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Managing Water in the West

Increasing Juvenile Fish Capture Efficiency at the Tracy Fish Collection Facility: An Analysis of Increased Bypass Ratios During Low Primary Velocities

Volume 35

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14. ABSTRACT

The Tracy Fish Collection Facility (TFCF), located in the southern portion of the California Sacramento-San Joaquin Delta, is a behavioral screening facility intended to divert and salvage fish prior to encountering the Bill Jones Pumping Plant (BJPP). During routine operation, the BJPP in conjunction with the California State's Harvey O. Banks Pumping Facilities, alter southern delta water flows and attract juvenile fish intending to migrate to the ocean. To combat this potential problem, the California State Water Resources Control Board initiated the Vernalis Adaptive Management Program in 2000, which experiments with reduced water exports during critical down-stream migrations of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Reduced exports from the BJPP result in low primary velocities at the TFCF, which in-turn create water hydraulics outside of operational criteria. It was determined during times of low primary velocities, by increasing the primary bypass ratio, secondary channel velocity criteria (3.0–3.5 ft/s, 0.9–1.1 m/s) and secondary bypass ratio criteria ($\geq$ 1.0) could be achieved. In addition, the largest primary bypass ratios tested provided the highest recovery rate of juvenile Chinook salmon and Sacramento splittail (*Pogonichthys macrolepidotus*).

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Increasing Juvenile Fish Capture Efficiency at the Tracy Fish Collection Facility: An Analysis of Increased Bypass Ratios During Low Primary Velocities

Volume 35

by

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TRACY FISH FACILITY IMPROVEMENT PROGRAM

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COVER

Fish photography by René Reyes, Tracy Fish Collection Facility, Tracy, California.
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EXECUTIVE SUMMARY

U.S. Department of the Interior, Bureau of Reclamation's (Reclamation) Tracy Fish Collection Facility (TFCF), located in the southern portion of the California Sacramento-San Joaquin River Delta, is a fish salvage facility intended to remove fish from approximately 4,600 cubic feet per second (129 cubic meters per second) of water pumped by the Bill Jones Pumping Plant (BJPP). Fish are extracted from the water and condensed into holding tanks using louvers, a behavioral barrier. Routine BJPP operations in conjunction with California State's Harvey O. Banks Pumping Facility alter south Delta water flows, potentially attracting out migrating Chinook salmon (*Oncorhynchus tshawytscha*). To reduce the impact of this potential problem, the California State Water Resources Control Board initiated the Vernalis Adaptive Management Program in 2000, which experiments with reduced water exports during critical downstream migrations of juvenile Chinook salmon. The reduction in pumping results in a TFCF primary channel velocity that is < 1 foot per second (ft/s), (0.3 meter per second [m/s]), which is significantly outside of the hydraulic criteria set in TFCF operational criteria. The slow primary channel velocity makes it nearly impossible to meet criteria for the primary bypass ratio (BR; 1.0–1.6) and the secondary channel velocity (3.0–3.5 ft/s, 0.9–1.1 m/s) simultaneously. The purpose of this study was to determine how sensitive capture efficiency is to changes in primary BR during VAMP. During our studies, secondary channel velocity criteria and secondary BR criteria (≥ 1.0) could be maintained, in most cases, if the primary BR was drastically increased (up to 7.2). In addition, as primary BR increased, recovery rate of juvenile Chinook salmon and Sacramento splittail (*Pogonichthys macrolepidotus*) increased. Bypass mouth water velocity was also determined to be linearly related to capture efficiency for both species tested, and for each 1.0 ft/s (0.3 m/s) increase in bypass mouth velocity, capture efficiency increased 14 percent. Based upon our results, we recommend when forced to operate the TFCF with low primary velocities, secondary channel velocity should meet salmon criteria (3.0–3.5 ft/s, 0.9–1.1 m/s) and primary BR should be allowed to increase as high as necessary.

INTRODUCTION

In combination California's two primary water pumping facilities, the Federal owned Bill Jones Pumping Plant (BJPP) and State owned Harvey O. Banks Delta Pumping Plant, export approximately 6 million acre feet of water annually from the Sacramento-San Joaquin River Delta (SSJD) to central and southern California for agriculture, municipal, and industrial needs (Figure 1). To reduce the number of fish entrained into the pumps; both facilities are equipped with fish salvaging facilities upstream from the canals leading to the pumping plants. The Federal Tracy Fish Collection Facility (TFCF) and the State Skinner Delta Fish Protective Facility use behavioral louver-bypass systems to guide fish out of canals and into collection tanks, where they are held until transported back to the central SSJD (Figure 2).

