Volume 25

Survival and Injury of Rainbow Trout (200–300 mm) Passed Through an Archimedes Lift and a Hidrostal Pump at Red Bluff Research Pumping Plant

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Sandra Borthwick and Charles Liston

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sandra Borthwick
Bureau of Reclamation, Mid-Pacific Region
Northern California Area Office
PO Box 159
Red Bluff CA 96080

Charles Liston
Bureau of Reclamation, Mid-Pacific Region
Division of Resources Management, MP-400
2800 Cottage Way
Sacramento CA 95825-1898

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by

Sandra M. Borthwick[1]
Charles Liston[2]

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United States Department of the Interior
Bureau of Reclamation
Mid-Pacific Region
Technical Service Center

[1] Bureau of Reclamation - Mid-Pacific Region
Northern California Area Office
PO Box 159
Red Bluff CA 96080

[2] Bureau of Reclamation - Mid-Pacific Region
Division of Resources Management, MP-400
2800 Cottage Way
Sacramento CA 95825-1898

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Doug Craft
U.S. Department of the Interior - Bureau of Reclamation
Technical Service Center - Fisheries Applications Research Group, D-8290
PO Box 25007
Denver CO 80225-0007

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ABSTRACT

Survival, descaling, and injury rates were determined for 200–300 mm fork length rainbow trout *Oncorhynchus mykiss* passed through an Archimedes lift and a Hidrostal pump at the Bureau of Reclamation's Red Bluff Research Pumping Plant, Red Bluff, California. Treatment fish were compared to control fish (released into the lift and pump discharges) for 16 paired trials conducted with the Archimedes lift and 25 paired trials with the Hidrostal pump during April, May, and June 2002. Trials were conducted at several pump speeds. For the Archimedes lift, there were no detectable differences between treatment and control groups in immediate or 96-h survival, scale loss, or frequency of injuries. Mean percent survival at capture and at 96 h was 100 percent for all speeds and groups, with one exception. For the Hidrostal pump, there were statistically detectable differences in immediate and 96-h survival between treatment and control groups. Average immediate survival ranged from 96.4 to 94.4 percent, while 96-h survival ranged from 94.0 to 88.0 percent. Scale loss was low with no detectable differences between treatment and control groups. The mean percent of surviving fish with injuries was low (2.5 to 9.8) for all groups; however, injury rates were significantly higher in the post-treatment group at the 321 revolutions per minute (r/min) pump speed. Both the Archimedes lift and the Hidrostal pump can pass small and large fish with high survival (> 90 percent) and low injury ($\leq$ 10 percent) rates. Fish passed through the Archimedes lift had slightly higher survival rates than fish passed through the Hidrostal pump. The results of this study support previous work suggesting that these devices can safely transport fish at diversion structures.

EXECUTIVE SUMMARY

Survival, descaling, and injury rates of large (200–300 mm fork length) rainbow trout *Oncorhynchus mykiss* passed through an Archimedes lift and a Hidrostal pump (treatment fish) were compared to those of control fish which were released into the pump's discharges. Sixteen paired trials were conducted with the Archimedes lift and 25 with the Hidrostal pump during April, May, and June 2002. Both the lift and the pump were large, with 122 cm (48 in) and 91 cm (36 in) intake diameters, respectively. Trials were conducted at several speeds. The Archimedes lift had no significant effect ($P > 0.05$) on immediate or 96-hour (h) survival, descaling, or body injury rates at each of the speeds. Mean percent survival of rainbow trout at capture and at 96 h was 100 percent for all speeds and groups (treatment and control), with one exception; survival at 96 h was 98.3 percent for treatment fish at a pump speed of 22.1 r/min. Average scale loss was less than 10 percent on most (> 88 percent) of the fish. Mean percent of surviving fish with injuries ranged from 0 to 10.4 percent. Abrasions were the most common type of injury.

For the Hidrostal pump, statistically detectable pump passage effects were observed for immediate survival in trials conducted at 321 r/min, and for 96-h survival at all speeds ($P \leq 0.05$). Immediate and 96-h survival of treatment fish decreased as pump speed was decreased, although this relationship was not statistically significant ($R^2 = 0.13$, $P = 0.077$). Average immediate survival ranged from 96.4 percent to 94.4 percent for the three speeds tested, while average 96-h survival ranged from 94.0 percent to 88.0 percent. All of the 96-h mortalities occurred within the first 24 hours, and most within 4 to 5 hours of capture. Immediate and 96-h survival of control fish was 100 percent at all pump speeds. There were no detectable descaling effects. Average scale loss was low, less than 10 percent on most (> 91 percent) fish. The mean percent of surviving fish with injuries ranged from 2.5 to 9.8. There was a detectable effect on body injury rates at the 321 r/min pump speed with the mean percent injured in the post-treatment group higher than the post-control and pre-passage groups. Abrasions and bruises were the most common injuries.

The results of this study support the conclusion of companion studies (Borthwick and Corwin, 2001; Helfrich et al., 2001; McNabb et al., 2003). Fish passed through the Archimedes lift had slightly higher survival rates than fish passed through the Hidrostal pump. For the Archimedes lift, there

were no detectable differences in survival between treatment and control fish, whereas there were detectable differences with the Hidrostal pump. Overall, both the Archimedes lift and the Hidrostal pump can pass small and large fish with high survival ($\geq$ 90 percent) and low injury rates ($\leq$ 10 percent).

INTRODUCTION

Red Bluff Research Pumping Plant (RPP) was constructed in 1995 to evaluate whether two types of large, experimental pumps could safely pass fish while making high-volume deliveries of water for irrigation and other uses. The two pump types were an Archimedes lift and a Hidrostal pump (also known as an internal helical pump). Between 1995 and 2000, the Bureau of Reclamation (Reclamation) conducted extensive biological and engineering evaluations of the pumps and other components of the RPP. Due to the concern for protecting chinook salmon, *Oncorhynchus tshawytscha*, they were the target species for most of the biological evaluations. Chinook salmon was also the species most frequently entrained into the pumps from the Sacramento River.

Results from trials in which juvenile chinook salmon were experimentally passed through the pumps at the RPP revealed low mortality, injury, and descaling for both pump types (McNabb et al., 2003). Mean percent survival after 96 h for fish passed through the Archimedes lifts exceeded 98 percent during two sets of experiments (n = 27 and n = 40). In experiments with the Hidrostal pump, mean percent survival at 96 h for pumped fish was 96.5 percent (n = 40). Post-passage examination of surviving individuals revealed very low incidence of debilitating injuries. Chinook salmon used in these trials averaged between 34 and 74 mm fork length. Stress, based upon plasma cortisol levels, to similarly sized chinook salmon passed through the RPP pumps was also low (Weber et al., 2002).

