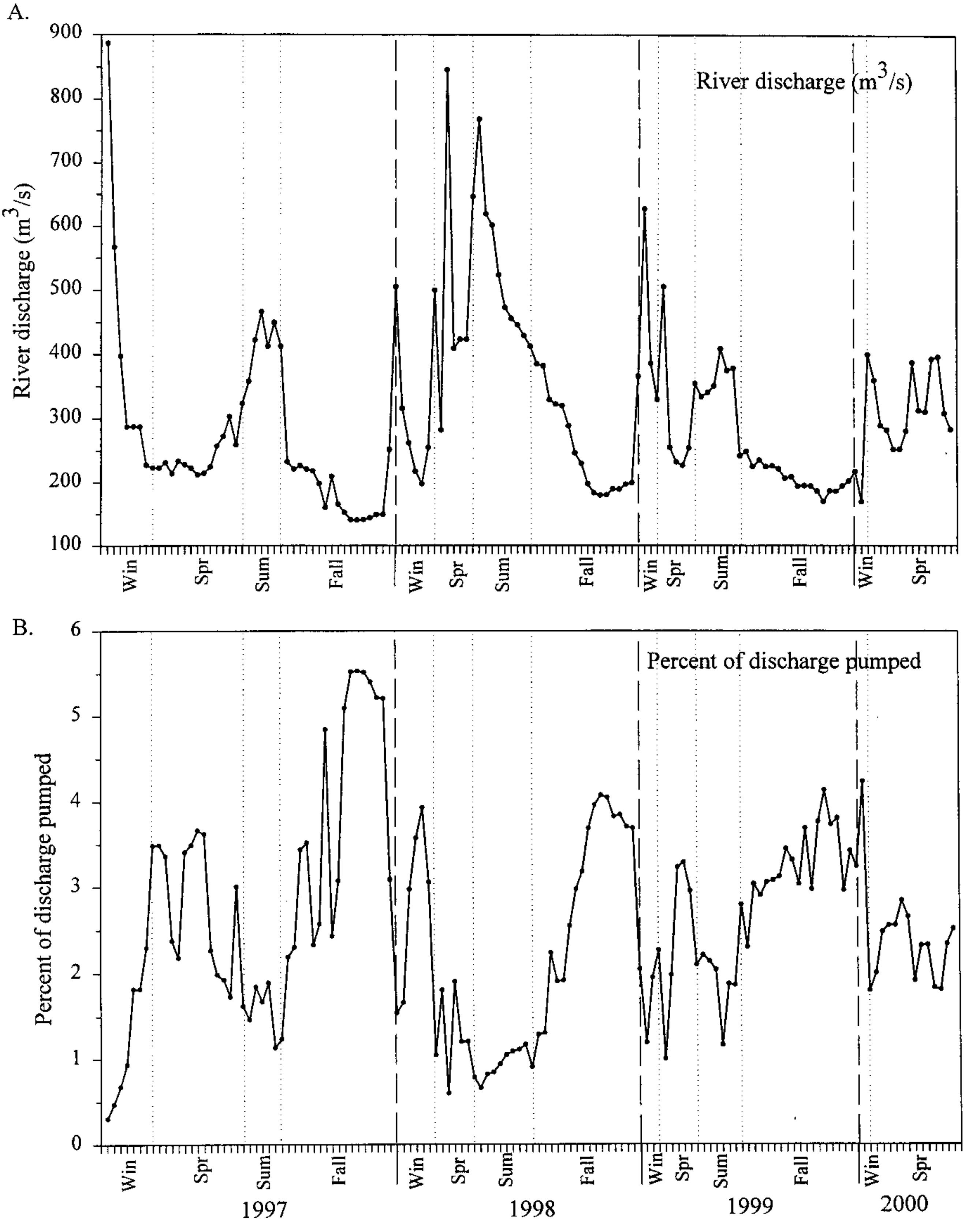


Figure 6. (A) Daily Sacramento River discharge (m^3/s) flowing past Red Bluff Research Pumping Plant on dates that entrainment trials were conducted. (B) Percent of discharge pumped into the plant during entrainment trials; February 1997 - May 2000. Seasons are defined as Win=Dec-Feb; Spr=Mar-May; Sum=Jun-Aug; Fall=Sep-Nov.

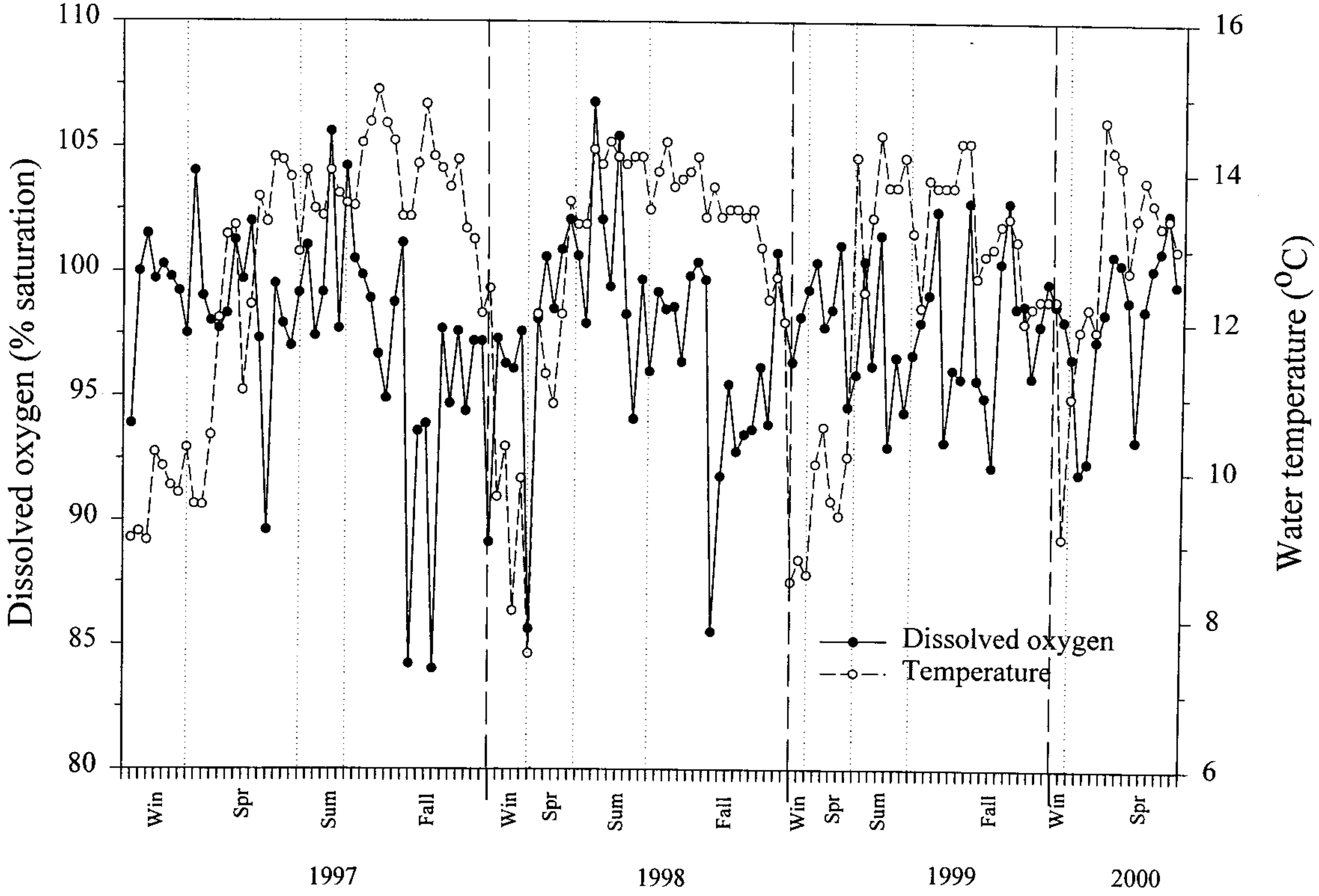


Figure 7. Mean water temperature and dissolved oxygen (% saturation) during entrainment trials conducted at Red Bluff Research Pumping Plant from February 1997 through May 2000. Measurements were collected from Sacramento River water flowing through holding tanks using a YSI dissolved oxygen meter. Seasons are defined as follows: Win = Dec - Feb; Spr = Mar - May; Sum = Jun - Aug; Fall = Sep - Nov.