When State and Federal pumping facilities are running at normal capacity, they move enough water to alter water flow patterns in the south Delta by approximately 20,000 cubic feet per second (ft^3/s; 560 cubic meter per second [m^3/s]). Consequently, pumping is creating flow patterns in the south Delta that mimic potential oceanic pathways for migratory fish. Juvenile fish species, such as Chinook salmon (*Oncorhynchus tshawytscha*), may follow these velocity cues in an attempt to reach the Pacific Ocean, but instead migrate to the southern portion of the SSJD (Cada *et al*., 1994; Giorgi *et al*., 1997).

The Vernalis Adaptive Management Program (VAMP) was initiated in 2000 by the California State Water Resources Control Board to study the effects of reduced pumping regimes on juvenile salmon migrating out of the San Joaquin River. VAMP is an experiment to reduce Federal and State water exports for approximately 1 month annually, between April and June, in an attempt to reduce entrainment losses of juvenile migratory salmon during critical downstream movements. During the VAMP period, lowered export rates create low water velocities (< 1 ft/s, 0.3 m/s) through the TFCF primary channel because fewer pumps are in operation at the BJPP. This could cause the salvage efficiency at the TFCF to decline because it is impossible to keep the primary bypass ratio (BR) and secondary channel velocity in criteria simultaneously.

Efficiency of louvering systems to properly guide Chinook salmon and striped bass (*Morone saxatilis*) through each fish collection facility is strongly dependent on water velocity in the facility's primary and secondary channels (Bates, 1960; CDWR, 1963; CDWR, 1973). In addition, achieving an appropriate BR, defined as the ratio of the water velocity entering the bypass openings to the average channel velocity, is critical in guiding fish to enter the bypass tubes. Designer's criteria for developing the TFCF required velocity in the mouth of the bypass not exceed the velocity approaching the bypass by more than 1 ft/s (0.3 m/s) (Bates and Visonhaler, 1957). BR criteria have been tested extensively, but most tests have stayed within a range of 1.0–3.0 (Bates, 1960; CDWR, 1963; CDWR, 1973). A BR below 1.0 or excessively high may reduce fish collection efficiency for some species (Bates and Visionhaler, 1957). However, little research has been completed at higher BR.