As part of Reclamation's Tracy Fish Facilities Research Program, there is interest in knowing if the pumps installed at the RPP can safely pass large (> 200 mm fork length) fish, in particular, steelhead trout, *O. mykiss*. Steelhead trout is the anadromous form of *O. mykiss* while rainbow trout is the non-anadromous form. Steelhead trout was listed in 1998 as threatened under the Endangered Species Act. Both the Archimedes lift and the Hidrostal pump are being considered for installation at the Tracy Fish Test Facility in Tracy, California (Liston et al., 2000). There is also interest in knowing the effect of pump speed on mortality and injury to fish. All previous fish passage trials at the RPP were conducted with the pumps operating at full speed, 26.5 r/min for the Archimedes lifts and 350 to 370 r/min for the Hidrostal pump.

Data on survival of ten species of large fish passed through pumps at the RPP were obtained during trials evaluating species, numbers, and condition of wild fish entrained from the Sacramento River (Borthwick and Corwin, 2001). During trials conducted between 1997 and 2000, survival of 405 large fish passed through the Archimedes lifts was 98.8 percent. Survival of 96 large fish passed through the Hidrostal pump was 95.8 percent. Survival of large *O. mykiss* was 100 percent for the Archimedes lifts and 86 percent for the Hidrostal pump, however, sample sizes were small (10 and 7 fish, respectively).

Besides studies at RPP, only one other study exists on evaluating survival and injury of fish passed through Archimedes-type lifts (Week et al., 1989). In that study, a prototype lift had no adverse effects on juvenile salmonids. More information is available in the literature regarding survival and injury to various fish species, including rainbow trout, passed through smaller versions of the Hidrostal pump. Several studies were conducted with a Hidrostal pump with an intake diameter of 15 cm (Patrick and Sim, 1985; Rodgers and Patrick, 1985; Patrick and McKinley, 1987). This pump operated from 400 to 1200 r/min and discharged water at low (0.2 m^3/s) rates. Results revealed that mortality of fish passed through the pump varied among species, with rainbow trout and American eel, *Anguilla rostrata,* experiencing higher survival than yellow perch, *Perca flavescens,* or alewife, *Alosa pseudoharengus*. Survival of rainbow trout and American eel was > 98 percent regardless of pump speed or fish density while survival of yellow perch and alewife decreased as pump speed increased. Eels ranged in size from 270 to 520 mm, while the other three species were 100 to 200 mm total length. Limited testing was also performed with larger fish including white sucker, *Catostomus commersoni* (150–400 mm), and brown bullhead, *Ictalurus nebulosus,* (200–300 mm) at a pump speed of 950 r/min. No mortality was observed for either species.

In 1998, a 41-cm (16 in) diameter Hidrostal pump was installed at Reclamation's Tracy Fish Collection Facility (TFCF), Tracy, California. Since then, Reclamation biologists have conducted pump passage trials with various fish species. Mortality, descaling, and injury rates were low for juvenile chinook salmon and splittail, *Pogonichthys macrolepidotus*, passed through the pump (Helfrich et al., 2001). Mortality and injury rates were also low for a variety of wild fish species entrained into the pump over a range of pump speeds and environmental conditions. Trials conducted with hatchery-reared steelhead trout (165–313 mm) at various pump speeds also revealed high immediate and 96-h survival (Helfrich et al., 2003).

The objectives of this study were (1) to assess survival, injury, and descaling rates of 200–300 mm fork length rainbow trout passed through a large Hidrostal pump and an Archimedes lift, and (2) to evaluate the effect of pump speed on fish survival (immediate and 96-h), descaling, and injury.

METHODOLOGY

Study Site

RPP is located at river-kilometer 391 (river-mile 243) above San Francisco Bay (figure 1), approximately 3.2 km (2 miles) southeast of Red Bluff, California. It consists of two Archimedes lifts and a Hidrostal pump. The Hidrostal 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 case with a rotating conical shroud (figure 2). 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 cylinders 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 (figure 3).

During this study, the Hidrostal pump was operated at speeds between 292 and 350 r/min, delivering 1.45 to 2.13 m^3/s (51.3 to 75.1 ft^3/s) of water. Only the Archimedes lift in bay 2 had the capability to operate on the variable speed drive. Therefore, it was used for all the Archimedes trials and operated at speeds between 19.9 and 26.5 r/min, delivering 1.80 to 2.55 m^3/s (63.4 to 90.1 ft^3/s) of water.

Water pumped by the Archimedes lift and Hidrostal pump was discharged into separate concrete channels, and continued downstream past vee-shaped vertical wedge-wire screens (2.4 mm gap; figure 4). Approximately 90 percent of the water passed through the screens and into the Tehama-Colusa canal. Ten percent of the water, along with fish and debris, continued downstream in an open fish bypass channel, then into an underground pipe that terminated in the Sacramento River. During the trials, a dewatering ramp was lowered into the open bypass channel to intercept the flow and divert a portion of it, along with fish and debris, into one of two holding