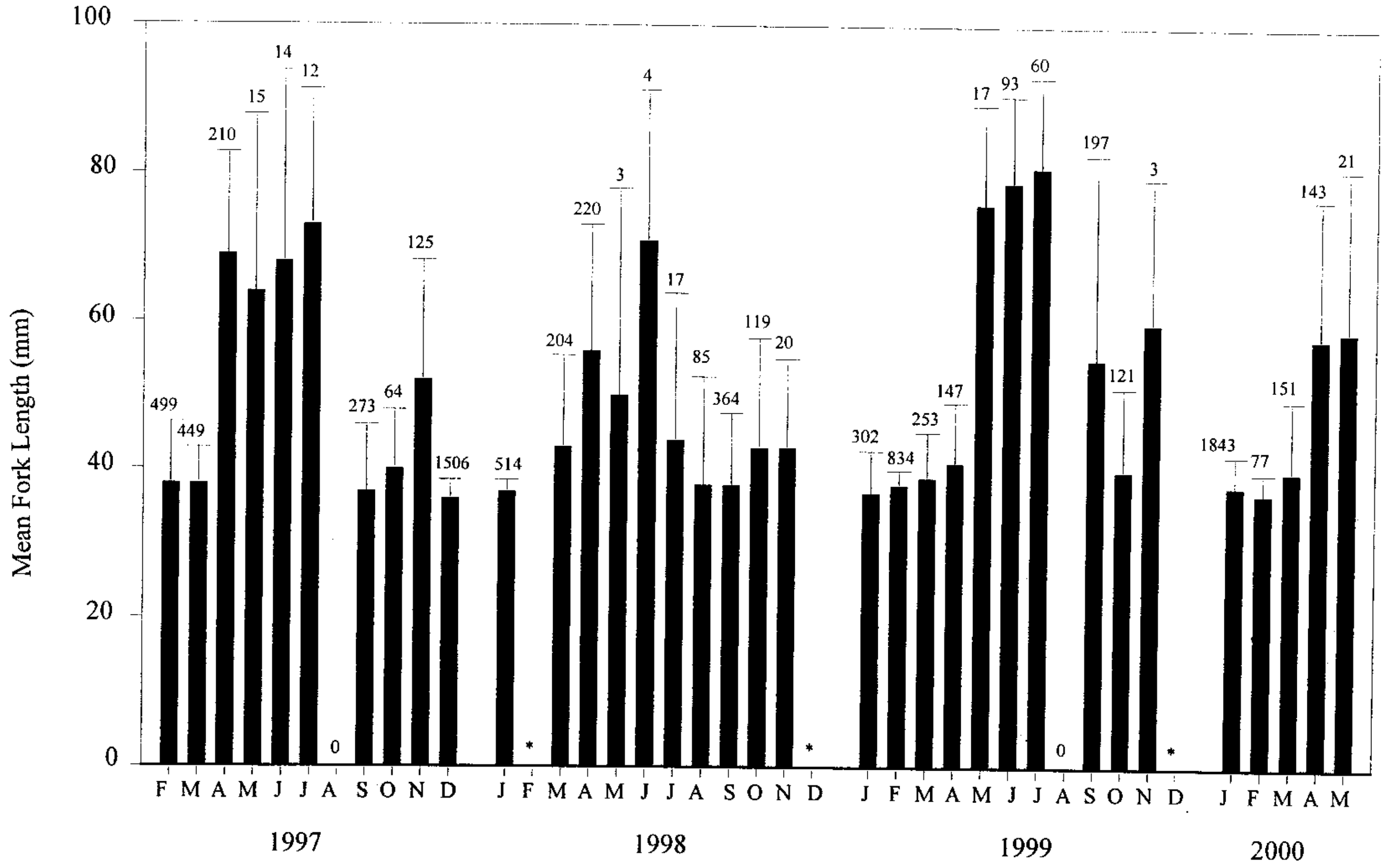
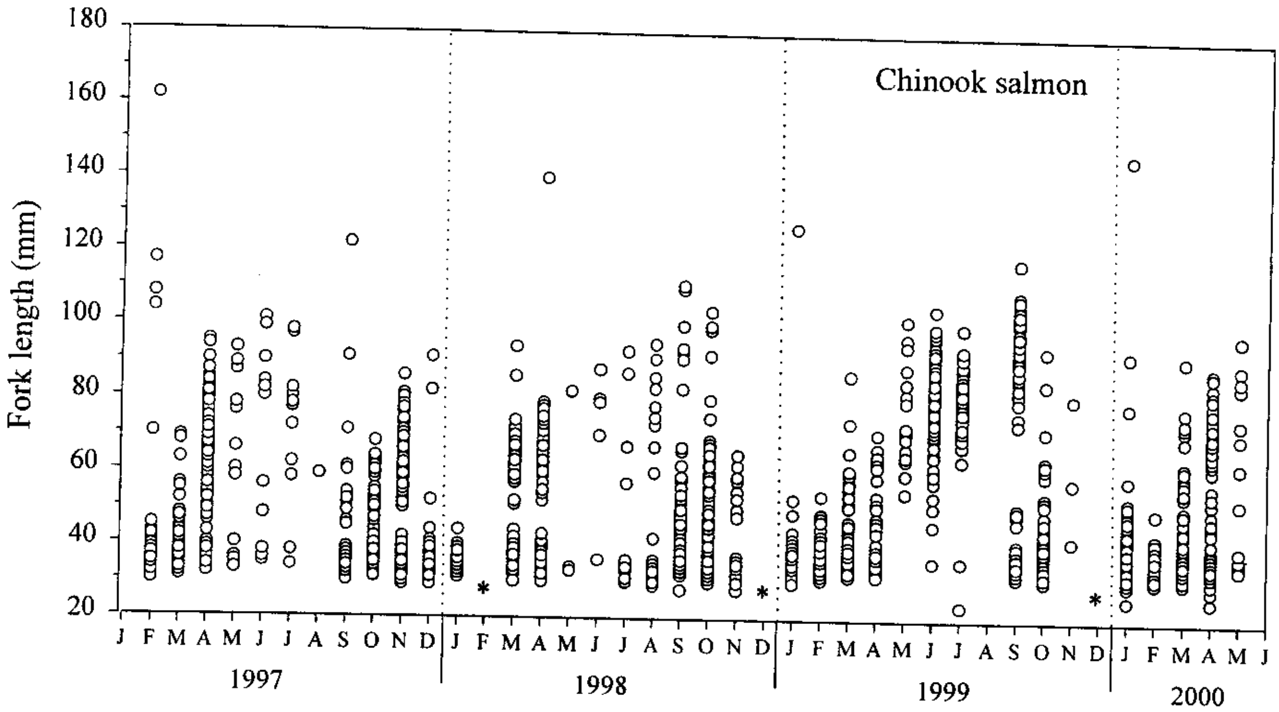


Figure 8. Monthly mean fork length (+ SD) of juvenile chinook salmon entrained into Red Bluff Research Pumping Plant during 24-h and short-duration entrainment trials; February 1997 through May 2000. Number of fish measured each month is shown above each bar. Asterisks indicate months when entrainment monitoring was not conducted.

A.



B.

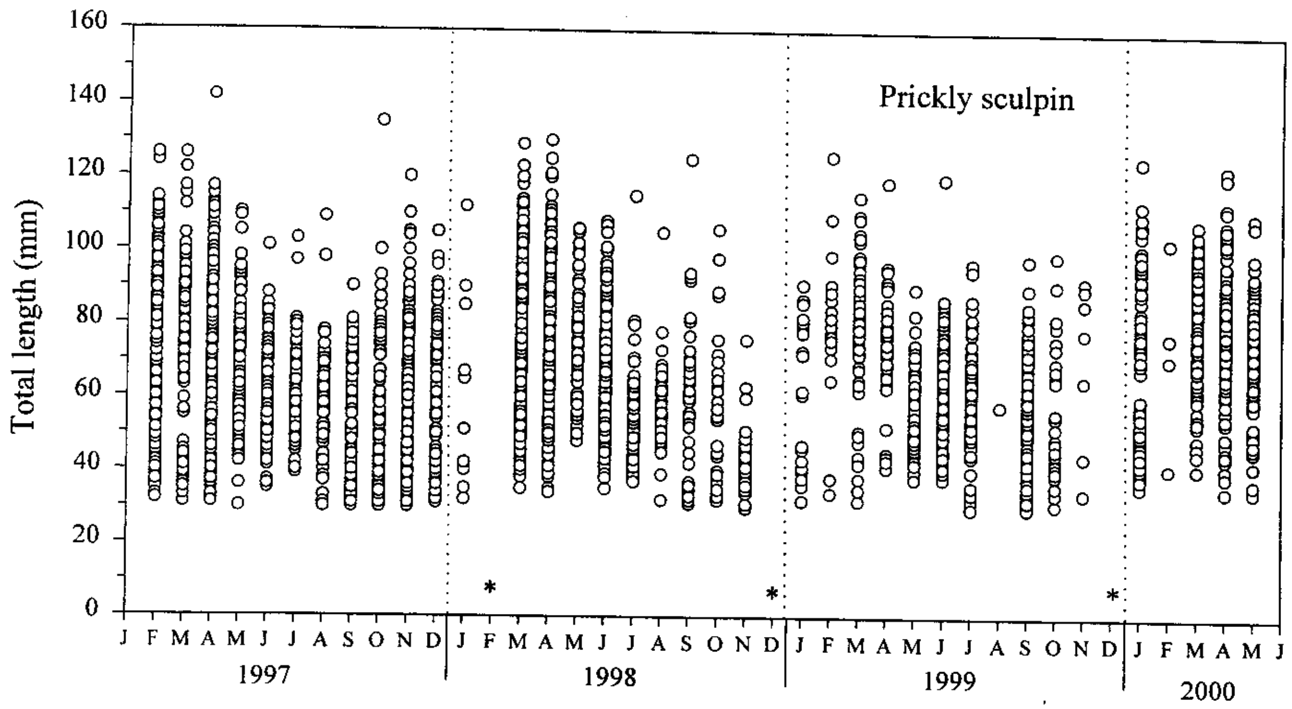
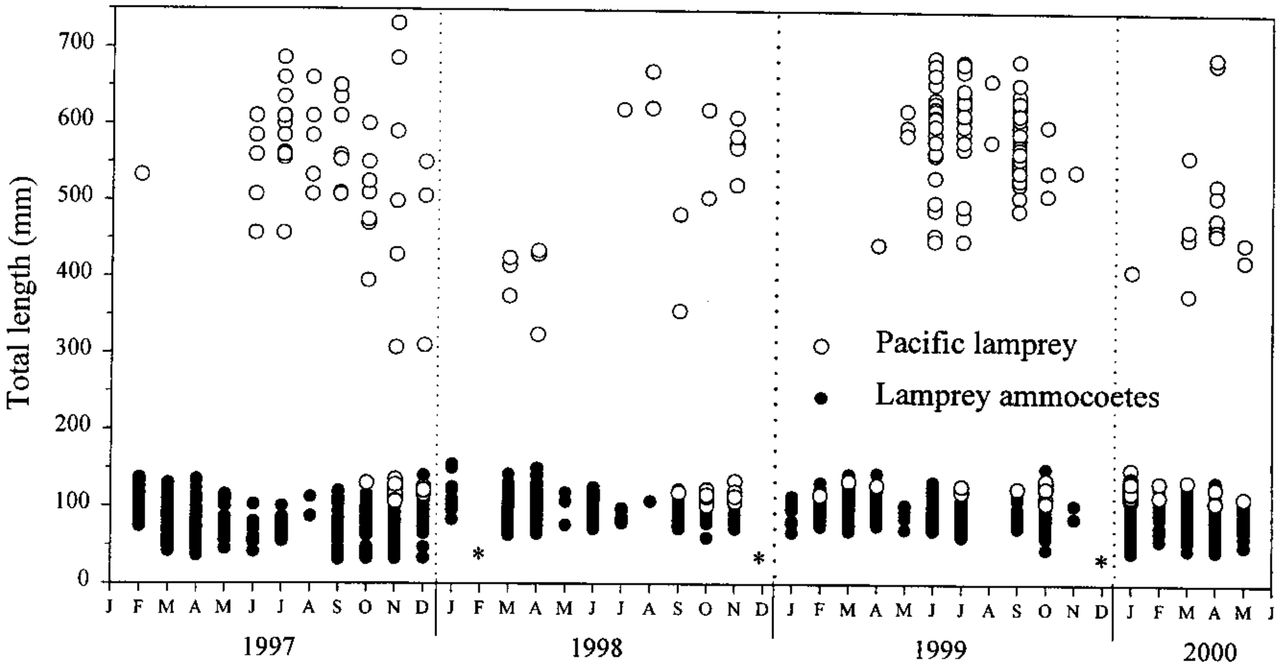