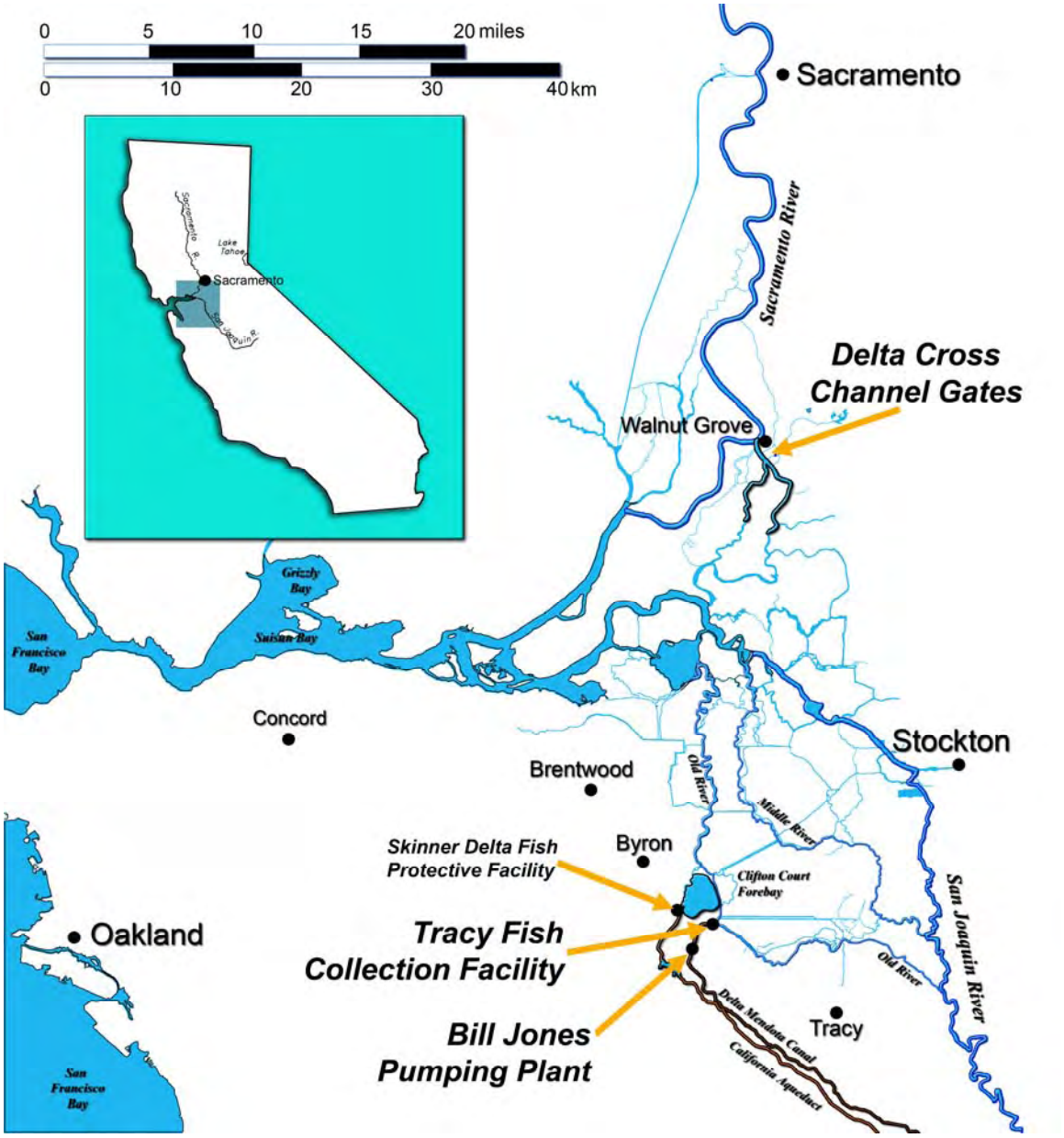


FIGURE 1.—Location of the Tracy Fish Collection Facility in the southern portion of the Sacramento-San Joaquin River Delta, California.