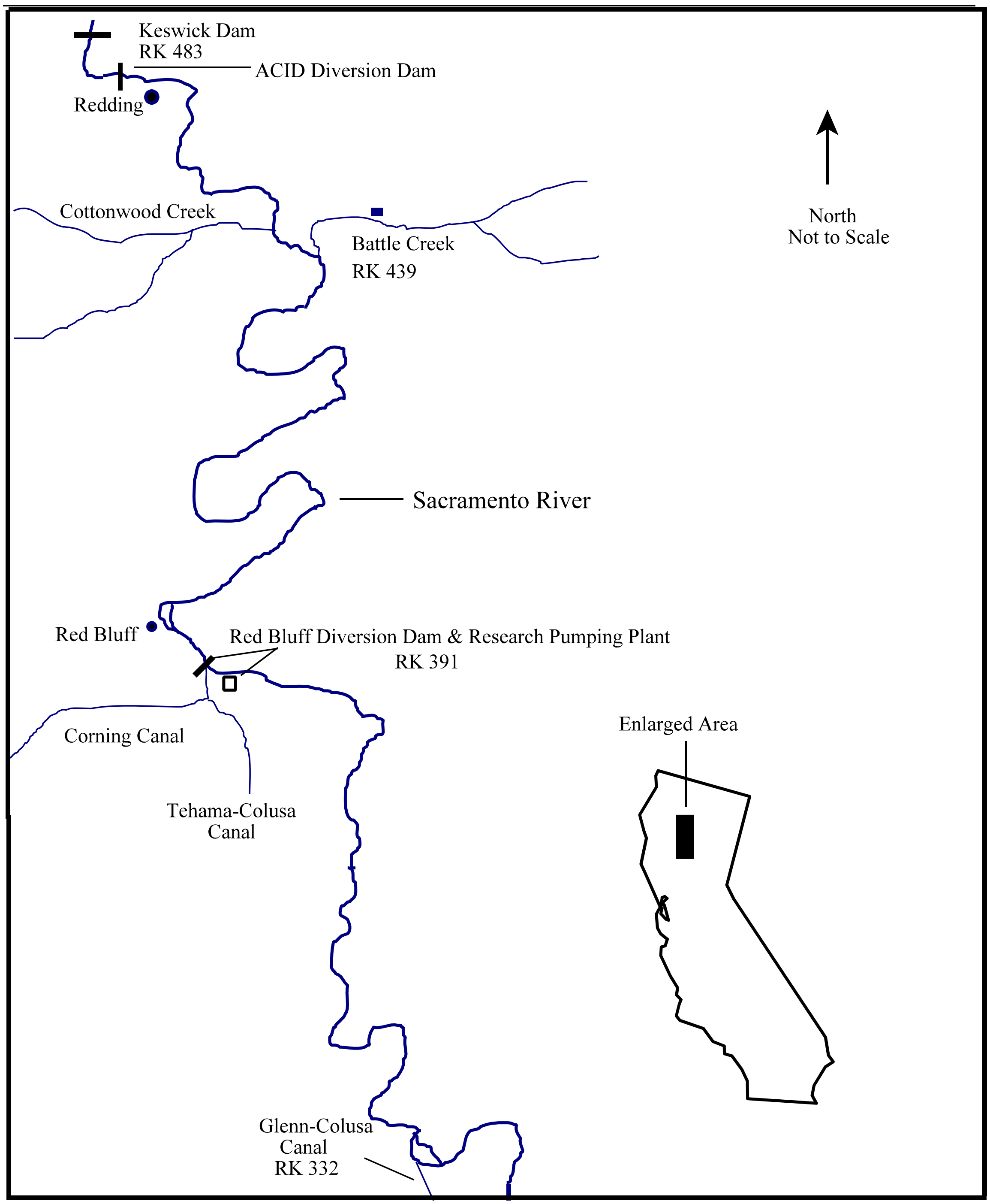

FIGURE 1.—Location of Red Bluff Research Pumping Plant on the Sacramento River at river kilometer 391 (river mile 243).

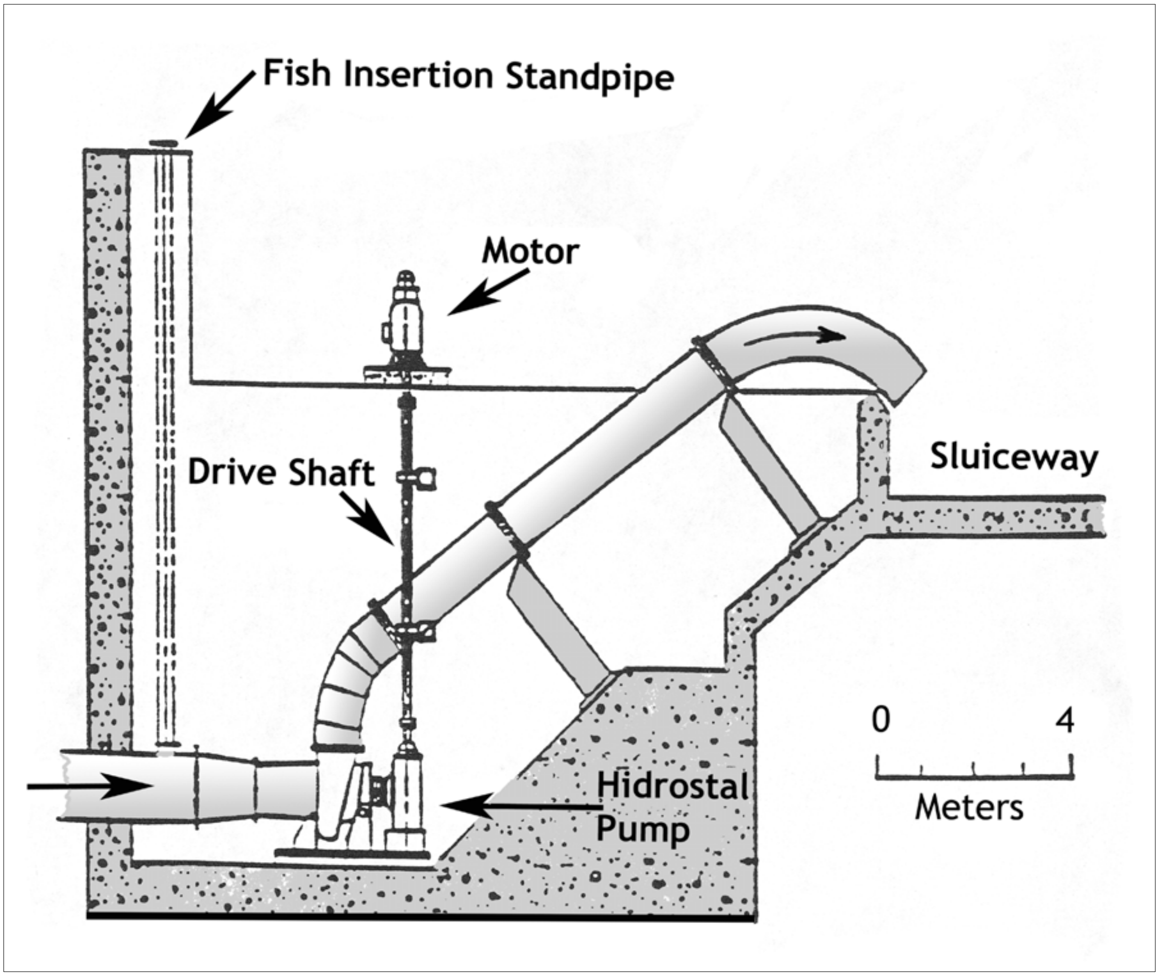

FIGURE 2.—Features of the Hidrostal pump installation at the Red Bluff Research Pumping Plant including the intake pipe, pump, discharge pipe, and fish insertion standpipe. During trials, treatment fish were lowered down the insertion standpipe, passed through the pump, and discharged into the sluiceway that led downstream to the vertical screens as shown in figure 4.

