Volume 24

Survival and Condition of Striped Bass, Steelhead, Delta Smelt, and Wakasagi Passed through a Hidrostal Pump at the Tracy Fish Collection Facility

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Volume 24

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Fish photography by Rene Reyes, Tracy Fish Collection Facility, Tracy, California.
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ABSTRACT

A 41-cm diameter Wemco-Hidrostal pump was evaluated for fish passage as part of research to improve salvage operations at the Bureau of Reclamation's Tracy Fish Collection Facility, Tracy, California. Immediate and 96-hour (h) mortality, descaling, and injury rates were evaluated for striped bass, *Morone saxatilis*, steelhead, *Oncorhynchus mykiss*, wakasagi, *Hypomesus nipponensis*, and delta smelt, *Hypomesus transpacificus*. Test fish inserted into the intake of the Hidrostal pump were compared to control fish that were inserted into the exit. The pump had no significant effect on immediate or 96-h mortality for all species tested, with immediate mortality less than 3 percent and 96-h mortality below 13 percent for all trials. Averaged scale loss was below 2.6 percent for all species. Some non-lethal injuries to the head, eyes, skin, and fins of pumped fish occurred; however, these injuries were not significantly different among quality control, control, and treatment fish. No statistically significant relationships were detected between fish mortality and pump speed, injected fish density, or debris load. Wakasagi appeared to be more tolerant to pump passage than delta smelt and may not be an appropriate surrogate species for delta smelt. Our results suggest that large Hidrostal pumps have the capacity to transport live fish with low mortality and minimal body injury.

EXECUTIVE SUMMARY

A 41-cm diameter Wemco-Hidrostal pump was evaluated for fish passage as part of research to improve salvage operations at the Bureau of Reclamation's Tracy Fish Collection Facility, Tracy, California. Immediate and 96-h mortality, descaling, and injury rates of striped bass, *Morone saxatilis*, steelhead *Oncorhynchus mykiss*, wakasagi, *Hypomesus nipponensis*, and delta smelt, *Hypomesus transpacificus,* that were inserted into the entrance (suction side) of a Hidrostal pump were compared to those of control fish that were inserted at the exit (pressure side). Comparisons were made in 168 paired trials with striped bass, 86 trials with steelhead, 34 trials with delta smelt, and 29 trials of wakasagi.

The Hidrostal pump had no significant effect on immediate or 96-h mortality of striped bass and steelhead. Immediate mortality for pumped striped bass and steelhead averaged 0.1 and 0 percent, respectively, and 96-h mortality averaged 4.6 and 0.1 percent, respectively. Immediate and 96-h mortality for delta smelt (mean, 0.5 and 12.9 percent) and wakasagi (2.5 and 4 percent) was similarly low.

Mean scale loss after pump passage for striped bass and steelhead was low, averaging 0.2 percent and 2.6 percent, respectively. Scale loss analysis was not possible on delta smelt or wakasagi. Frequency of body injury to the head, eyes, skin, and fins of pumped striped bass averaged 14.0, 2.0, 7.5, and 40 percent, respectively, and those of steelhead averaged 3.5, 0.1, 4.7, and 62.5 percent. Frequency of body injury to the head, eyes, skin, and fins of pumped delta smelt averaged 0, 0, 0, and 19.0 percent, and those of wakasagi averaged 9.1, 0, 0, and 27.0 percent. These injuries were non-lethal and not significantly different among quality control, control, and treatment fish. Relatively high fin abrasion was largely the result of holding and handling conditions, rather than pump effect.

No consistently significant relationships were detected between fish mortality and pump speed, injected fish density, or debris load. Wakasagi appeared to be a hardier species (subspecies), slightly more tolerant to pump passage than delta smelt and, therefore, may not be an appropriate surrogate species for delta smelt. Our results suggest that large Hidrostal pumps have the capacity to transport live fish at high density with little mortality and body injury.

INTRODUCTION

The Tracy Fish Collection Facility (TFCF) was constructed in the 1950s by the U.S. Department of the Interior, Bureau of Reclamation (Reclamation), to intercept and salvage fish that had become entrained into water being diverted into the Delta Mendota Intake Channel in the Sacramento-San Joaquin Delta (Delta), California (Liston et al., 1993). Following several years of testing and development, a louver system was installed to guide fish into holding tanks prior to transport back to Delta waters. Fish are concentrated in holding tanks with accumulating debris for several hours before being lifted into transport tanks (Bureau of Reclamation, 1957). Stresses associated with holding (circular swirling currents) and subsequent transfer to fish hauling trucks with a bucket may stress fish and reduce their survival following transport and release in the San Joaquin River.

During the late 1980s, Reclamation began implementing studies and processes at TFCF to increase the understanding of fish problems at the facility, aimed at eventually improving the TFCF through alterations of the existing system or possible total facility replacement (Liston et al., 2000). This group of activities was collectively called the Tracy Fish Facility Improvement Program (TFFIP) by Reclamation, which was given more validity and necessity by passage of the Central Valley Project Improvement Act (CVPIA) in 1992. An especially significant requirement of the CVPIA is in Section 3406(b)(4), which states that Reclamation must “develop and implement a program to mitigate for fishery impacts associated with operations of the Tracy Pumping Plant. Such a program shall include, but is not limited to, improvement or replacement of the fish screens and fish recovery facilities and practices associated with the Tracy Pumping Plant.”

Developing technologies for TFCF to replace recessed holding tanks was one approach considered to address CVPIA requirements. If fish could be lifted to above ground holding tanks where flows could be controlled and debris removed prior to transport, fish stress may be reduced. Earlier work using fish-friendly internal screw type pumps at TFCF (Hiebert, 1994), other sites (Patrick and Sim, 1985; Rodgers and Patrick, 1985; Patrick and McKinley, 1987), and at Red Bluff, California (McNabb et al., 2003) indicated high survival of pumped fish. Reclamation installed a Hidrostal pump and tank system in 1998 at TFCF, and successful fish passage was determined, both for experimentally introduced juvenile chinook salmon, *Oncorhynchus tshawytscha*, splittail, *Pogonichthys macrolepidotus*, and incidentally entrained fish of 26 other species (Helfrich et al., 2001). Especially notable were 108 juvenile delta smelt, *Hypomesus transpacificus*, passed through the pump with high (99 percent) immediate survivorship.