Figure 9. Monthly length distributions of (A) chinook salmon and (B) prickly sculpin entrained into Red Bluff Research Pumping Plant during 24-h and short-duration entrainment trials; February 1997 through May 2000. Asterisks indicate months when entrainment trials were not conducted.

A.



B.

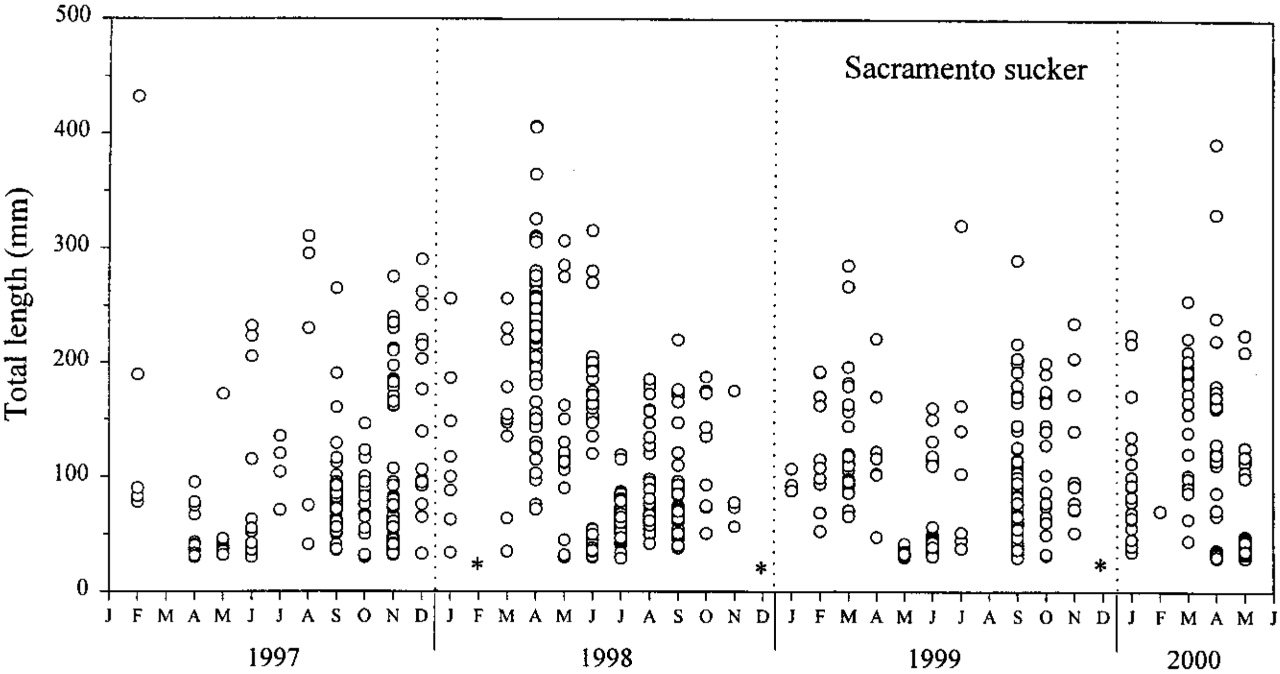


Figure 10. Monthly length distributions of (A) lamprey ammocoetes and Pacific lamprey and (B) Sacramento suckers entrained into Red Bluff Research Pumping Plant during 24-h and short-duration entrainment trials; February 1997 through May 2000. Asterisks indicate months when entrainment trials were not conducted.

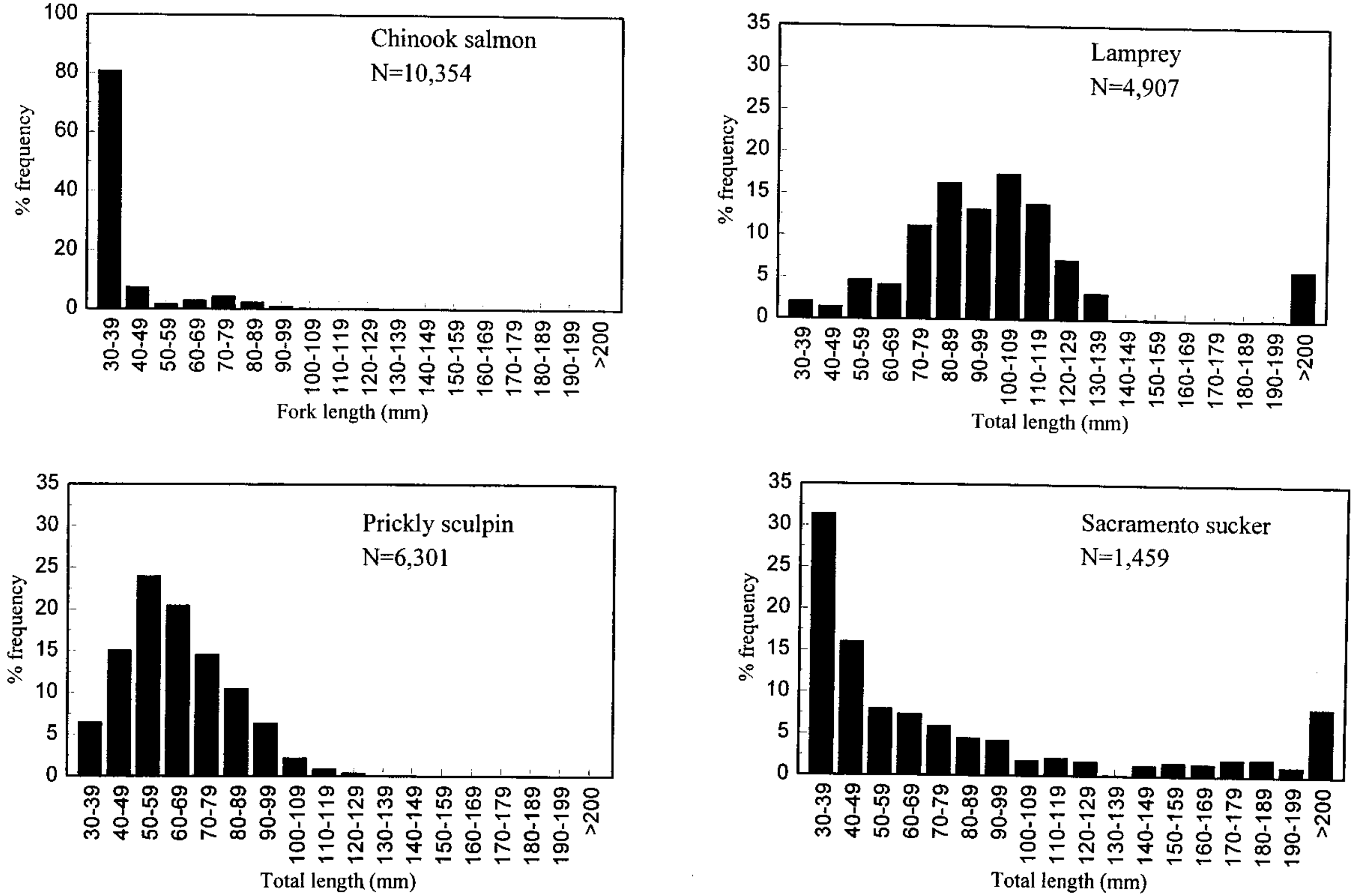


Figure 11. Size-frequency distribution of chinook salmon, lamprey, prickly sculpin, and Sacramento sucker entrained into Red Bluff Research Pumping Plant during 24-h and short-duration entrainment trials; February 1997 through May 2000.