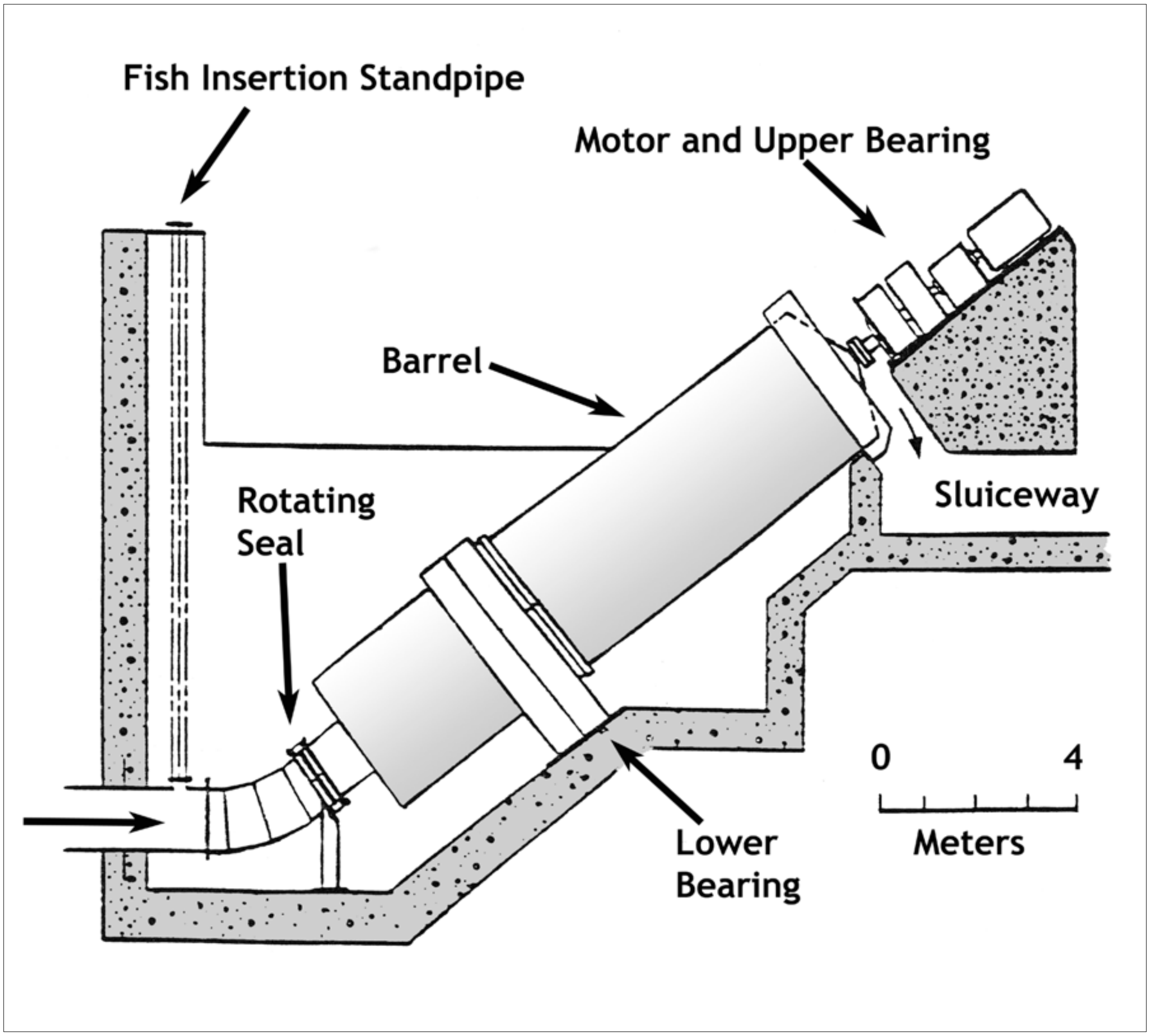

FIGURE 3.—Features of the Archimedes lift installation at the Red Bluff Research Pumping Plant including the intake pipe, pump barrel, and fish insertion standpipe. During trials, treatment fish were lowered down the insertion standpipe, passed through the pump, and discharged into the sluiceway that led downstream to the vertical screens as shown in figure 4.