Fish passage and protection at water export facilities and at dams are fundamental to maintaining and restoring anadromous and nonanadromous fishes. The cumulative impact of dams, hydropower facilities, and irrigation water diversions on riverine fish populations has become increasingly apparent with the decline of Pacific salmon species and other fish stocks (Nemeth and Kiefer, 1999; Williams et al., 1999). Catastrophic ecological and economic consequences have accompanied the collapse of important commercial and recreational fisheries as a result of dam impassability and canal and turbine entrainment of fish (National Research Council, 1996).

Moreover, the occurrence of threatened species such as the delta smelt, a federally listed threatened species, entrained in water export facilities, can significantly alter operations. Collection of delta smelt, in numbers greater than the “take threshold” set by State and Federal fisheries regulatory agencies (U.S. Fish and Wildlife Service, National Marine Fisheries Service, California Department of Fish and Game), initiates a series of actions including reduced water export rates. Methods to minimize entrainment and maximize survival and recovery of threatened and endangered species is imperative for predictable water delivery for irrigation and municipal uses. Here we test the sensitivity of both delta smelt and wakasagi, *Hypomesus nipponensis*, a similar, unprotected exotic species that is taxonomically nearly indistinguishable from delta smelt.

Significant declines in worldwide river fisheries may be partially mitigated by using less damaging pumping technologies. The Hidrostal pump, which uses a screw-type centrifugal impeller and has been used to move fruits and produce for shipping without damage, may prove useful for the safe passage of fish at dams and at water export facilities. Pumps that can safely transport fish from a water diversion canal through a bypass return to a river or around a dam would have significant fisheries management applications.

Few comprehensive investigations of Hidrostal pump systems with fish have been published. Limited evaluations of small (15 and 25 cm diameter inlet) Hidrostal pumps have demonstrated relatively low mortality (0–28 percent) and injury rates (< 3 percent) for a few species and sizes of fish (Baldwin, 1973; Rodgers and Patrick, 1985; Patrick and McKinley, 1987; Grizzle et al., 1992; Grizzle and Lovshin, 1994; Wagner and Driscoll, 1994). However, the feasibility of using a large (41 cm diameter) Hidrostal pump to move commercial volumes of water and transfer diverse species of fishes, sizes, and densities over a range of pump speeds back into a river system is uncertain.

The objectives of this research were to assess survival, descaling, and injury rates of striped bass, *Morone saxatilis*, steelhead, *Oncorhynchus mykiss*, wakasagi, and delta smelt transported by a large Hidrostal pump and to relate fish mortality and injury to pump speed, fish density injected, and debris load.

METHODOLOGY

The Reclamation Tracy Pumping Plant (TPP), located in the Central Valley of California, exports over 678 million cubic meters of water per year into the Delta Mendota Canal (DMC) for irrigation, municipal, and industrial water needs. The TFCF, located 2 miles upstream from the TPP, was designed to exclude adult sport fish inhabiting the Sacramento and San Joaquin rivers from export water (Helfrich et al., 1999). At the TFCF, fish are directed by louvers into underground tanks where they are held for stocking back into the Sacramento-San Joaquin Delta.

A 41-cm diameter Hidrostal pump (internal helical, centrifugal) built by Wemco Pump (EnviroTech Pumpsystems) was installed at the TFCF in October 1998 for these experiments (figure 1). The Hidrostal pump used was larger but similar in design to helical pumps that have been widely used in the aquaculture industry to grade, harvest, and move fish. This pump was designed to minimize shear, pressure change, turbulence, and abrasion. The screw-type impeller is completely enclosed (shrouded) to protect the fish. The pump is turned by a 50-hp electric motor controlled with a variable speed drive to produce selected water discharge and velocity. During these trials, pump speed ranged from 461 to 601 revolutions per minute (r/min) and water flows ranged from 178 to 299 L/s, depending on canal hydraulics and tidal conditions. Pumping time per trial ranged from 5 to 10 minutes.

Experimental trials were conducted during December 1999 through February 2002. Months were selected to evaluate passage through the pump by native and non-native species during different seasons and over a range of environmental conditions. Dissolved oxygen (DO), pH, water temperature (T), electrical conductivity (EC), and salinity were all within the physiological limits for fish. DO ranged from 9.9 to 8.4 mg/L, pH from