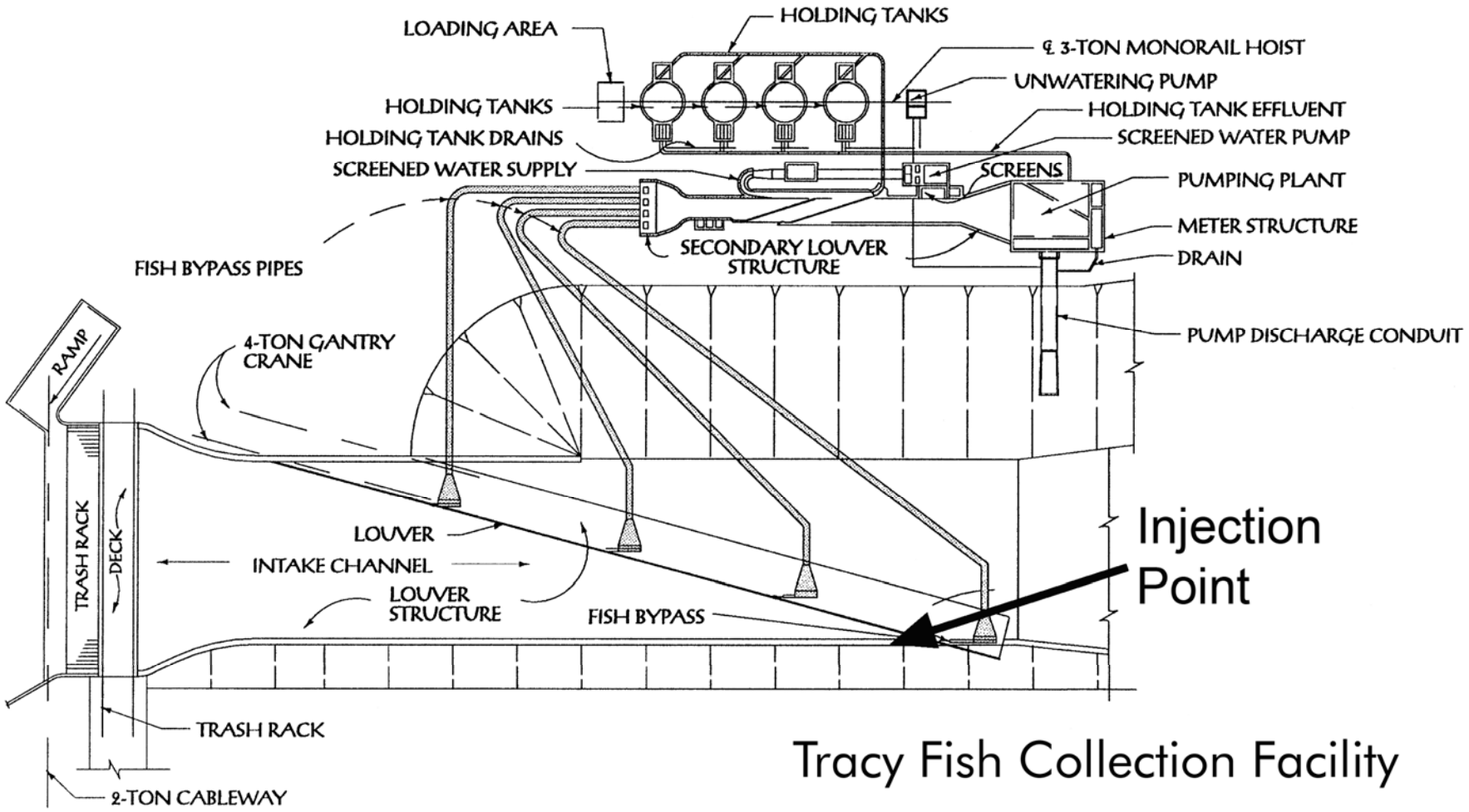


FIGURE 2.—Planned view schematic of Reclamation's Tracy Fish Collection Facility.

Since water velocity and BR are critical components that assure fish facilities run properly, special operating guidelines have been developed (SWRCB, 1978; Table D-1485). Primary velocity is controlled by the BJPP, not TFCF pumps, and there are no legal requirements for maintaining a set primary velocity.

The minimal operational criteria as stipulated by D-1485 are:

- Primary BR always > 1.0 (average primary bypass entrance velocity/average primary channel velocity)
- Secondary BR always > 1.0 (average secondary bypass entrance velocity/ average secondary channel velocity)
- Striped bass criteria: Secondary channel velocity < 2.5 ft/s (0.7 m/s), 1.5 ft/s (0.46 m/s) preferred, June 1 through August 31
- Chinook salmon criteria: Secondary channel velocity 3.0 to 3.5 ft/s (0.9–1.1 m/s) February 1 through May 31

When the TFCF primary channel is running below normal during VAMP (< 1 ft/s, 0.3 m/s) it is impossible to meet all regulatory flow and BR requirements. In fact, if either primary BR or secondary velocity is in criteria, the other will be severely out of criteria. For example, to achieve the recommended primary BR (~1.0 to 1.6), when the primary channel is 18 ft (5.5 m) deep, water velocity in the secondary channel must be maintained at 0.3–0.5 ft/s (0.09–0.15 m/s), which is severely below recommended criteria 3.0–3.5 ft/s (0.9–1.1 m/s).

Two species of concern salvaged at SSJD fish collection facilities during VAMP are Sacramento splittail (*Pogonichthys macrolepidotus*) and Chinook salmon. Juvenile life stage of these species were selected for study as they are readily available, commonly salvaged in spring and early summer, native to the SSJD, and have been involved historically in setting facility criteria. The splittail is a large cyprinid (> 30 centimeter [cm] fork length [FL]) endemic to the San Francisco Bay-Delta-River system, and considered a species of special concern (Moyle, 2002). The Central Valley spring and winter run Chinook salmon are currently listed by both State and Federal agencies as threatened and endangered, respectively.

The primary objective of this study was to determine if primary BR influences primary channel louvering efficiency of juvenile splittail and Chinook salmon during VAMP. Our second objective was to determine if depth fish encountered the louver-bypass system influenced louver efficiency. The third objective was to measure vertical velocity profiles at varying distances upstream from the bypass entrance to see if changing BR skewed velocity profiles.