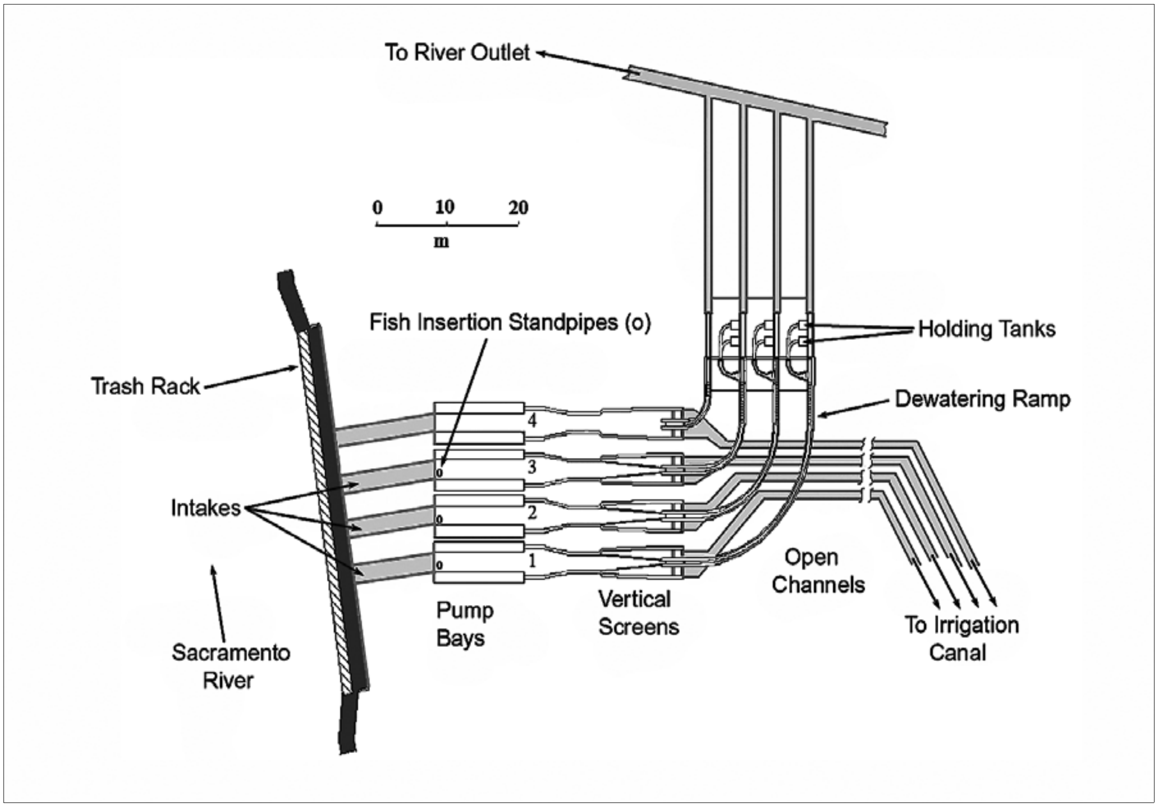

FIGURE 4.—Schematic of the Red Bluff Research Pumping Plant showing major features. Pump bays 1 and 2 contain Archimedes lifts. The lift in bay 2 was used in this study. The Hidrostal pump is in bay 3. Bay 4 is empty. Underground portions of the plant's fish bypass system are shaded gray.

tanks. The tanks were lined with delta weight, knotless nylon nets with 3.2 mm (⅛-in) mesh to facilitate retrieval of fish. The 1.2 m^2 (4.0 ft^2) holding tanks contained water to a depth of 0.9 m when full. They operated as a flow-through system maintaining ambient river water quality conditions.

Passage Trials

Trials were conducted during April 9–11, May 20–23, and June 24–28, 2002. The April trials were conducted at night while the May and June trials were conducted during the day. Eagle Lake rainbow trout were used as surrogates for steelhead trout. They were obtained from Darrah Springs State Hatchery six to eight days before each trial week began. The fish were held in 1.2-m (4-ft) diameter, 708-L (206-gal) fiberglass flow-through tanks continuously supplied with fresh river water in Reclamation's fish holding facility near the

RPP. Three to five days before the trials began, fish were marked to differentiate groups used in the trials and to distinguish them from wild fish entrained during the trials. In the April and May trials, fin clips were used to mark fish. A photonic marking gun was used to mark fish for the June trials. The average fork length of trout used in the April, May, and June trials was 220 mm, 239 mm, and 258 mm, respectively.

Because the variable speed drive could only operate one pump at a time, trials with the Hidrostal pump and Archimedes lift were conducted on different days. For each of the pumps, survival, descaling, and injury were compared between treatment and control groups of rainbow trout. Treatment samples were released into fish insertion standpipes, and then crowded downward into the pumps' intake pipe (figure 4). Control samples were released downstream of the pumps' outfall for the Archimedes lift and through a port in the discharge pipe for the Hidrostal pump. Fish from both samples were collected in downstream holding tanks.

Twelve treatment and 12 control fish were used in each trial. Fish were transported to the RPP in 68.5-L (18-gal) plastic tubs containing a mixture of river water, NaCl (5 g/L) and PolyAqua® (0.13 mL/L) to promote osmotic balance, reduce stress, and minimize secondary infections (Summerfelt and Smith, 1990; Wedemeyer, 1992). Six fish were placed in each of the tubs.

At the release site, fish and water from each tub were gently poured into separate 19-L (5-gal) buckets lined with lightweight (0.4-mil) plastic bags (49-L, 13-gal). Bags were tied shut and lowered by rope to the water surface. The rope was then pulled, breaking the bag and releasing the fish into the water. Treatment and control fish were released within five minutes of each other.

Three to four paired trials were conducted each day. Holding tanks were continuously tended over the three to four hours required to complete all the trials. A large dip net was used to remove fish from a holding tank and place them into a tub of river water. A high percentage of fish held position in the channel between the vertical screens rather than moving to the holding tanks. Within an hour of completing the last trial of a day, the pump/lift was turned off and fish were seined from the vertical screen channel. Survival of the recaptured fish was recorded, and they were transported to the river water facility. Fish recaptured in the holding tanks and fish seined from the channel were placed in separate fiberglass tanks. Delayed mortality of fish in each tank was evaluated at 24-h intervals for 96 hours. Because they were differentially marked, control and treatment fish from each trial conducted during the day could be identified. Survival for each trial was the percentage of the total number of treatment or control fish recovered from a holding tank or seined from the channel that were alive at capture (immediate survival) or that survived until the end of the 96-h post-passage period (cumulative survival). The Wilcoxon signed-rank test was used to test for differences in survival between paired treatment and control groups for each pump. The level of significance for all statistical tests conducted for this study was " = 0.05.

Trial fish were handled carefully throughout each step of the experiment to minimize injury and descaling due to non-passage related activities. Before each trial, six treatment and six control fish were randomly selected and placed into two separate tubs containing Finquel® (tricaine methaneosulfonate; 80 mg/L) buffered with an equal weight of sodium bicarbonate. This solution anaesthetized the fish so each could be inspected for descaling and injury to fins, head, eyes, and skin. The percent descaled on each side of a fish was categorized and recorded as < 10 percent, 10–25 percent, 26–50 percent, 51–75 percent, or > 75 percent. Some abnormalities associated with hatchery rearing were noted on most of the pre-passage fish. These included fin erosion and eroded opercula and snouts, and were not considered injuries during the injury assessments. These twelve fish were the pre-passage sample used to evaluate injuries due to pre-trial handling. They were resuscitated in the mixture of fresh river water, salt and PolyAqua® before being transported to the RPP. After completing a day's trials, these same methods were used on all recaptured treatment and control fish to evaluate descaling and injury associated with passing through the pumping plant. One person did the injury and descaling assessments for all the trials. Optivisor® magnifying glasses with 1.5 to 2.0X power were used for these assessments. The Kolmogorov-Smirnov test for goodness of fit (Zar, 1984) was used to test for differences in the frequency distribution of descaling and injury among pre-passage (quality control), post-treatment (pump passage), and post-control (no pump passage) groups.

During each trial, water temperature, dissolved oxygen, and turbidity were measured from river water flowing into the holding tanks. Pump speed and total discharge were recorded from the plants' automated data collection system.