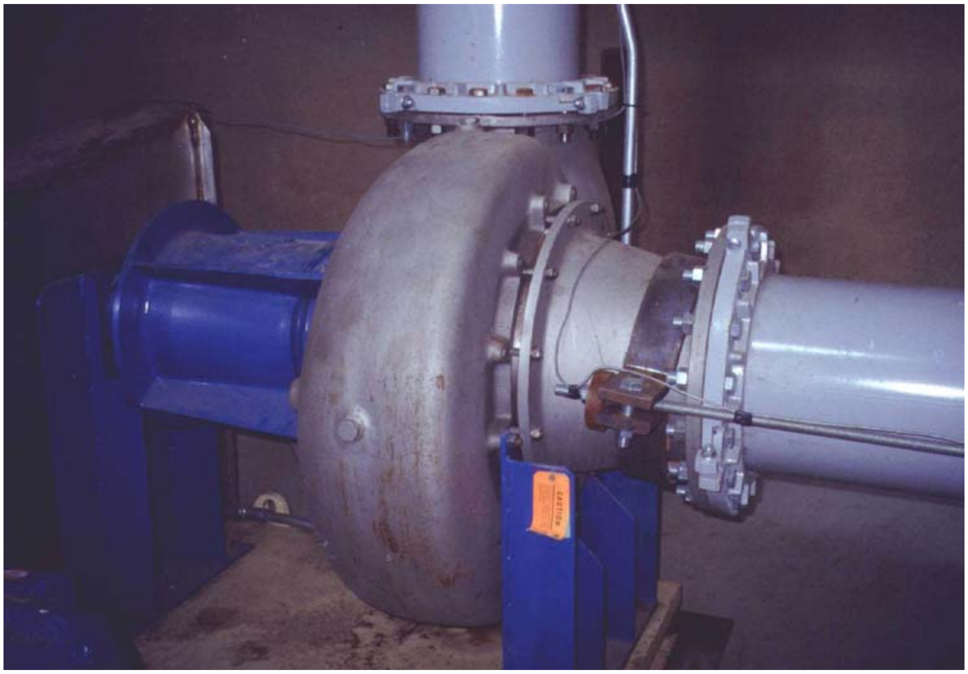

FIGURE 1.—Wemco-Hidrostal centrifugal pump used for the fish passage experiments.

7.3 to 8.2, T from 8.8 to 24.1 °C, EC from 0.09 to 0.65 mS/cm, and salinity from 0.01 to 0.33 parts per thousand. All herbaceous and woody debris naturally entrained in the pump were weighed (wet weight) for each trial.

Striped bass (mean = 177 mm total length; range 78 to 360 mm) were collected from the TFCF. Steelhead (mean = 252 mm total length; range 165 to 313 mm) were obtained from California Department of Fish and Game Nimbus Hatchery, Rancho Cordova, California. Delta smelt were reared at the State of California Skinner Aquaculture Facility using eggs collected from wild adults in the Spring 2001. Wakasagi were collected using seine and dip nets from San Luis Reservoir, Gustine, California.

All experimental fish were held in well water near 18 °C, and acclimated for 24 hours in canal water at ambient temperatures before the experiments. Fish were carefully handled and transferred in water treated with a solution of NaCl (5 g/L) and PolyAqua® (0.13 mL/L) to promote osmotic balance and reduce stress. In some trials, striped bass were marked with bismarck brown dye one day prior to the experiments to distinguish them from similar size wild fish entrained during the trials. Steelhead, delta smelt, and wakasagi in most trials were marked with photonic color dye injected into the fins.

After the Hidrostal pump was operating at constant test speed, a group of treatment fish (*n* = 4 to 42), held in water-filled plastic bags, were inserted with water flow into a 30.5-cm diameter port (standpipe) located immediately upstream (suction side) of the pump (figure 2). Fish were released from the bag into the flow. Fish remaining in the standpipe were forced into the flow by inserting a fish crowder and slowly pushing it downward in the standpipe. In separate paired control trails, fish were subjected to the same conditions as the treatment fish, but were inserted into a standpipe downstream (pressure side) of the pump. Paired treatment and control trials were tested consecutively and simultaneously to assure that experimental fish experienced identical physical and chemical conditions. Fish densities instantly injected into the pump ranged from 4 to 42 fish per trial depending on the species and sizes used. After injection, treatment and control fish were lifted in the flow 3.7 m vertically and conveyed 13.7 m horizontally through smooth pipe and discharged into a large rectangular holding pool (4.4 x 9.0 x 1.2 m deep).

The holding pool (figure 3) was designed to convey a 400 L/s flow at an

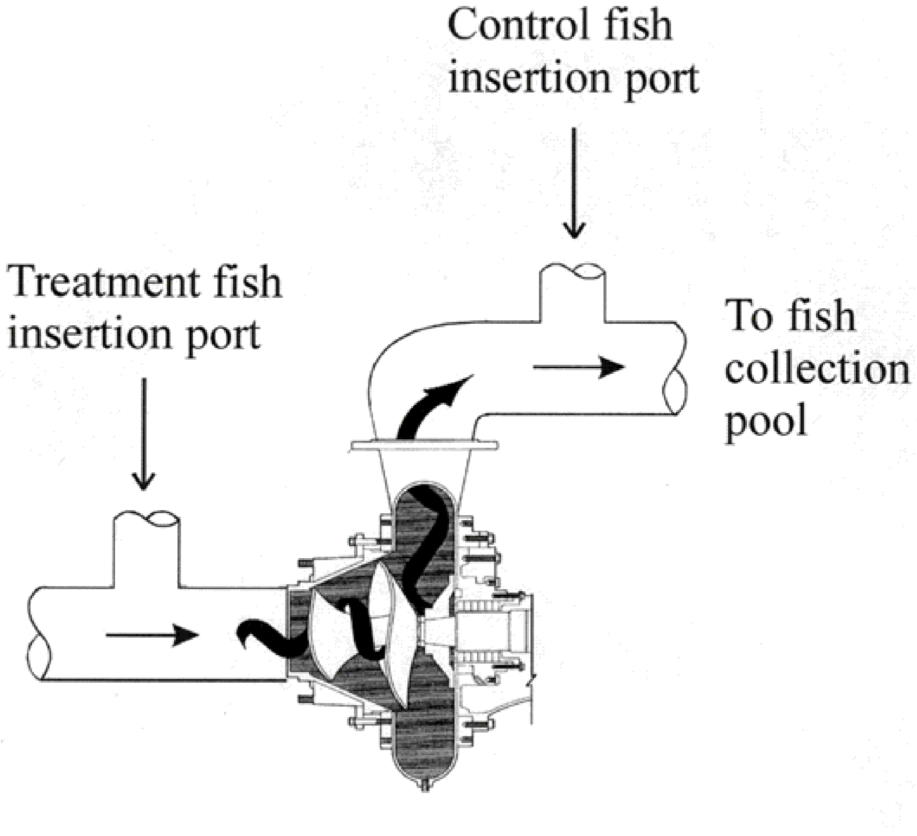

FIGURE 2.—Cross section view of the Hidrostal pump and fish injection ports (fish protective impeller shroud is not shown in this drawing).

average velocity of 3.67 cm/s in order to reduce the potential for fish impingement on the rotating debris screen at the pool discharge. Fish were collected by handnet in the pool sump, (4.4 x 0.6 x 0.3 m deep) after excess water was gradually drained through a rotating drum screen (perforated plate, 0.24-cm mesh). The rotating drum screen was mounted at the downstream end of the holding pool to prevent escape of fish and to remove debris. A stationary perforated plant (0.24-cm mesh) was placed diagonally in front of the sump drain to prevent escape of fish and to collect and remove debris for analysis.