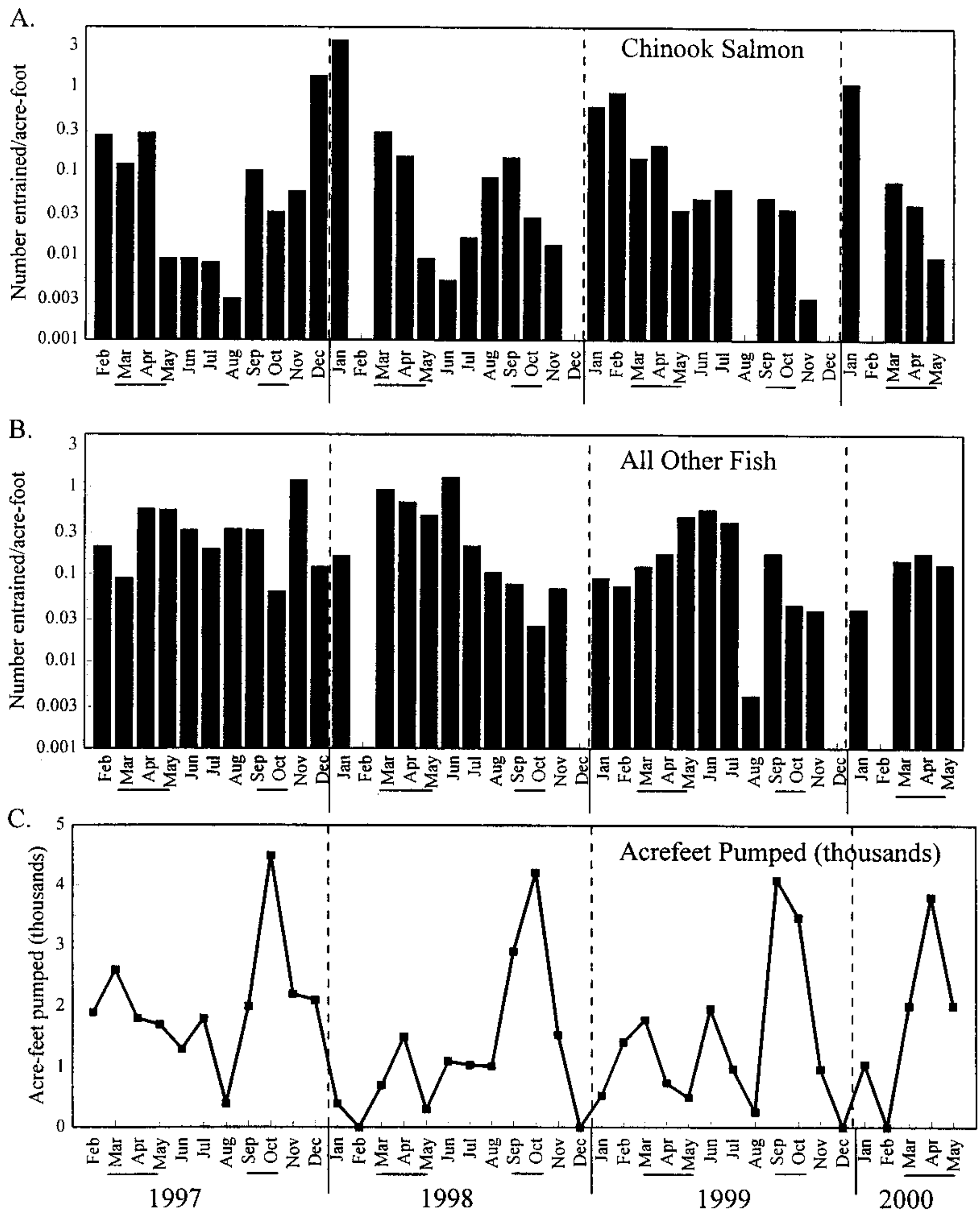


Figure 12. Seasonal entrainment patterns of (A) chinook salmon and (B) all other fish into Red Bluff Research Pumping Plant during 24-h entrainment trials; February 1997 through May 2000. (C) Sampling effort is indicated by acre-feet of water pumped during entrainment trials each month. Lines beneath months indicate periods when the plant would typically be operated to provide water to the canals. A log scale is used on the y-axis in A and B because of the large range in number entrained per acre-foot.

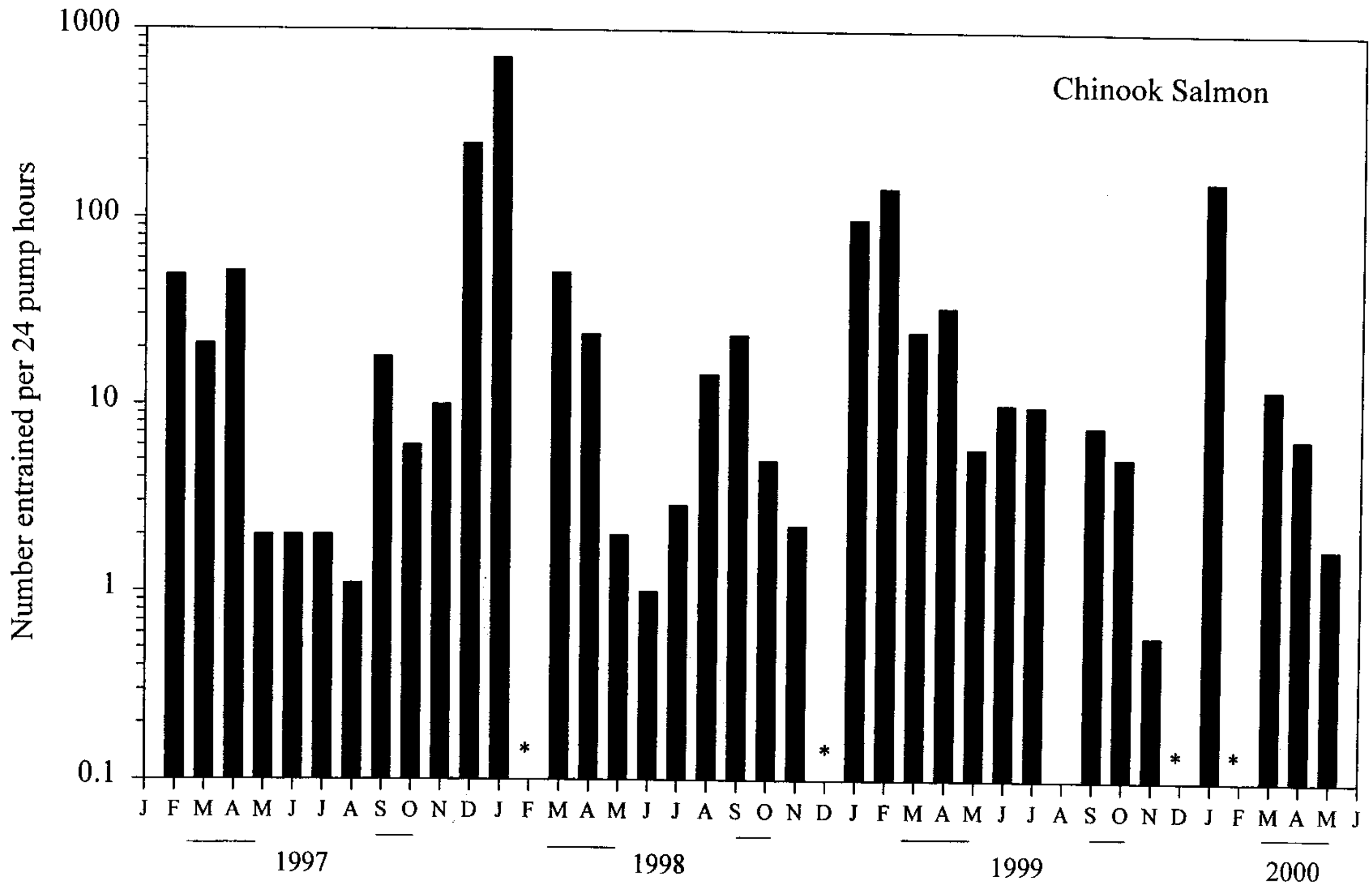


Figure 13. Number of chinook salmon entrained into Red Bluff Research Pumping Plant per 24 h of pump operation during 24 h entrainment trials; February 1997 through May 2000. Askerisks indicate months when trials were not conducted. Lines beneath the months indicate periods when the plant would typically be operated to provide water to canals. A log scale was used on the y-axis because of the large range in number entrained per 24 h.