Trials with the Hidrostal pump were conducted at six different speeds. Seven trials were conducted at 350 r/min (i.e., full speed), ten trials at 321 r/min, and two trials each at 315, 309, 303, and 292 r/min. Mean discharge at those speeds was 2.21, 1.83, 1.79, 1.72, 1.62, and 1.45 m^3/s (77.9, 64.7, 63.1, 60.7, 57.1, and 51.3 ft^3/s), respectively (table 1). The reduction from full speed ranged from 8 to 17 percent. During the trials, it was revealed that at the four lowest speeds, less than 100 percent of the treatment fish injected into the intake pipe were recovered. At those speeds, the calculated velocity in the 1.2-m (4-ft) diameter intake pipe was 1.5 m/s (5.0 ft/s) or less. At those velocities, rainbow trout have been shown to hold their position (Webb, 1971). The missing fish were not used in our mortality estimate since experience during these and other trials conducted at the RPP revealed that dead fish did not hold up in the system, rather they were swept promptly into holding tanks by currents (McNabb et al., 2000). Data from the eight trials conducted at the four lowest speeds were combined for analyses. Regression analysis was used to evaluate any significant relationships between survival and pump speed (Zar, 1984).

Trials with the Archimedes lift were conducted under three different speeds. Six trials were conducted at 26.5 r/min (i.e., full speed), six trials at 22.1 r/min, and four trials at 19.9 r/min. Mean discharge at these speeds was 2.47, 2.14, and 1.80 m^3/s (87.3, 75.6, and 63.7 ft^3/s), respectively (table 1). Speeds were not reduced further since, based upon experience with the Hidrostal pump, it was known that fish could hold their position in the intake pipe at discharges less than 1.78 m^3/s (63.0 ft^3/s). The reduction from full speed was 17 and 25 percent respectively, for the medium and low speeds.

TABLE 1.—Pump speed in terms of Hz and r/min and mean total discharge for each pump operated at three different speeds

Pump	Speed Hz	 r/min	Percent reduction from full speed	Discharge Mean m^3/s (SE)
Archimedes	60	26.5	0	2.50 (0.04)
	50	22.1	17	2.16 (0.02)
	45	19.9	25	1.80 (0.01)
Hidrostal	60	350	0	2.19 (0.03)
	55	321	8	1.84 (0.02)
	50–54	292–315	10–17	1.45 (0.01) to 1.79 (0.01)

RESULTS

Average water temperatures were 14.8, 13.1, and 14.0 °C during the April, May, and June trials, respectively. April trials were conducted in the early evening when water temperatures were near their daily maximum, while May and June trials were conducted in the mornings. Mean dissolved oxygen levels (mg/L) ranged from 8.91 to 10.3, and mean turbidity (NTU) was low, ranging from 4.1 to 5.0.

Archimedes Lift Trials

All but one of the 367 fish (0.3 percent) used in trials with the Archimedes lift were recovered. More than 90 percent of the recovered fish were seined from the screening facility channel (table 2). The relatively low velocities in the screening facility allowed fish to hold their position rather than move downstream to the holding tanks.

TABLE 2.—Percent of fish in treatment and control groups that were recaptured in the holding tanks, seined from the channel, or not recovered

Pump	Group	No. of Fish	Percent Captured in Holding Tanks	Percent Seined From Channel	Percent Not Recovered
Archimedes	Treatment	187	7.0	92.5	0.5
	Control	180	9.4	90.6	0.0
Hidrostal	Treatment	285	13.3	79.0	7.7
	Control	286	1.7	98.0	0.3

Mean percent survival of rainbow trout at capture and at 96 h was 100 percent for all speeds and groups, with one exception: 96-h survival was 98.3 percent for treatment fish at a pump speed of 22.1 r/min (table 3). That mortality occurred within the first 24 hr of the 96-h post-passage holding period. When data from all speeds were combined, 96-h survival was 99.4 percent and 100 percent for treatment and control fish, respectively. There was no significant difference in immediate or 96-h survival between treatment and control fish at any speed or when all data were combined ($P \geq 0.05$; table 3). The percent survival of rainbow trout at 96 h was unrelated to pump speed ($R^2 = 0.01$, $P = 0.698$).

TABLE 3.— Percent recaptured and percent survival at capture and at 96 h for rainbow trout passed through the Archimedes lift operated at three different speeds. The Wilcoxon signed-rank test was used to compare percent survival at 96 h between the treatment and control groups

Speed (r/min)	Group	No. of Trials	Percent Recaptured Mean (SE)*	Percent Survival at Capture Mean	Percent Survival at 96 h Mean (SE)*	*P*-value
26.5	Treatment	6	98.6 (1.4)	100	100	—
	Control	6	100	100	100	
22.1	Treatment	6	100	100	98.3 (1.7)	0.32
	Control	6	100	100	100	
19.9	Treatment	4	100	100	100	—
	Control	4	100	100	100	
Overall	Treatment	16	99.5 (0.5)	100	99.4 (0.63)	0.32
	Control	16	100	100	100	

* SE=standard error of the estimate.

Mean percent of fish with injuries at the three speeds ranged from 0 to 10.4 percent with no differences among pre-passage, post-treatment, and post-control groups ($P \geq 0.05$; table 4). Abrasion was the most common type of injury. All abrasions were small, comprising less than 5 percent of the surface area of a fish. The percent of fish with > 10 percent surface area descaled ranged from 0 to 11 percent with no differences among pre-passage, post-treatment, and post-control groups ($P \geq 0.05$; table 4). Fish descaled > 10 percent were in the 10-25 percent range; none exceeded 25 percent descaling.

TABLE 4.— Descaling and injury for pre-passage, control (no pump passage), and treatment (pump passage) groups of rainbow trout during trials with the Archimedes lift. The Kolmogorov-Smirnov test for goodness of fit was used to compare descaling and injury among the three groups at each pump speed. No detectable differences were found ($P > 0.05$)

Speed (r/min)	Group	No. Fish	Percent Descaled > 10 Percent	Percent Injured Mean (SE)*
26.5	Pre-passage	96	0	2.1 (1.4)
	Treatment	71	0	1.4 (1.4)
	Control	67	4	7.2 (4.0)
22.1	Pre-passage	72	3	1.4 (1.4)
	Treatment	67	2	0.0 (—)
	Control	66	2	4.2 (2.9)
19.9	Pre-passage	48	10	10.4 (6.3)
	Treatment	48	6	10.4 (4.0)
	Control	47	11	6.4 (2.2)

* SE=standard error of the estimate.