FIGURE 3.—Collection pool where fish were collected by handnet.

Before each trial, two fish from each live cage were randomly selected to be quality controls to determine potential handling and transport impact. Quality control fish were compared to all post-treatment and post-control fish after each trial by microscopic analysis for descaling and physical injury.

Quality control fish were used to establish base line injury levels for non-pump related handling and holding conditions in the aquaculture facility. For descaling analyses, 100 percent of the total scaled body surface was microscopically examined and scale loss (as a percent of body surface area) was estimated according to Kostecki et al. (1987). Body injury rates (percent of fish) were used to enumerate any abnormalities or abrasions to the head, eyes, skin, and fins.

After each trial, survival rates of fish in the holding pool were recorded. Two live fish from each trial were anesthetized with an overdose (> 300 mg/L) of tricaine methanesulfonate (MS-222), placed in a plastic bag with water, and examined for descaling and external injury within 60 minutes of collection. A non-lethal dose of MS-222 was used to relax the fish during examination for all steelhead and some of the striped bass trials. The remaining fish were transferred to live cages and examined for 96-h mortality at 24-h intervals for four days.

Paired trials (n = 2 to 25 per month) were conducted for each treatment (pump passage) and control (no pump passage) group for striped bass, steelhead, delta smelt, and wakasagi. Our null hypothesis, H_o, was: no difference between control and treatment fish in mean immediate survival, 96-h survival, descaling, or body injury rates.

The Wilcoxon signed-rank test was used to test for differences in survival between paired treatment and control groups for each monthly testing period. Variables were group (treatment or control) and time after pump passage (0, 24, 48, 72, and 96 h). The Kolmogorov-Smirnov test for goodness of fit (Sokal and Rohlf, 1981; Zar, 1984) was used to examine differences in frequency distributions between descaling and body injury among treatment, control, and quality control (handling) groups. Regression analysis was used to detect any significant relationships between 96-h survival and injected fish density of striped bass and steelhead. Expected frequencies were computed for data on the control group trials. An alpha level of 0.05 was used as the criterion for detecting statistical significance.

RESULTS AND DISCUSSION

Striped Bass

Immediate survival after pump passage for striped bass (table 1) was high, averaging 99 percent, and did not differ significantly between treatment and control groups (Wilcoxon sign rank test, $z = 1.3$, $P = 0.18$). Four-day survival after pump passage remained high, averaging 96 percent, and no differences

TABLE 1.—Mean percent immediate (0-h) and 96-h survival of striped bass passed through the Hidrostal pump (treatment) and those of the control fish during 169 trials

				Daily Mortality (n)					Survival Rate (percent)				
Group	**Date**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
Treatment	Dec-99	16	316	0	5	2	0	0	100	97.7	245	201	482
Control		16	316	0	5	2	0	0	100	97.7	245	201	482
Treatment	Feb-00	20	485	0	7	6	47	84	100	74.4	440	227	500
Control		20	484	0	5	10	39	71	100	77.5	372	239	507
Treatment	May-00	10	133	0	0	0	0	0	100	100	327	278	546
Control		10	127	0	1	0	0	0	100	99.2	168	269	541
Treatment	Jun-00	13	143	0	0	3	0	0	100	97.7	135	276	540
Control		13	143	0	0	0	0	0	100	100	352	280	539
Treatment	Jul-00	23	268	0	0	0	0	1	100	99.6	567	202	499
Control		23	284	0	0	0	0	0	100	100	448	201	494
Treatment	Aug-00	20	203	0	0	0	0	2	100	99	597	230	513
Control		20	179	0	1	0	0	0	100	99.4	500	230	513
Treatment	Oct-00	16	156	1	1	0	0	0	99.4	98.8	881	179	482
Control		16	136	0	0	0	0	0	100	100	1130	178	482
Treatment	Jun-01	16	173	0	0	0	0	1	100	99.5	3890	233	508
Control		16	175	0	0	0	0	0	100	100	4770	233	507
Treatment	Jul-01	15	266	0	3	0	0	0	100	99.1	525	224	502
Control		15	276	0	0	0	0	0	100	100	630	226	503
Treatment	Dec-01	20	92	0	1	2	0	2	100	93.8	1420	196	489
Control		20	98	0	0	1	0	1	100	97.5	1420	196	489
				Daily Mortality (n)					**Survival Rate (percent)**				
Group	**All Dates**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
	Treatment	169	2235	1	17	13	47	90	99.9	95.4	911	221	503
	Control	169	2218	0	12	13	39	72	100	96.7	1010	221	503

between treatment and control groups for striped bass ($z = 2.19$, $P = 0.28$) were detected. Unusually high 96-h mortality (20 percent) of control and treatment striped bass during February 2000 resulted from reduced aeration and oxygen flow to the holding tanks and was unrelated to pump effects.

Fish survival (percent, was unrelated to pump speeds between 409 to 598 r/min ($r^2 = 0.01$, $P = 0.34$), flow rates between 178 to 278 L/s ($r^2 = 0.01$, $P = 0.36$), and fish density between 4 and 42 fish per trial ($r^2 = 0.03$, $P = 0.68$).

Natural debris loading varied greatly in weight and characteristics, ranging from 0 to 4.8 kg wet weight per trial depending on the season (table 1). Despite large differences in debris loading within and between seasons, fish survival was not significantly related to debris loading over the ranges encountered (regression, $r^2 = 0.01$, $P = 0.23$). Debris loads were dominated (98 percent) by herbaceous matter, largely fragments of *Egeria densa* and woody debris (twigs, bark, and sticks).