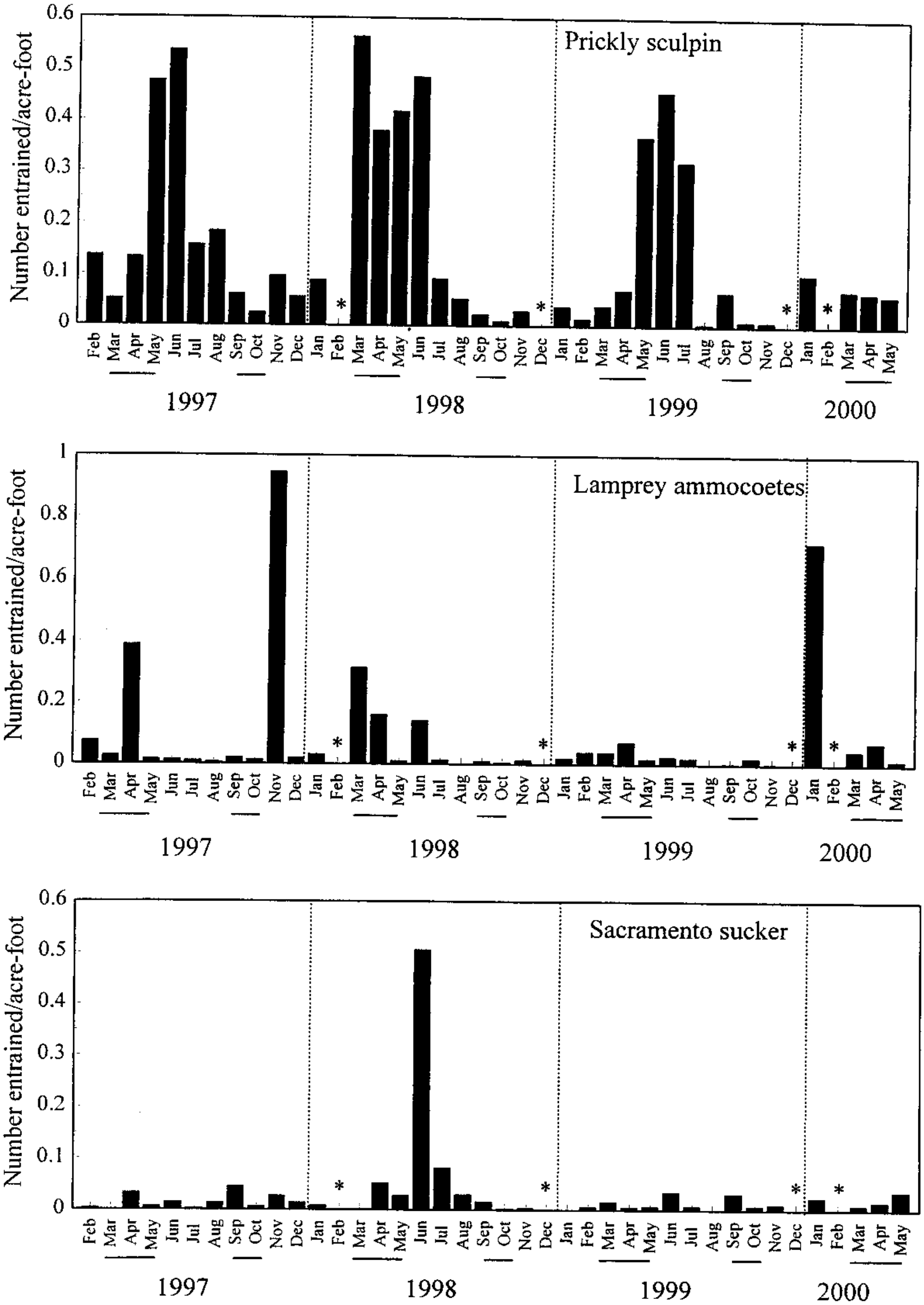


Figure 14. Seasonal entrainment patterns of three species frequently entrained into Red Bluff Research Pumping Plant during 24-h entrainment trials; February 1997 through May 2000. Asterisks indicate months when entrainment monitoring was not conducted. Lines beneath the months indicate periods when the plant would typically be operated to provide water to the canals.

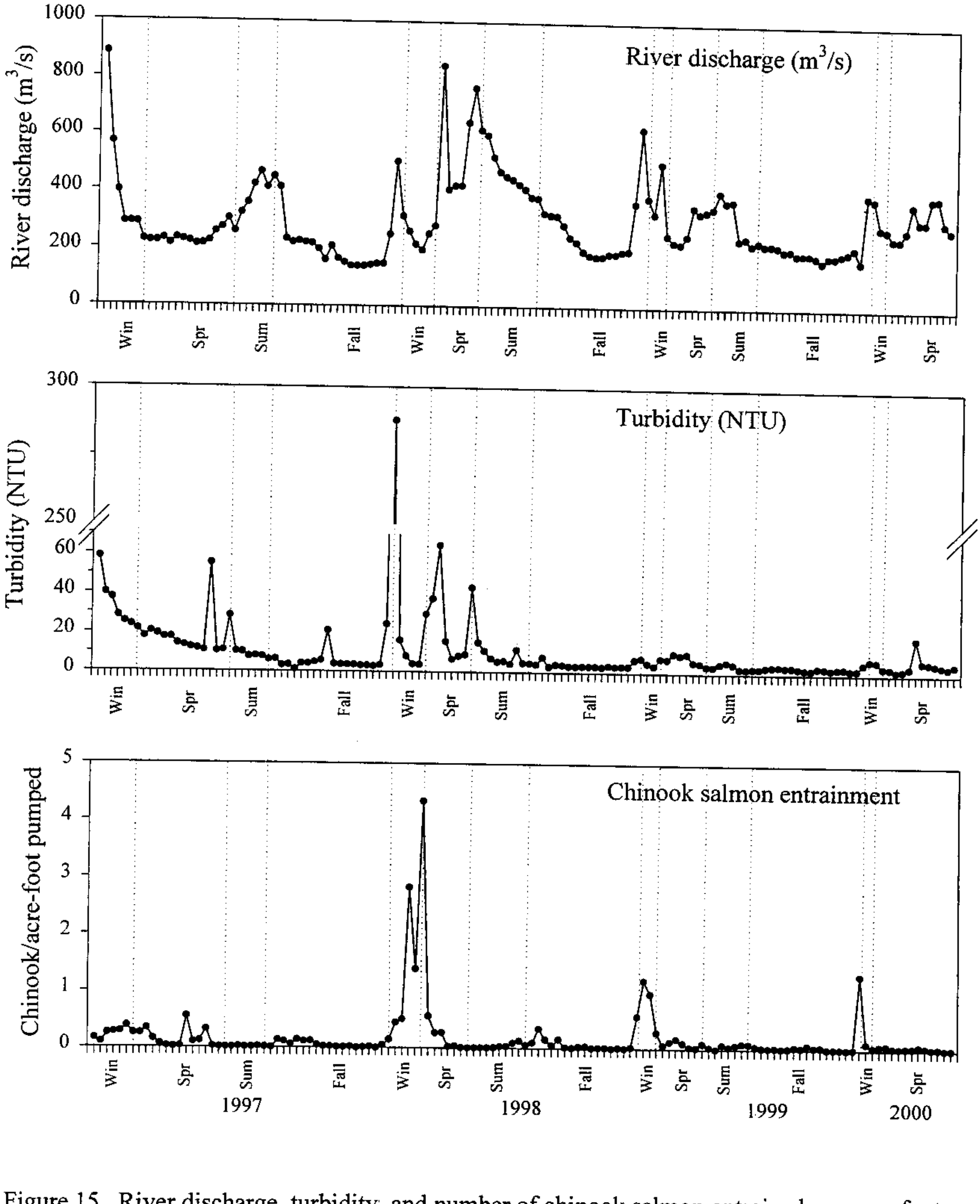


Figure 15. River discharge, turbidity, and number of chinook salmon entrained per acre-foot into Red Bluff Research Pumping Plant on each date that 24-h entrainment trials were conducted; February 1997 through May 2000. Seasons are defined as follows: Win = Dec - Feb; Spr = Mar - May; Sum = Jun - Aug; Fall = Sep - Nov.

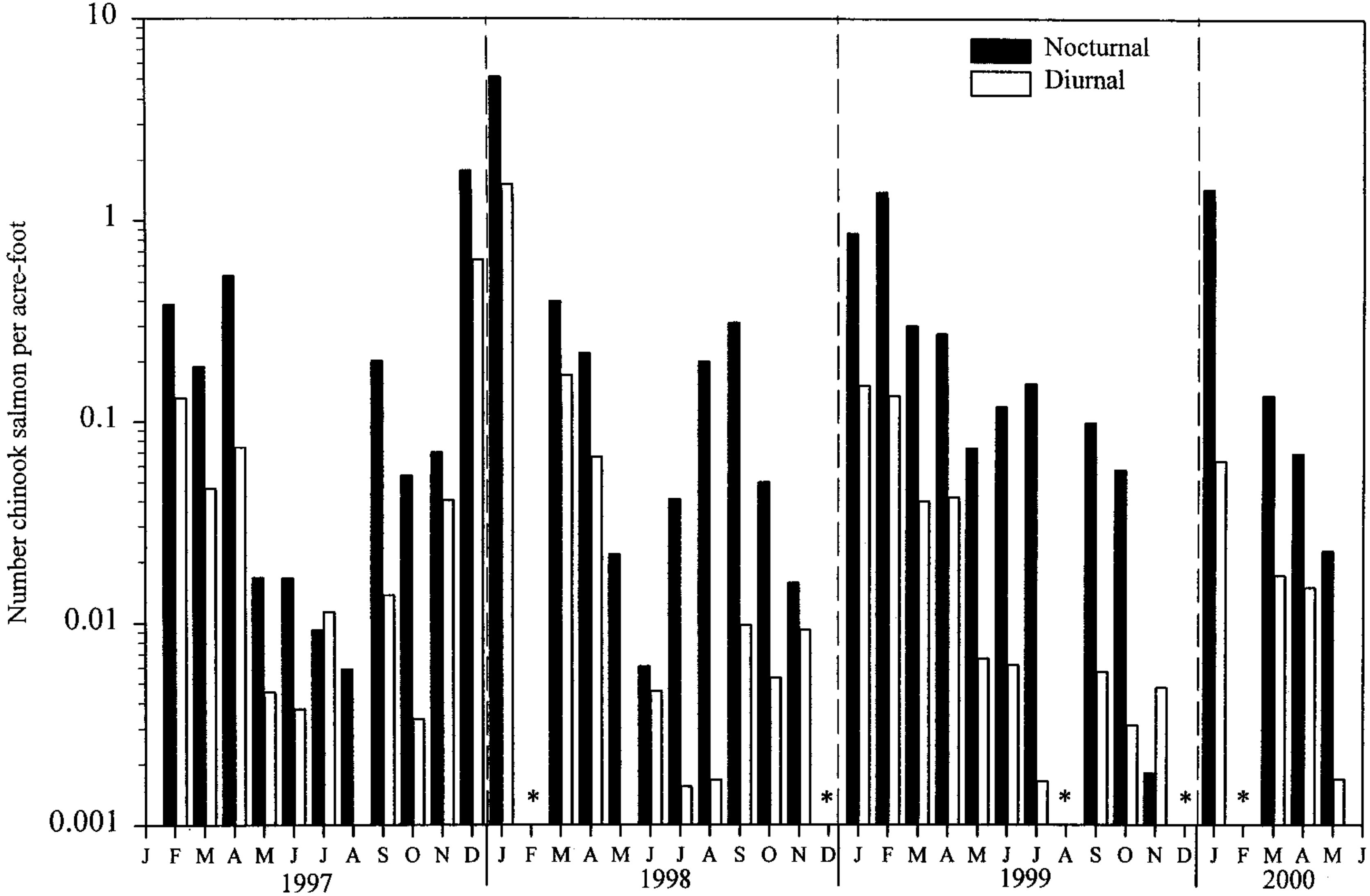


Figure 16. Monthly number of juvenile chinook salmon entrained per acre-foot during nocturnal and diurnal entrainment trials conducted at the Red Bluff Research Pumping Plant; February 1997 through May 2000. Asterisks indicate months when 24-h entrainment trials were not conducted. A log scale was used on the y-axis.