Hidrostal Pump Trials

In trials with the Hidrostal pump, 23 of the 571 fish (4.0 percent) were not recovered. All but one of these 23 fish were treatment fish which held up in the intake pipe during trials conducted at speeds less than 321 r/min. As with the Archimedes lift, most recovered fish were seined from the screening facility channel (table 2).

Mean percent survival of rainbow trout at capture ranged from 96.4 at the highest speed to 94.4 at the lowest speed (table 5). Mean percent survival at 96 h was nearly 94.0 at full speed and dropped to 88.0 at the lowest speed. Although there was a decreasing trend in survival as pump speed decreased, the relationship between survival and pump speed was not statistically significant for immediate ($R^2 = 0.04$, $P = 0.319$) or 96-h survival ($R^2 = 0.13$, $P = 0.077$). The difference in immediate survival between treatment and control groups was statistically detectable at the medium speed of 321 r/min ($P = 0.01$; table 5). The difference in 96-h survival between treatment and control groups was statistically detectable at all speeds ($P < 0.05$). All of the 96-h mortalities occurred within the first 24-h period, and most within 4 to 5 hours of capture.

TABLE 5.—Percent recaptured and percent survival at capture and at 96 h for rainbow trout passed through the Hidrostal pump operated at three different speeds. The Wilcoxon signed-rank test was used to compare percent survival between the treatment and control groups at capture and at 96 h

Speed (r/min)	Group	No. of Trials	Percent Recaptured Mean (SE)*	Percent Survival at Capture Mean (SE)*	*P*-value	Percent Survival at 96 h Mean (SE)*	*P*-value
350	Treatment	7	100	96.4 (1.7)	0.08	94.0 (1.6)	0.03
	Control	7	98.8 (1.2)	100		100	
321	Treatment	10	100	95.0 (1.4)	0.01	90.8 (2.6)	0.02
	Control	10	100	100		100	
292–315	Treatment	8	76.8 (1.2)	94.4 (2.1)	0.07	88.0 (2.4)	0.02
	Control	8	100	100		100	
Overall	Treatment	25	92.6 (2.9)	95.2	0.001	90.8 (1.4)	< 0.001
	Control	25	99.7 (0.3)	100		100	

* SE=standard error of the estimate.

When data from all twenty-five trials were combined, immediate and 96-h survival of treatment fish was 95.2 percent and 90.8 percent, respectively. Immediate and 96-h survival of control fish was 100 percent. The difference in survival between treatment and control fish was statistically significant at capture and at 96 h ($P \leq 0.001$; table 5).

The mean percent of surviving fish with injuries ranged from 2.5 to 9.8 for the three speeds (table 6). At each speed, the mean percent injured in the post-treatment group exceeded the mean percent injured in the pre-passage and the post-control groups. This difference was statistically significant for the middle speed of 321 r/min (table 6). At 321 r/min, the mean percent injured for post-treatment was significantly higher than post-control fish ($P = 0.006$, Wilcoxen test statistic = 0.7) and pre-passage fish ($P = 0.03$, test statistic = 0.6). Abrasions and bruises were the most common injuries on surviving fish. The percent of surviving fish with > 10 percent surface area descaled ranged from 4 to 8 percent, with no detectable differences among pre-passage, post-treatment, and post-control groups ($P \geq 0.05$; table 6). Fish descaled > 10 percent were in the 10–25 percent range; none exceeded 25 percent descaling.

TABLE 6.— Descaling and injury for pre-passage, control (no pump passage), and treatment (pump passage) groups of rainbow trout during trials with the Hidrostal pump. The Kolmogorov-Smirnov test for goodness of fit was used to compare descaling and injury among the three groups at each pump speed. The only detectable difference found was for percent injured at 321 r/min ($P < 0.05$)

Speed (r/min)	Group	No. Fish	Percent Descaled > 10 Percent	Percent Injured Mean (SE)*
350	Pre-passage	108	4	3.0 (1.5)
	Treatment	80	5	7.4 (3.7)
	Control	82	5	6.0 (3.0)
321	Pre-passage	120	7	4.2 (1.9)
	Treatment	113	8	9.8 (0.9)
	Control	117	4	2.5 (1.3)
292–315	Pre-passage	97	5	3.1 (2.2)
	Treatment	69	8	8.2 (3.4)
	Control	95	8	3.1 (2.2)

* SE=standard error of the estimate.

Of the 13 fish that were dead at capture, all but one had obvious injuries. Some fish had more than one type of injury. One fish was decapitated, seven had abrasions, four had bruises, two had open wounds, one was missing an eye, and two had hemorrhaging eyes. Of the 12 fish that died within 24 h of pump passage, four had no apparent injury, seven had abrasions, four had bruises, one had hemorrhaging eyes, and one had a hemorrhaging pectoral fin.

DISCUSSION

Rainbow trout passed through the Archimedes lift had higher survival than those passed through the Hidrostal pump. Similar pump passage trials conducted at the RPP using juvenile chinook salmon also found higher survival in fish passed through the Archimedes lift (McNabb et al., 2003). In their study, 96-h survival of juvenile chinook salmon passed through an Archimedes pump was > 98.5 percent while survival through the Hidrostal pump was 96.5 percent. These trials were conducted with the pumps operating at full speed. Survival of rainbow trout at 96 h in trials conducted at full speed was 100 percent for the Archimedes lift and 94 percent for the Hidrostal pump.

Although there was not a statistically detectable relationship between pump speed and trout survival, survival decreased as Hidrostal pump speed decreased (table 5). This trend was apparent even though the range of speeds was relatively small (292–350 r/min). At full speed, the Hidrostal pump at the RPP operates at its engineered highest efficiency with uniform, streamlined flow throughout the impeller. When the pump speed is reduced, the flow becomes more turbulent (Mefford, 2003). This may result in fish being disoriented and having a higher probability of being injured. Helfrich et al., (2001) found no significant relationship between pump speed and fish survival even though their speeds were more wide-ranging, from 461 to 600 r/min. The engineered optimum speed of the smaller Hidrostal pump used in their study was 400 to 600 r/min. Passage studies with this smaller pump operated at 409 to 598 r/min found no relationship between survival and pump speed for steelhead trout of similar size to fish used in this study (Helfrich et al., 2003). Studies using a 15-cm Hidrostal pump found that the relationship between survival and pump speed varied by species (Patrick and Sim, 1985; Rodgers and Patrick, 1985). Survival of yellow perch and alewife decreased as pump speed increased, while survival of rainbow trout and American eels showed no relationship to pump speed.