Descaling rates for striped bass (table 2) passed through the pump were low, averaging 0.3 and 0.2 percent for the controls and treatment fish, respectively. No differences in descaling between treatment, quality control, and control trials for striped bass ($z = 1.0$, $P = 0.31$) were detected throughout the experiment.

The percent of fish with body injury to the head, eyes, skin, and fins of striped bass after pump passage was minimal. However, fin abrasions averaged 40 percent for all groups (table 2). No significant differences ($P < 0.05$) of body injury percentage were detected between the quality control, control, and treatment groups except for June 2001 when the incidence of skin injury was significantly greater ($P < 0.05$) for treatment compared to control fish. The high incidence in skin bruises evident in striped bass in June, July, and December 2001 trials likely resulted from crowding of larger-sized fish (232 to 299 mm) into the pump insertion port. High fin abrasion was attributed more to culture conditions than pump impact as indicated by the quality control fish. Non-pumped control and quality control fish exhibited high fin abrasion, averaging 39 and 44 percent. Nearly all body injuries were non-lethal.

TABLE 2.—Mean percent body scaling and percent fish injured for quality control (handling), control (no pump passage), and treatment (pump passage) groups of striped bass

Group	Date	Fish (n)	Descaling (percent body)	Body Injury (percent frequency) Head	Eyes	Skin	Fins	Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)	Monthly Mean Total Length (mm)	Size Range (mm)
Quality Control	Dec-99	64	0	3	0	0	42	109	103	14	108	85–136
Control		32	0	0	0	0	34	106	101	13		84–127
Treatment		32	0	2	0	0	37	109	104	14		80–137
Quality Control	Feb-00	80	0	0	0	0	28	124	118	17	122	83–155
Control		40	0	0	0	0	26	123	118	17		78–138
Treatment		40	0	0	0	0	28	120	115	16		90–141
Quality Control	May-00	40	1	0	0	0	28	138	132	24	136	95–167
Control		20	0	0	0	0	50	135	129	22		111– 158
Treatment		20	0	0	0	0	50	135	129	23		113–172
Quality Control	Jun-00	52	0	0	0	0	44	167	158	46	165	139–195
Control		26	0	0	0	0	54	164	155	44		130–189
Treatment		26	0	0	0	0	15	161	152	39		136 –181
Quality Control	Jul-00	92	0	0	0	0	27	169	159	46	167	114–244
Control		46	0	0	0	0	48	164	153	43		122–238
Treatment		46	0	2	2	0	39	168	159	46		125–220
Quality Control	Aug-00	80	0	0	0	0	46	171	164	51	171	120–223
Control		40	0	3	1	0	54	166	158	45		128 –195
Treatment		40	0	0	3	0	58	175	167	53		145–201
Quality Control	Oct-00	64	0	0	0	0	41	195	185	77	197	158–253
Control		32	0	0	3	0	69	199	190	87		164–283
Treatment		32	0	0	0	0	47	200	188	88		162–288
Quality Control	Jun-01	32	1	0	3	22	38	266	254	183	264	233–308
Control		16	1	13	0	6	25	259	249	168		222–290
Treatment		16	2	0	6	31	50	264	252	185		235–305
Quality Control	Jul-01	48	0	0	0	20	37	229	219	139	232	166–303
Control		24	1	0	0	16	28	233	223	139		164–265
Treatment		24	0	4	4	12	35	236	226	153		177–325
Quality Control	Dec-01	46	0	0	7	43	57	292	277	302	299	220–360
Control		23	0	4	9	48	52	302	285	338		230–355
Treatment		23	0	4	4	39	57	310	295	379		250–350

Group	All Dates	Fish (n)	Descaling (percent body)	Body Injury (percent frequency) Head	Eyes	Skin	Fins	Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)		Size Range (mm)
	Quality Control	600	0	12	1	8	39	178	168	76		83–360
	Control	300	0	13	1	10	44	176	167	77		78–355
	Treatment	300	0	14	2	8	40	178	170	84		80–350

Steelhead

Immediate survival after pump passage for steelhead (table 3) was high, averaging 100 percent, and did not differ significantly between treatment and control trials (Wilcoxon sign rank test, $z = 1.0$, $P = 0.31$). Four-day survival after pump passage remained high, averaging 99 percent.
No differences between treatment and control trials ($z = 1.0$, $P = 0.32$) were detected for immediate or 96-h post-treatment. Testing of steelhead was discontinued after March because of increasing water temperatures.

Fish survival was unrelated to pump speed between 409 and 598 r/min ($r^2 = 0.01$, $P = 0.34$), flow rates between 232 and 298 L/s ($r^2 = 0.01$, $P = 0.37$), fish density between 9 and 12 fish per trial ($r^2 = 0.03$, $P = 0.51$), or debris loads between 0.4 and 1.1 kg ($r^2 = 0.01$ and $P = 0.23$).

Descaling rates for steelhead (table 4) passed through the pump were low, averaging 2.6 percent . No differences in descaling between treatment and control trials ($z = 0.70$, $P = 0.49$) were detected throughout the experiment.

Steelhead with injury to the head, eyes, skin, and fins averaged 3.5, 0, 1.0, and 62.5 percent, respectively, whereas that of the non-pumped control fish averaged 3.5, 0, 4.7, and 68 percent, respectively. Quality control steelhead averaged 1.5, 0, 0, and 62.8 percent, respectively (table 4). No significant ($P < 0.05$) differences of body injury rates were detected between the quality control, control, and treatment groups. Fin injury was attributed to the culture holding conditions rather than pump effect, as suggested by relatively high fin abrasion for unpumped control (58.0 percent), and quality control fish (64.0 percent).