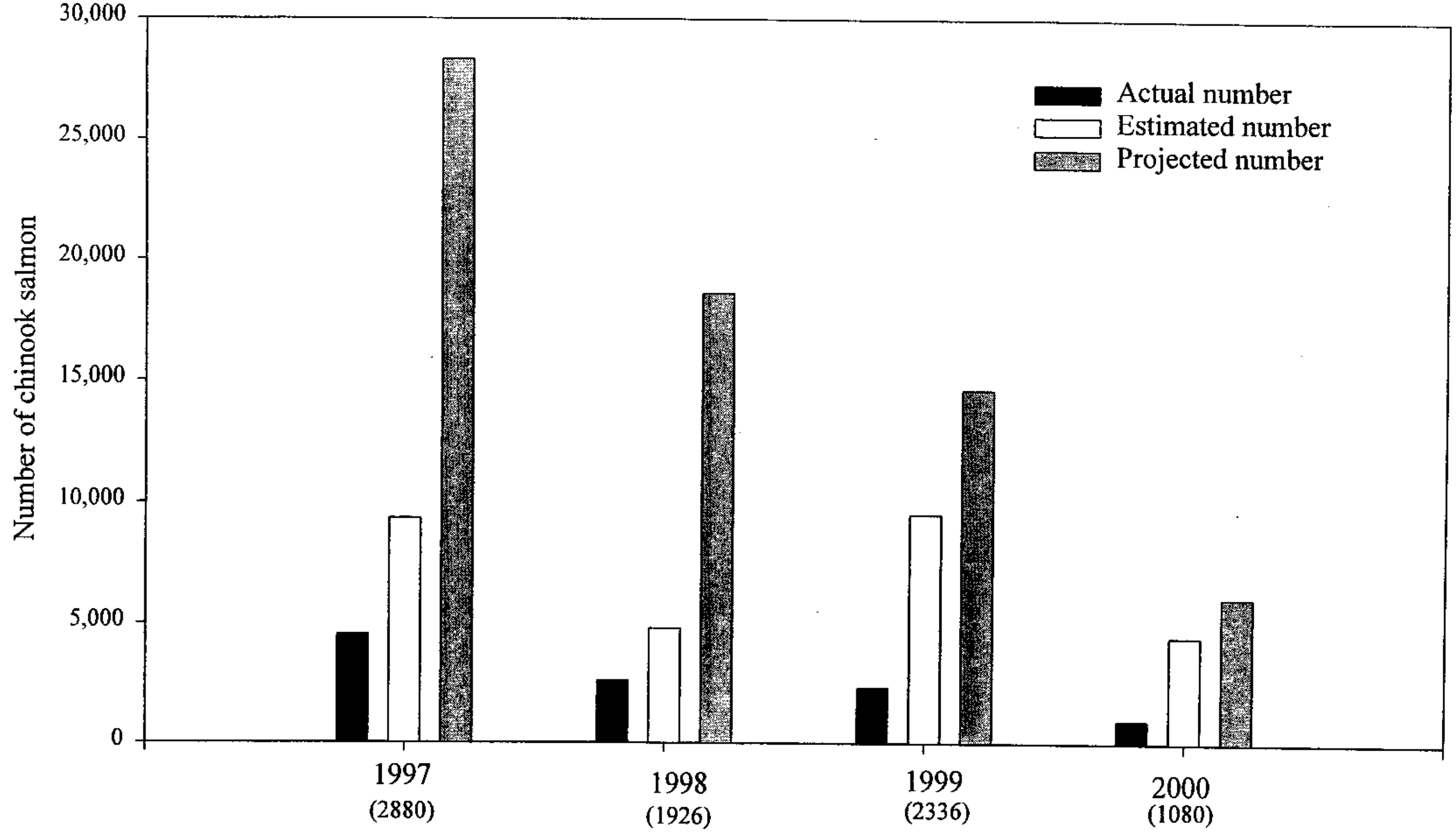


Figure 17. Actual, estimated, and projected number of juvenile chinook salmon entrained annually based on data from weekly 24-h trials; February 1997 through May 2000. See text (page 6) for definitions of estimated and projected numbers. Numbers in parentheses are the total hours pumps operated each year during entrainment trials.

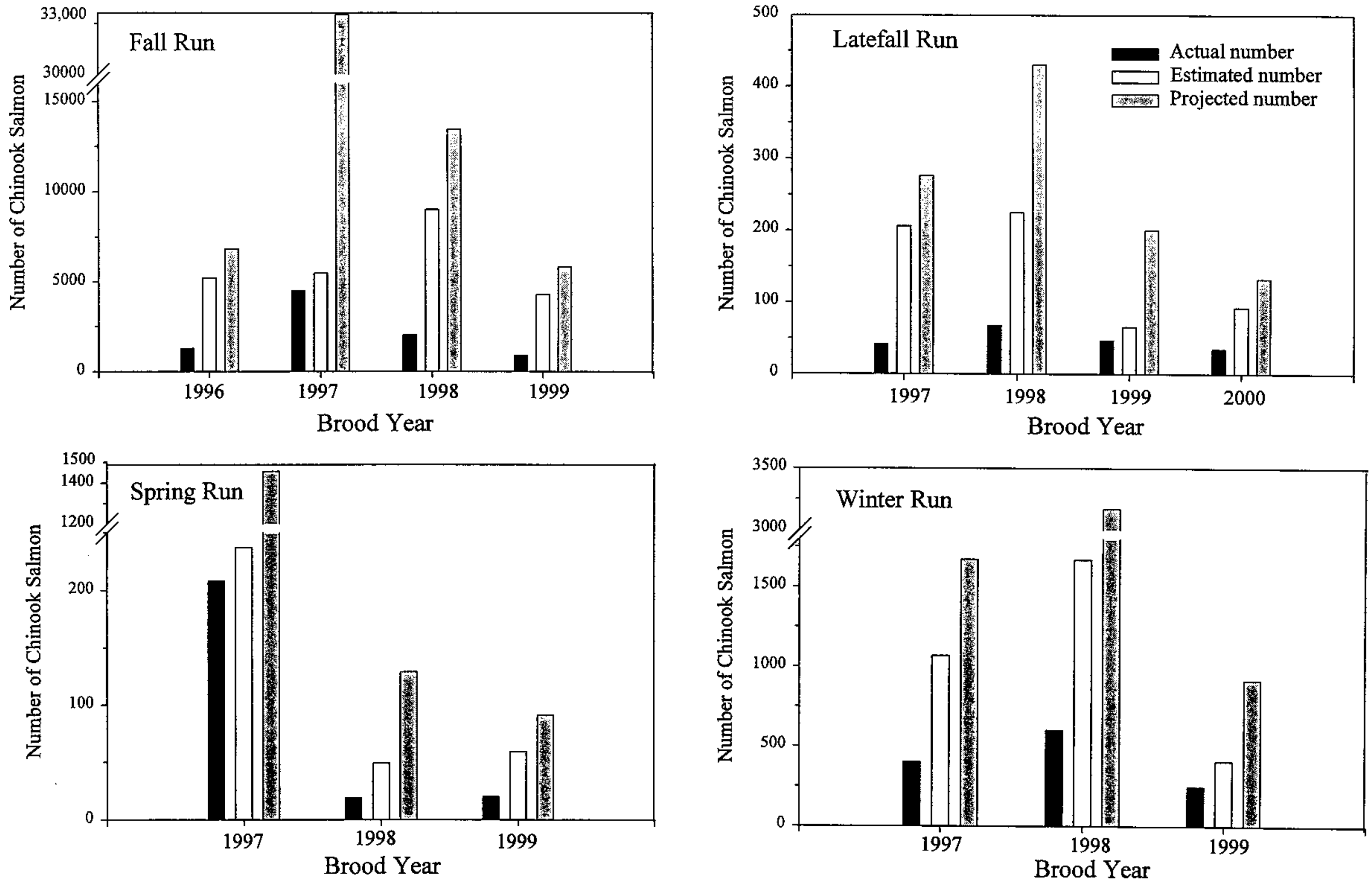


Figure 18. Actual, estimated, and projected number of juvenile chinook salmon, by run and brood year, entrained annually based on data from weekly 24-h trials; February 1997 through May 2000. See text (page 6) for definitions of estimated and projected numbers.