For the Hidrostal pump, detectable differences in immediate survival between treatment and control fish occurred only at the medium speed of 321 r/min. Similarly, the percent of post-treatment fish injured was significantly higher than post-control and pre-passage fish only at the 321 r/min speed. This anomaly in the results of the statistical analyses is likely due to sampling error and different sample sizes among the three speeds tested. The number of trials conducted was greater at the medium r/min speed (n = 10) than for the low (n = 8) or high (n = 7) speed.

During entrainment trials conducted at the RPP between 1995 and 2000, 143 large fish (> 200 mm) of various species passed through the Hidrostal pump and were collected in the holding tanks. Although immediate survival of these fish was 96 percent, similar to that of rainbow trout inserted into the Hidrostal pump, trout inserted during experiments had more severe injuries. Injuries to inserted fish included decapitation, missing eyes, hemorrhaging eyes, cuts with extruded organs, large bruises, and abrasions. Injuries to entrained fish were primarily bruises and abrasions. There were no decapitations, missing eyes, or cuts as seen with the inserted fish. Severe injuries, such as deep cuts across the dorsal area, were also found on large (> 200 mm) striped bass, *Morone saxitilis,* inserted into the Hidrostal pump at the RPP (Bark, 2000). There are several possible reasons for the difference in the severity of injuries between entrained and inserted fish: (1)

Entrained fish consisted of a variety of species, including Pacific lamprey, whose body shape may be less susceptible to injury. Our sample of large entrained trout consisted of only 7 fish, all uninjured. (2) Wild entrained fish may be instinctively better able to protect themselves from injury when passing through the pump. (3) The distance a fish travels through the intake pipe before encountering the pump differs between entrained and inserted fish. An entrained fish travels 18.2 m (60 ft) before encountering the pump, whereas a fish introduced through the insertion tube travels only 3.3 m (11 ft). At full pump speed, the velocity in the intake pipe is about 2.0 m/s (6.5 ft/s), so an entrained fish going with the flow would reach the pump in about 9 seconds. An inserted fish would reach the pump in less than 2 seconds. This may not be sufficient time for the fish to orient to the flow, making it more vulnerable to injury. An inserted fish could be in a variety of positions (i.e., forward, upside-down) and is likely at the top of the water column when it encounters the impeller, whereas an entrained fish is likely tail-first and in the center of the water column.

Severe injuries as observed on large trout and striped bass inserted into the Hidrostal pump at the RPP have not been seen on large fish of these and other species inserted through the smaller Hidrostal pump at Reclamation's Tracy Fish Salvage Facility. This pump is also installed such that inserted fish encounter the pump within one to two seconds of release. Therefore, reasons for the differences in the injuries may be due to differences in the pumps themselves including the size and weight of the impellers and the pump speed.

Not all of the rainbow trout used in these trials were recaptured. The fraction of control fish captured was high ($\geq$ 99.7 percent) for both pumps (table 2). For treatment fish, a greater fraction was captured in trials conducted with the Archimedes lift (99.5 percent) than with the Hidrostal pump (92.3 percent). Low-speed trials were initially conducted with the Hidrostal pump and revealed that speeds must be sufficient to create velocities in the intake pipe of $\geq$ 1.5 m/s (5 ft/s) to force fish into the pumps. Based upon this information, all trials conducted with the Archimedes lift were done at speeds sufficiently high to move the fish through the intake pipe. The one treatment fish missed during an Archimedes trial at full speed and one control fish missed with the Hidrostal pump likely jumped from the holding tanks into the bypass channel.

Ninety percent of the fish used in the trials remained in the screening facility rather than move downstream to the holding tanks. The fraction of fish captured in the holding tanks varied among groups and pumps (table 2). In the Hidrostal pump trials, a higher fraction of treatment fish (13.3 percent) were recovered in the holding tanks compared to control fish (1.7 percent). The fact that 100 percent of the control fish survived through the 96 h holding period indicates that these fish were sufficiently robust to hold in the screening facility. In contrast, treatment fish that were dead or injured passed directly through the screening facility to the holding tanks. Of the 38 treatment fish captured in the holding tanks, 13 were dead at capture and 12 were injured to the extent that they died within 24 h. In the Archimedes trials, a similar fraction of treatment and control fish were recovered in the holding tanks (7.0 and 9.4 percent, respectively). Although there were no immediate mortalities to explain why these fractions exceeded that of the Hidrostal control fish, more Archimedes trials than Hidrostal trials (38 percent versus 17 percent) were conducted at night when fish tend to more readily move through the screening facility (McNabb et al., 2000).

A fraction of the fish released during trials conducted with juvenile chinook salmon also remained in the screening facility (Borthwick and Corwin, 2001; McNabb et al., 2000). Frizell and Atkinson (1999) suggest that passage delays in the screening facility are due to the ramp located at the downstream end which creates a recirculating eddy preventing flow from accelerating into the open bypass channel. The ramp creates a zone of deceleration with low sweeping velocities near the bottom, ranging from approximately 0.12 to 0.61 m/s (0.40 to 2.0 ft/s) for a distance of 2.4 m (8 ft) upstream of the bypass entrance (Frizell and Atkinson, 1999). Rainbow trout of the size used in these trials likely would be able to maintain their positions indefinitely in these low velocities (Webb, 1971). Also, fish 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, fish that encounter low velocity zones in the screening facility likely resist moving back into high velocity waters.

CONCLUSIONS

Previous pump passage trials conducted at the RPP used small chinook salmon < 80 mm full-length (McNabb et al., 2003). Those trials, along with our trials with large rainbow trout, show that Archimedes lifts and Hidrostal pumps can pass large and small fish with low rates of mortality, injury and descaling. Pump speed did not affect survival of fish passed through the Archimedes lift, however, there was a trend of decreasing survival with decreased pump speed in the Hidrostal pump trials. This trend was not observed in trials with the smaller Hidrostal pump currently installed at

Tracy, and therefore may be related to the larger size of the RPP pump. The ability of the larger fish to hold their position in the intake pipes at velocities less than 1.5 m/s (5 ft/s) is an important finding of this study and should be considered when designing new fish passage facilities. Facilities should be designed to ensure that fish move efficiently through the system and predators do not congregate in low velocity zones.

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