Delta Smelt and Wakasagi

Immediate survival of delta smelt was high (99.5 percent) and did not differ between treatment and control groups in three monthly sets of trials (table 5). Ninety six-hour survival was generally lower than immediate survival, and significantly lower than in the treatment trials in November, but did not differ between treatment and control trials in October and March ($z = 1.0$, $P = 0.35$). Percent body injury to the head, eyes, skin, and fins of pumped delta smelt (table 6) was low, typically < 3.0 percent. No significant ($P < 0.05$) differences in body injury percentages were detected between the

TABLE 3.—Mean percent immediate (0-h) and 96-h survival of steelhead passed through the Hidrostal pump (treatment) and those of the control fish during 86 trials

				Daily Mortality (n)					Survival Rate (percent)				
Group	**Date**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
Treatment	Jan-01	25	268	0	0	0	0	0	100	100	535	298	554
Control		25	270	0	0	0	0	1	100	99.6	389	299	555
Treatment	Mar-01	21	229	0	0	0	0	1	100	99.6	405	298	549
Control		21	229	1	0	0	0	0	99.6	99.6	433	297	549
Treatment	Jan-02	20	236	0	0	0	0	0	100	100	1142	232	522
Control		20	240	0	0	0	0	0	100	100	1142	232	522
Treatment	Feb-02	20	238	0	0	0	0	0	100	100	863	249	530
Control		20	237	0	0	0	0	0	100	100	863	249	530
				Daily Mortality (n)					**Survival Rate (percent)**				
Group	**All Dates**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
	Treatment	86	971	0	0	0	0	1	100	99.9	639.4	266	535.8
	Control	86	976	1	0	0	0	1	99.9	99.8	604.0	266	536.0

TABLE 4.—Mean percent body descaling and percent injured fish for quality control (handling), control (no pump passage), and treatment (pump passage) groups of steelhead

Group	Date	Fish (n)	Descaling (percent body)	Body Injury (percent frequency)				Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)	Monthly Mean Total Length (mm)	Size Range (mm)
				Head	Eyes	Skin	Fins					
Quality Control	Jan-01	50	1	4	0	0	44	238	227	126	240	165–289
Control		25	1	4	0	0	32	239	229	129		187–290
Treatment		25	1	12	0	0	60	244	236	139		195–305
Quality Control	Mar-01	42	2	0	0	0	88	264	249	165	263	224–300
Control		21	2	0	0	0	95	264	254	167		225–306
Treatment		21	3	0	0	10	90	260	252	160		230–307
Quality Control	Jan-02	20	3	0	0	0	40	252	240	148	250	187–313
Control		20	4	0	0	0	20	251	241	141		235–276
Treatment		20	4	0	0	10	15	248	235	134		195–305
Quality Control	Feb-01	20	4	0	0	0	90	258	246	153	258	203–296
Control		20	4	10	0	0	90	251	241	146		205–310
Treatment		20	3	0	0	0	85	265	253	170		230–300

Group	All Dates	Fish (n)	Descaling (percent body)	Body Injury (percent frequency)				Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)		Size Range (mm)
				Head	Eyes	Skin	Fins					
Quality Control		132	2	2	0	0	64	251	239	146		165–313
Control		86	3	3	0	0	58	251	241	145		187–310
Treatment		86	3	3	0	5	63	254	244	150		195–307

TABLE 5.—Mean percent immediate (0-h) and 96-h survival of delta smelt passed through the Hidrostal pump (treatment) and those of the control fish during 34 trials

Group	Date	Trials (n)	Fish (n)	Daily Mortality (n)					Survival Rate (percent)		Debris (g)	Flow (L/s)	Pump Speed (r/min)
				0 h	24 h	48 h	72 h	96 h	0 h	96 h			
Treatment	Oct-01	2	44	0	0	0	1	5	100	86.4	175	249	507
Control		2	44	0	0	0	0	0	100	100	125	252	515
Treatment	Nov-01	20	209	2	12	2	6	8	99.0	85.6	1460	230	511
Control		20	208	1	6	3	3	4	99.5	91.8	1460	230	511
Treatment	Mar-01	12	118	0	10	1	1	0	100	89.8	1800	203	497
Control		12	117	0	7	3	0	0	100	91.5	1800	203	497
Group	**All Dates**	**Trials (n)**	**Fish (n)**	**Daily Mortality (n)**					**Survival Rate (percent)**		**Debris**	**Flow**	**Pump Speed (r/min)**
				0 h	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**(g)**	**(L/s)**	
	Treatment	34	371	2	22	3	8	13	99.5	87.1	1510	222	506
	Control	34	369	1	13	6	3	4	99.7	92.7	1500	222	506

TABLE 6.—Mean percent injured fish for quality control (handling), control (no pump passage), and treatment (pump passage) groups of delta smelt

Group	Date	Fish (n)	Body Injury (percent frequency) Head	Eyes	Skin	Fins	Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)	Monthly Mean Total Length (mm)	Size Range (mm)
Quality Control	Oct-01	8	0	0	0	0	62	56	1.6	62.1	40–77
Control		4	0	0	0	0	65	60	1.7		51–72
Treatment		4	0	0	0	25	61	56	1.5		50–70
Quality Control	Nov-01	40	3	3	0	10	70	64	2.2	69.6	52–78
Control		20	5	0	0	20	67	61	1.9		56–77
Treatment		20	0	0	0	25	71	65	2.4		55–82
Quality Control	Mar-02	24	0	0	0	17	81	75	3.7	81.1	62–96
Control		12	0	0	0	25	84	78	4.3		72–93
Treatment		12	0	0	0	8	79	73	3.6		61–94

Group	All Dates	Fish (n)	Body Injury (percent frequency) Head	Eyes	Skin	Fins	Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)		Size Range (mm)
Quality Control		220	1	1	0	11	72.5	66.8	2.6		40–96
Control		110	3	0	0	19	72.2	66.2	2.7		51–93
Treatment		110	0	0	0	19	72.6	66.3	2.7		50–94

quality control, control, and treatment groups. Descaling analysis was not possible on delta smelt or wakasagi because of their transparency (Wang, 2003).