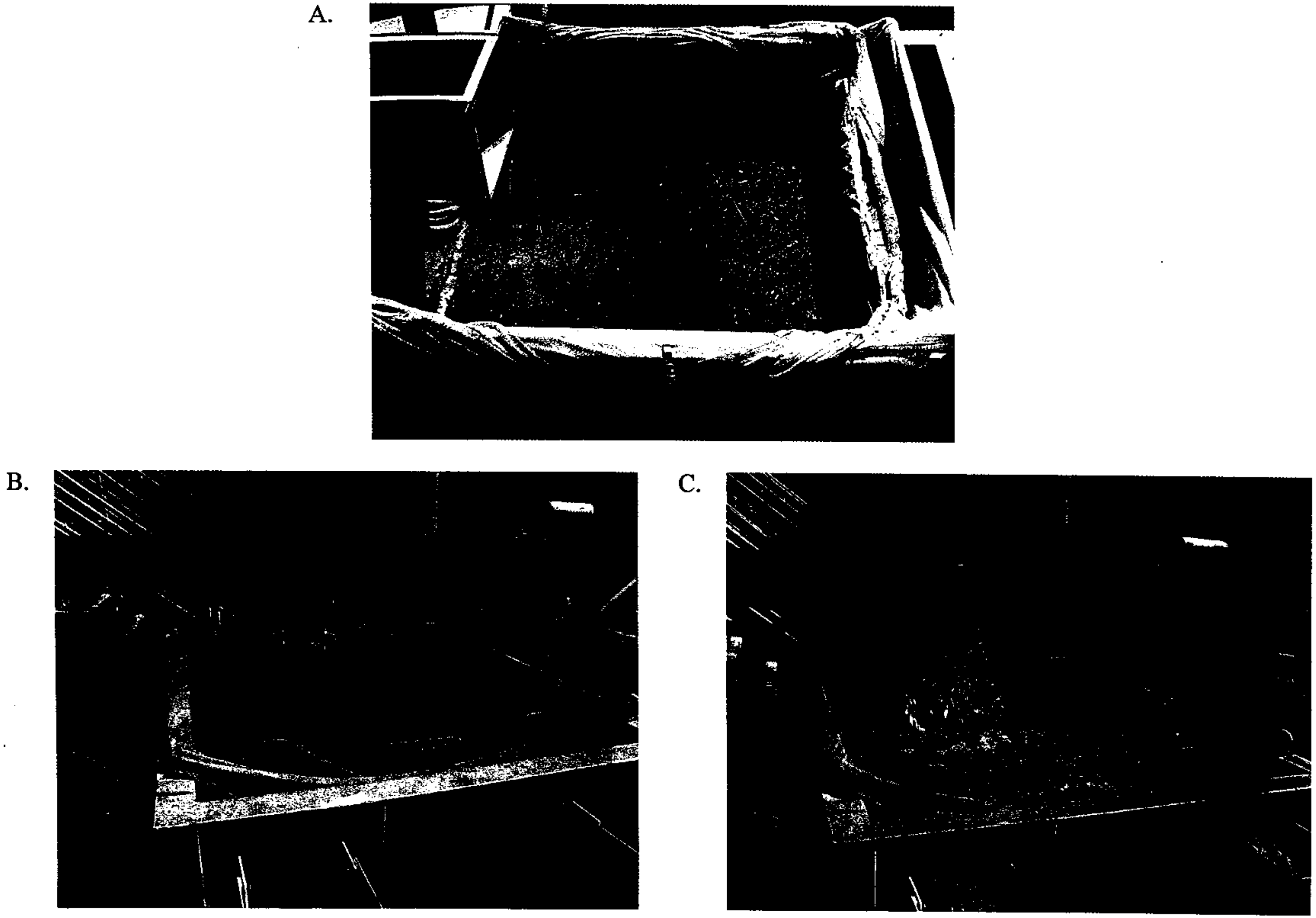


Figure 19. (A) Debris-laden holding tank at Red Bluff Research Pumping Plant. (B) Typical low flows into a holding tank at the beginning of an entrainment trial. (C) High, turbulent flows into a holding tank caused by debris obstructing water flow through the dewatering ramp screen.

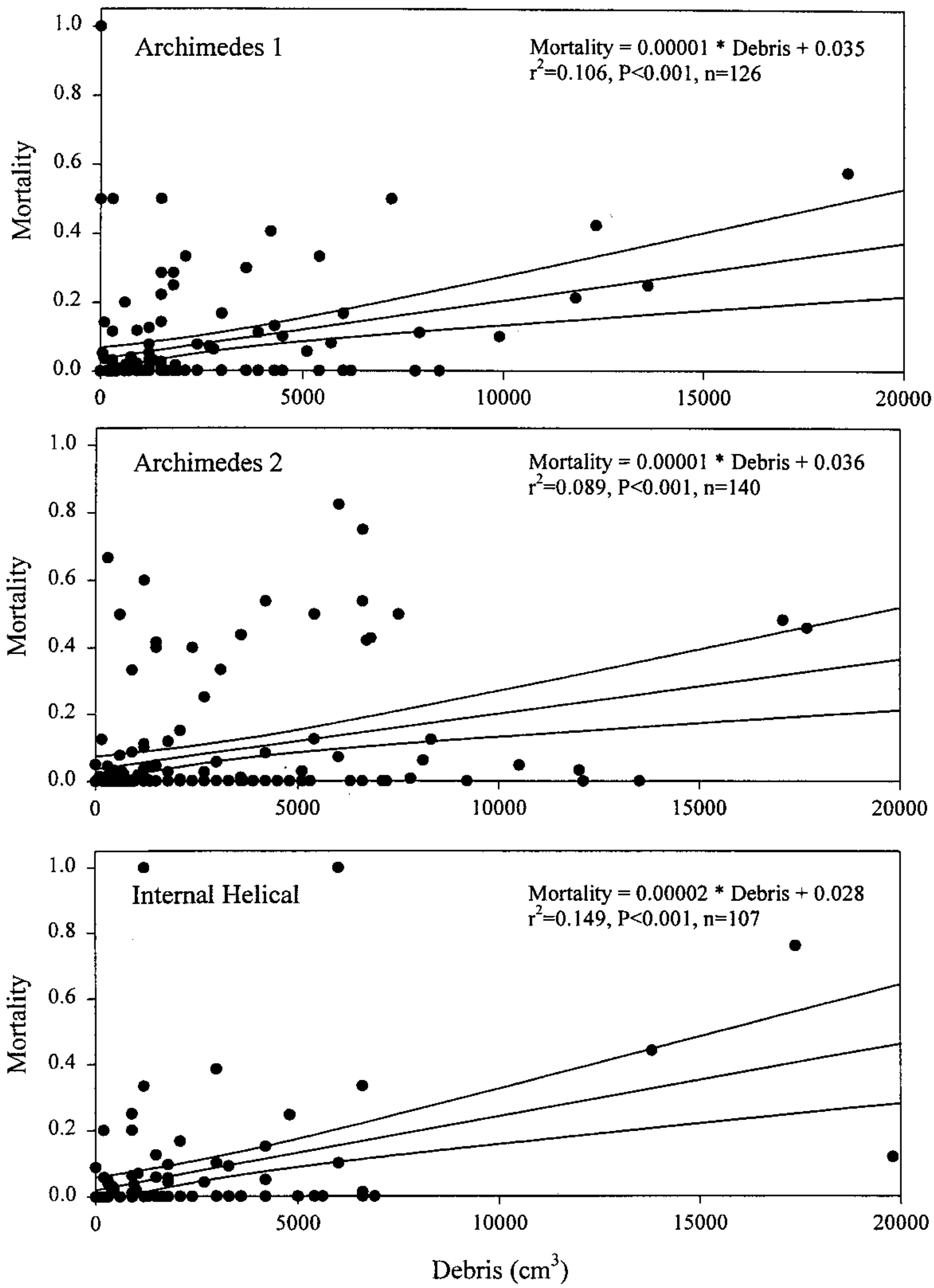


Figure 20. Mortality of juvenile chinook salmon entrained versus the volume of debris entrained for each 24-h entrainment trial conducted with each of the three pumps at Red Bluff Research Pumping Plant; February 1997 through May 2000. The confidence interval is 95%.

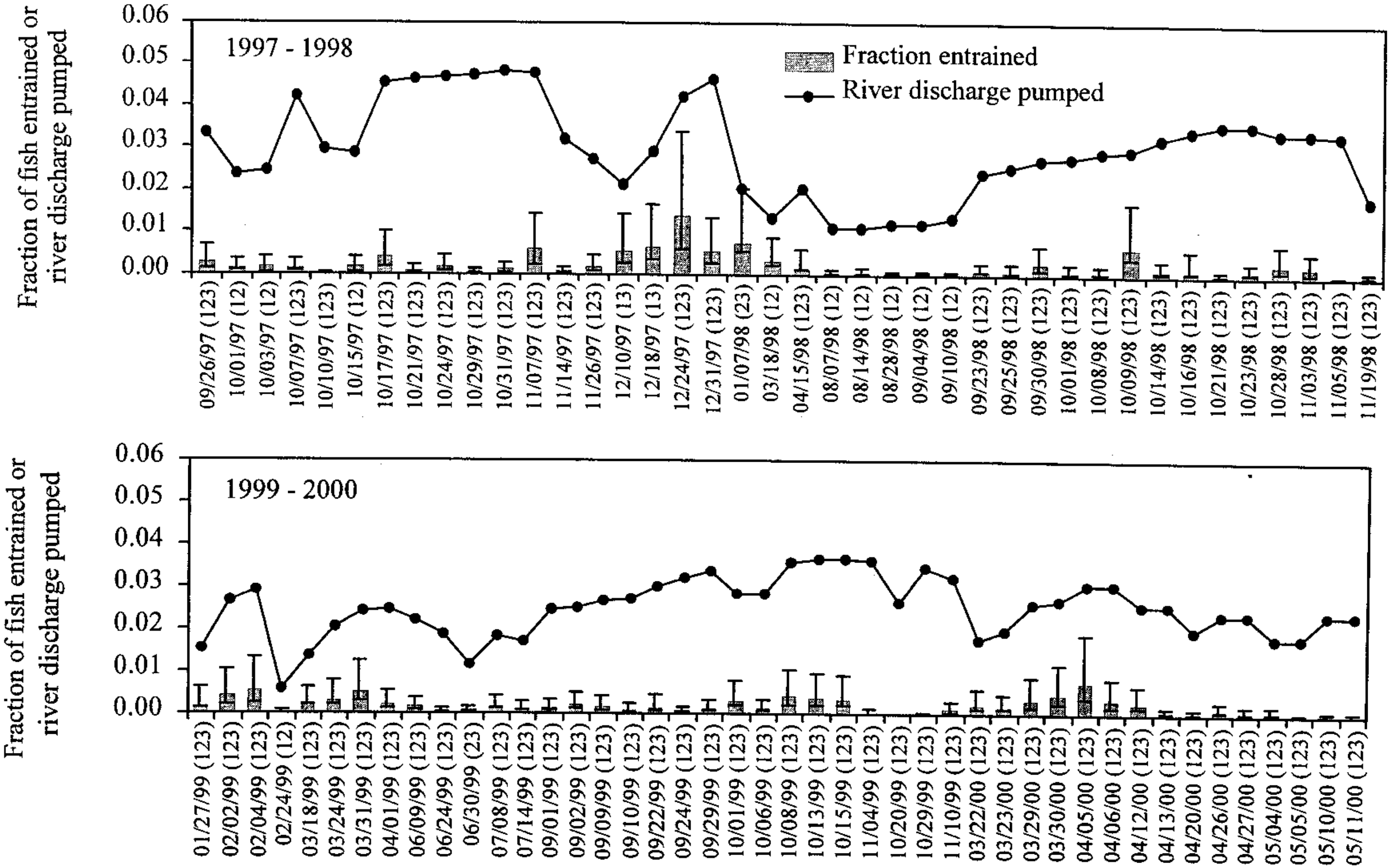


Figure 21. Fraction of riverine chinook salmon (+90% CI) entrained into Red Bluff Research Pumping Plant. Fraction entrained was calculated from catch in pumps divided by number passing RBDD each day as estimated by rotary screw traps. Numbers in parentheses after dates are the pumps that were operated; 1=Archimedes 1, 2=Archimedes 2, 3=internal helical pump. The fraction of river discharge pumped by the plant is the expected fraction of fish entrained if fish were uniformly distributed and entrained in proportion to density.