Wakasagi, tested as a potential surrogate species for delta smelt, exhibited slightly lower immediate and 96-h survival, averaging 97 and 96 percent respectively throughout three monthly trials (table 7). Immediate survival of pumped wakasagi was significantly lower than in the control trials in February, but did not differ between treatment and control trials in May and October ($z = 1.2$, $P = 0.38$). When all trials ($n = 29$ pairs) were pooled, no significant differences between treatment and control fish were detected for 96-h mortality. Body injury rates for wakasagi (table 8) were low and similar to those of delta smelt. As with delta smelt, no significant differences in body injury percentages were detected between the quality control, control, and treatment groups of wakasagi, except for head injury in October. The high percentages of fin erosion observed in quality control fish strongly suggests that these injuries are caused by confinement and artificial culture conditions.

Wild Fish

A large variety of native and introduced fishes (29 species, 23,348 individuals) were entrained incidentally to the pumping trials (table 9).

Immediate mortality of wild fish was low, with survival percentages greater than 98 percent. It is possible that the mortality of wild fish is unrelated to any pump effect and simply the result of entrainment of post-mortem fish. A number of small, delicate species, including delta smelt, threadfin shad, *Dorosoma petenense*, American shad, *Alosa sapidissima*, and chinook salmon fry, were sampled in good condition after pump passage in the collection tank. Most fish entrained were small (< 100 mm) but even large fish (> 400 mm) were unharmed after pump passage.

TABLE 7.—Mean percent immediate (0-h) and 96-h survival (percent) of wakasagi passed through the Hidrostal pump (treatment) and those of the control fish during 29 trials

				Daily Mortality (n)					**Survival Rate (percent)**				
Group	**Date**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
Treatment	Feb-01	18	208	5	0	0	0	1	97.6	97.1	288	263	551
Control		18	210	0	0	0	0	0	100	100	290	265	553
Treatment	May-01	8	85	3	0	2	0	0	96.5	94.1	61	271	523
Control		8	86	1	3	2	0	0	98.8	93.0	56	272	524
Treatment	Oct-01	3	64	1	0	0	0	1	98.4	96.9	67	243	534
Control		3	63	0	0	0	0	0	100	100	200	230	522
				Daily Mortality (n)					**Survival Rate (percent)**				
Group	**All Dates**	**Trials (n)**	**Fish (n)**	**0 h**	**24 h**	**48 h**	**72 h**	**96 h**	**0 h**	**96 h**	**Debris (g)**	**Flow (L/s)**	**Pump Speed (r/min)**
Treatment		29	357	9	0	2	0	2	97.5	96.0	175	267	537
Control		29	359	1	3	2	0	0	99.7	98.2	182	256	533

TABLE 8.—Mean percent injured fish for quality control (handling), control (no pump passage), and treatment (pump passage) groups of wakasagi

Group	Date	Fish (n)	Body Injury (percent frequency)				Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)	Monthly Mean Total Length (mm)	Size Range (mm)
			Head	Eyes	Skin	Fins					
Quality Control	Feb-01	38	5	5	3	18	85	79	4.4	87.6	61–102
Control		19	0	0	5	47	89	83	5.2		72–110
Treatment		19	5	0	0	42	91	85	5.4		81–102
Quality Control	May-01	16	13	0	0	6	94	87	4.9	96.9	66–115
Control		8	0	0	0	0	102	94	6.1		92–114
Treatment		8	13	0	0	13	99	92	5.9		86–107
Quality Control	Oct-01	12	0	0	0	50	70	65	2.0	68.5	55–79
Control		6	0	0	0	83	66	60	1.6		48–79
Treatment		6	17	0	0	0	69	63	2.0		52–80

Group	All Dates	Fish (n)	Body Injury (percent frequency)				Mean Total Length (mm)	Mean Fork Length (mm)	Mean Wt. (g)		Size Range (mm)
			Head	Eyes	Skin	Fins					
Quality Control		66	6	3	2	21	84.4	78.5	4.1		55–115
Control		33	0	0	3	42	87.9	81.5	4.8		48–114
Treatment		33	9	0	0	27	88.8	82.6	4.9		52–107

TABLE 9.—Numbers and sizes of wild fish entrained during the pumping trials

Common Name	**Genus-Species**	**Fish (n)**	**Total Length (mm)**	**Mean Length (mm)**
White catfish	*Ameiurus catus*	287	34–398	159
Threadfin shad	*Dorosoma petenense*	11,858	17–182	94
American shad	*Alosa sapidissima*	1787	40–423	123
Splittail	*Pogonichthys macrolepidotus*	38	76–303	230
Yellowfin goby	*Acanthogobius flavimanus*	3,464	58–210	173
Tule perch	*Hysterocarpus traski*	13	92–178	139
Channel catfish	*Ictalurus punctatus*	97	40–403	130
Brown bullhead	*Ameiurus nebulosus*	3	71–332	229
Redear sunfish	*Lepomis microlophus*	5	116–240	197
Bluegill	*Lepomis macrochirus*	753	25–195	69
Chinook salmon fry	*Oncorhynchus tshawtscha*	712	19–45	35
Chinook salmon	*Oncorhynchus tshawtscha*	111	55–220	144
Delta smelt	*Hypomesus transpacificus*	108	23–75	50
Striped bass	*Morone saxatilis*	3,292	76–349	112
Golden shiner	*Notemigonus crysoleucas*	107	50–194	120
Red shiner	*Notropis lutrensis*	2	43–52	48
Bigscale logperch	*Percina macrolepida*	9	89–103	94
Carp	*Cyprinus carpio*	1	257	257
Black crappie	*Pomoxis nigromaculatus*	24	71–278	138
Inland silverside	*Menidia beryllina*	376	28–102	61
Largemouth bass	*Micropterus salmoides*	70	63–280	161
Prickly sculpin	*Cottus asper*	8	41–112	85
Steelhead trout	*Oncorhynchus mykiss*	60	165–360	255
Shimofuri goby	*Tridentiger trigonocephalus*	4	107–141	116
Smallmouth bass	*Micropterus dolomieu*	1	107	107
Mosquitofish	*Gambusia affinis*	25	20–50	33
Pacific lamprey	*Lampetra tridentata*	27	97–153	131
Pumkinseed	*Lepomis gibbosus*	2	51–125	88
Warmouth	*Lepomis gulosus*	3	44–71	53
Threespine Stickelback	*Gasterosteus aculeatus*	1	45	45

CONCLUSIONS

The results presented here suggest that the Hidrostal pump was an effective and safe transport for striped bass, steelhead, delta smelt, and wakasagi of various sizes and densities over a wide range of environmental conditions. We reported similarly high survival and low injury and descaling of Sacramento splittail and chinook salmon subject to Hidrostal pump passage (Helfrich et al., 2001).