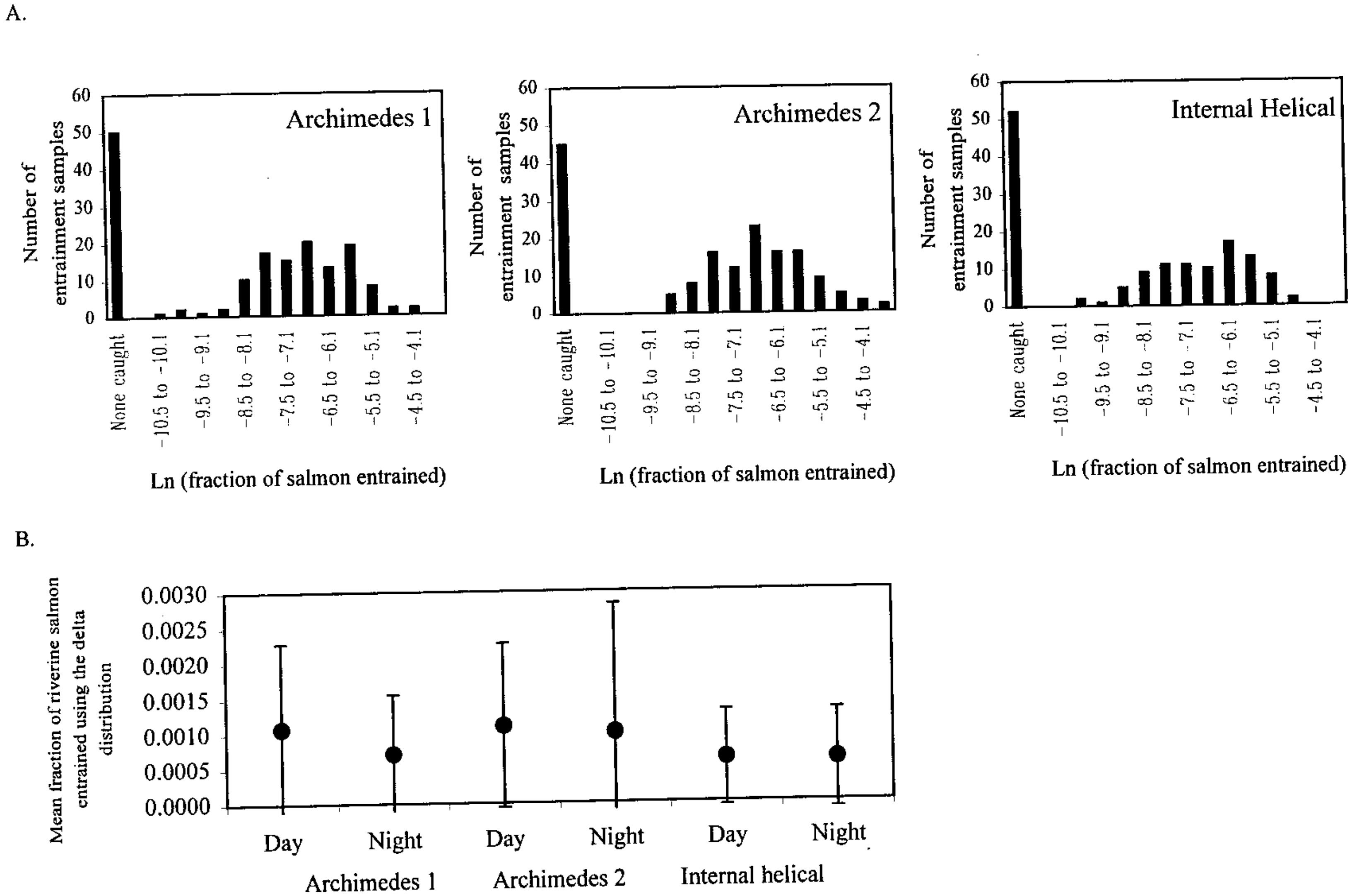


Figure 22. (A). Histogram of the natural log of the fraction of riverine chinook salmon entrained into each pump at Red Bluff Research Pumping Plant. Samples where no salmon were caught are indicated by the left-most bar. (B) Mean fraction of riverine salmon entrained per acre-foot (± 95% CI) for each pump and diel period using the delta-distribution which adjusts estimates for the probability of catching no fish.

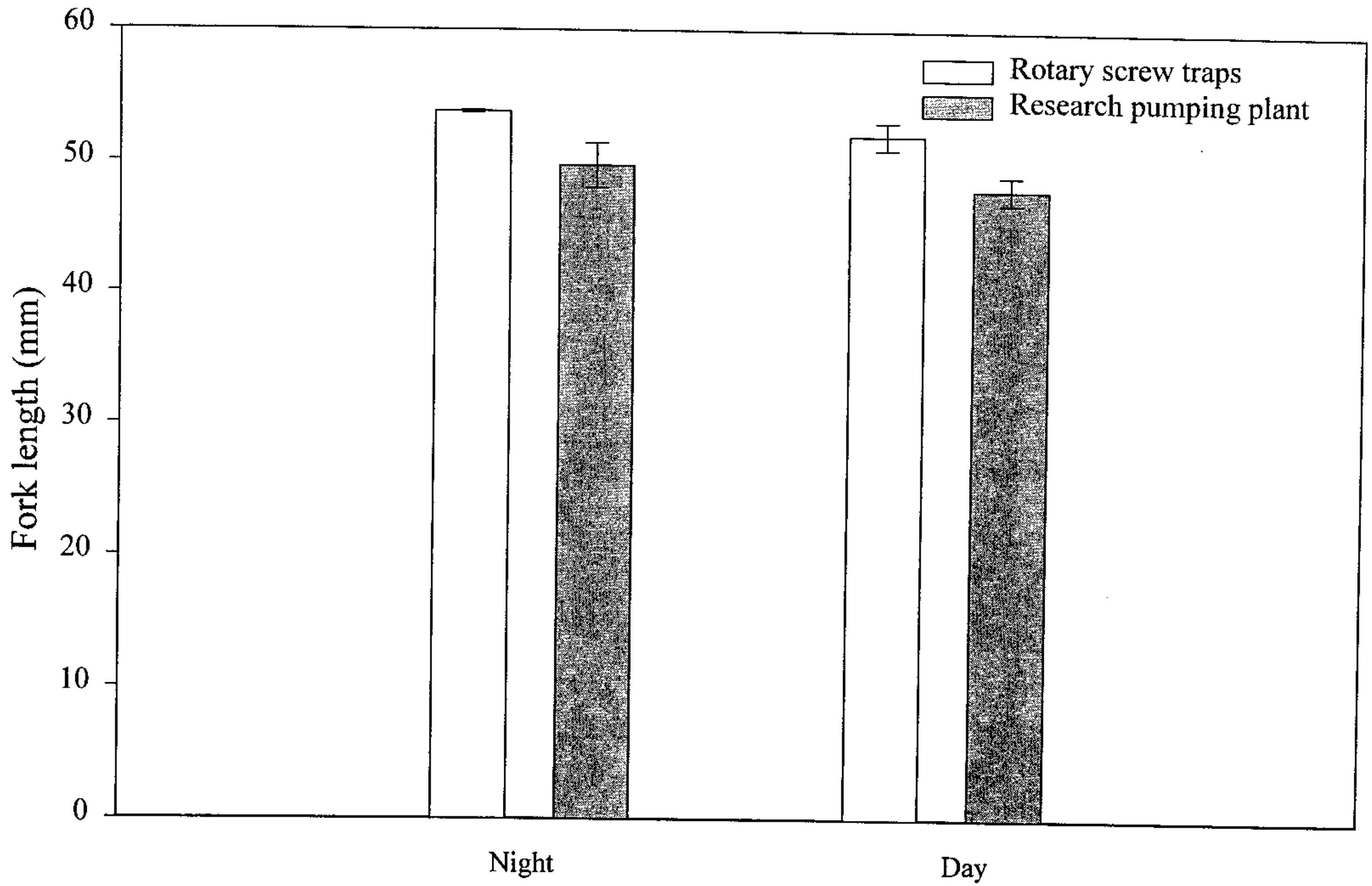


Figure 23. Diel length distributions (mean, SE) for chinook salmon captured in the Research Pumping Plant and rotary screw traps at Red Bluff Diversion Dam. Salmon entrained into the pumps were significantly smaller in length than salmon captured in rotary screw traps (Wilcoxan sign-ranked test, Day, $P = 0.016$, n=109; Night, $P < 0.001$, n=203).