Other authors have reported similar results among different species of fish. Rodgers and Patrick (1985) used a small (10-cm diameter) Hidrostal pump and reported low (< 2 percent) mortality for steelhead, but higher mortality for yellow perch, *Perca flavescens,* (0–29 percent) and alewife, *Alosa pseudoharengus,* (5–22 percent), depending on pump speed and transport times. Patrick and McKinley (1987) found no mortality and minimal (< 3 percent) injury for American eels, *Anguilla rostrata*, when passed through a small (15 cm diameter) Hidrostal pump. Wagner and Driscoll (1994) compared the stress response in cutthroat trout, *Oncorhyncus clarki*, in three fish loading systems—including a small helical pump, a conveyer system—and dip netting, and reported only minor differences in plasma cortisol, glucose, and chloride concentrations. Weber et al. (2002) reported minor (50 ng/mL) cortisol stress response in juvenile chinook salmon 3 h after passage through a 91-cm diameter Hidrostal pump, but also demonstrated that most of the measured stress response was due to capture, confinement, and transport of the fish prior to pump passage. McNabb et al. (2003) observed high immediate survival (> 96.5 percent) and low injury (< 2.4 percent) of juvenile chinook salmon passed through a large (91-cm diameter) experimental Hidrostal pump.

Pump size may play an important role in quickly passing high densities of adult fish safely. The 41-cm Hidrostal pump used in this study was the largest commercial model available and nearly twice as large as those typically used in aquaculture. Theoretically, larger size pumps should be less damaging than smaller ones because of the reduced contact surface relative to the volume of water pumped and the resulting lower probability of abrasion and impact. However, McNabb et al. (2003) found that rainbow trout passing through a 91-cm Hidrostal pump had lower survival rates and similar injury rates, compared to those we report here for striped bass and steelhead passing through a 41-cm Hidrostal pump. Beyond a minimum pump size other factors, including pump speed, fish species, fish size, fish density, fish health, water quality and other environmental variables, play a role in survival and injury of pump-harvested fish.

Several authors have reported that survival and injury varied with impeller speed, particularly for small Hidrostal pumps operated at high pump speed (Baldwin, 1973, Grizzle et al., 1992; Grizzle and Lovshin, 1994). Rodgers and Patrick (1985) reported high mortalities of yellow perch, *Perca flavescens*, and alewife, *Alosa pseudoharengus*, at pump speeds above 600 r/min. Grizzle and Lovshin (1994) found increased skin hemorrhage in channel catfish, *Ictalurus punctatus*, at pump speeds above 385 r/min. They and others have emphasized the importance of determining optimum pump speed for each circumstance, size, and species of fish. In contrast, we found no significant relationship between pump speed or discharge and fish survival at speeds up to 600 r/min and discharges up to 299 L/s. When our Hidrostal pump was operating within its engineered optimum velocity (400–600 r/min) and discharge (100 to 400 L/s), the resultant hydraulic conditions proved to be acceptable and fish mortality, descaling, and injury rates were low.

Overall, 357 wakasagi (29 trials), 371 delta smelt (34 trials), 971 steelhead (86-trials), and 2,235 striped bass (169 trials) were passed through the pump. Fish density did not influence survival or injury rates over the injected densities (4 to 42 fish per trial). We observed little mortality and injury, even when entrained wild fish substantially increased the fish densities pumped. Sensitive species like delta smelt (Swanson et al., 1996) and wakasagi showed no density effect, although only relatively low densities of these small fish were injected. Patrick and McKinley (1987) reported no mortality and < 3 percent injury to American eels pumped at densities of 340 to 5,500 fish/m^3, despite a fish:water ratio of 80:20, which exceeded the optimum efficiency ratio (40:60 solid to liquid) for a 15-cm pump. Although we did not determine the fish passage capacity of this pump, lower survival and greater injury rates may be experienced when dense schools of fish larger than 40 cm are injected through the pump. However, a large American eel (76 cm total length), was passed undamaged.

Species-specific responses to pump passage were similar throughout the trials. Survival rates (immediate and 96-h) for steelhead (100 and 99 percent) were not significantly higher ($P < 0.05$) than those for striped bass (99 and 95 percent). Mean immediate survival percentages for pumped wakasagi and delta smelt were similar (97 and 99 percent, respectively), whereas 96-h mortality differed (96 and 87 percent, respectively). Body injury percentages were similar for wakasagi and delta smelt.

Wakasagi may not be an appropriate surrogate species for testing the sensitivity of delta smelt to pump passage or other impacts. In terms of mortality, wakasagi appeared to be a hardier species (subspecies), slightly more tolerant to pump passage than delta smelt.

The Hidrostal pump used in this study was designed to minimize shear, pressure changes, turbulence, and abrasion and, indeed, did not damage fish. The majority (> 99 percent) of striped bass, steelhead, delta smelt, and wakasagi pumped in this study were live and healthy. Low mortality, skin bruising, discoloration, and fin fraying occurred during pumping, even for sensitive species such as delta smelt (Swanson et al., 1996) and wakasagi. The hidrostal pump used in this study transported fish with high survival and low injury.

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