METHODS

Testing Limitations

The louver-bypass efficiencies generated from this study are not intended to reflect salvage efficiency for all TFCF bypasses or the entire primary louver system; therefore, they will be called capture efficiency to reduce confusion about terminology. The capture efficiencies generated should only be used to compare treatments tested to determine if changing BR or insertion depth effects catch rate. Capture efficiency was also calculated with and without flushing bypass pipes, and it was assumed velocity in the bypass system was sufficient (> 7 ft/s [> 2.1 m/s]) during flushing to remove all fish holding their position under normal flow (0.25–7 ft/s [0.08–2.1 m/s]). During the flushing process, it was also assumed fish holding outside of the bypass were not entrained into the bypass. These are critical points to understand as the methods used in this experiment have limitations:

- only a small portion of the primary louver panel was used during testing
- fish were not permitted a significant acclimation period prior to approaching the louver and bypass
- fish may not have been at their natural depth when approaching the bypass entrance
- bubbles exiting the insertion pipe may have affected fish behavior and altered louver efficiency

Knowledge gained from this study should be utilized in designing an experiment on a larger scale, capable of reporting a more accurate estimation of primary louver efficiency during VAMP conditions.

Bypass Ratio

BR were calculated using the following equation:

$$\text{bypass ratio (BR)} = \frac{\text{average bypass mouth velocity}}{\text{average channel velocity}}$$

where average bypass mouth velocity is the water velocity at the entrance to bypass No. 4, and average channel velocity is the average water velocity in the TFCF primary channel. Four BR (1.1, 2.5, 5.3, and 7.2) were tested to determine if secondary velocity criteria could be reached without detriment to primary louver capture efficiency. These BR were selected to span the entire range of possible combinations available during VAMP, were above the

minimal 1.0 BR stipulated in the TFCF operating criteria, and were achieved by step-wise increases in the number of operational control pumps in the secondary channel.

Test Location and Equipment

All tests were conducted at the TFCF. The area in front of primary channel bypass No. 4, the furthest downstream bypass, was selected for the study because this location allowed for safe access for taking flow measurements and injecting fish (Figure 2). In addition, test fish released at this location would be less likely to swim out of our study area, as they were bordered by a concrete wall and louver panel. Further more, the concrete wall provided an attachment point for equipment to insert fish into the primary channel. Three fish insertion tubes, made from 3 inch (in; 7.6 cm) diameter schedule 80 PVC (polyvinyl chloride) pipe, were placed approximately 11 ft (3.35 m) upstream from the entrance to bypass No. 4 (Figure 3). The bottom of each pipe was at a unique depth below the water's surface: 2.75 ft (0.84 m), 8.75 ft (2.67 m), and 14.75 ft (4.50 m), when the primary channel depth was 20 ft (6 m). The goal was to inject fish at the top, middle, and bottom of the water column. However, the actual depth of injection varied as tide varied channel depth by ± 1.9 ft (0.6 m) over all experiments. The bottom of each tube extended out away from the wall 18 in (45 cm) and the discharge opening was oriented downstream. A forth insertion pipe was used to inject control fish directly into the mouth of the primary bypass at a depth of 3 ft (1 m) below the surface, and 3 ft (1 m) inside the opening. The control fish insertion pipe was constructed of 3 in (7.6 cm) diameter ABS (Acrylonitrile butadiene styrene) plastic pipe.

To retrieve fish after they passed through the bypass, a sieve net was anchored in the secondary channel. The sieve net (mouth: 68 in [173 cm] by 39 in [99 cm]; length: 360 in [914 cm]; mesh: 0.12 in [0.32 cm]) and frame constructed of 1.5 in (3.75 cm) diameter stainless steel pipe was deployed and attached to primary bypass opening No. 4 as it entered the secondary channel. Installing the sieve net required dewatering the secondary channel and bolting the frame in place. Similarly, checking the net for fish required lowering the secondary channel.

Fish Source and Care

Juvenile Chinook salmon (71–90 millimeter [mm] FL) were obtained from the California Department of Fish and Game's Mokelumne River Fish Hatchery, one month before tests and were held at the Tracy Aquaculture Facility (TAF). Larval Sacramento splittail (51–65 mm FL) were obtained from the University of California, Davis' Fish Conservation and Culture Laboratory, located at the Skinner Fish Protection Facility, and reared to the late-juvenile life-stage at the TAF prior to testing. Fish were fed 1 mm Silver Cup salmon feed and were held in outdoor, flow-through tanks (198 gallons [gal], 750 liters [L]) supplied with well water (18.0 degrees Celsius [°C], 3,500 milligrams per liter [mg/L], NaCl). They were reared in appropriate water quality as recommended by Meade, 1989 (O_2 > 7 mg/L, unionized ammonia < 0.02 mg/L, nitrite < 0.2 mg/L, and 6.9 < pH < 7.8).

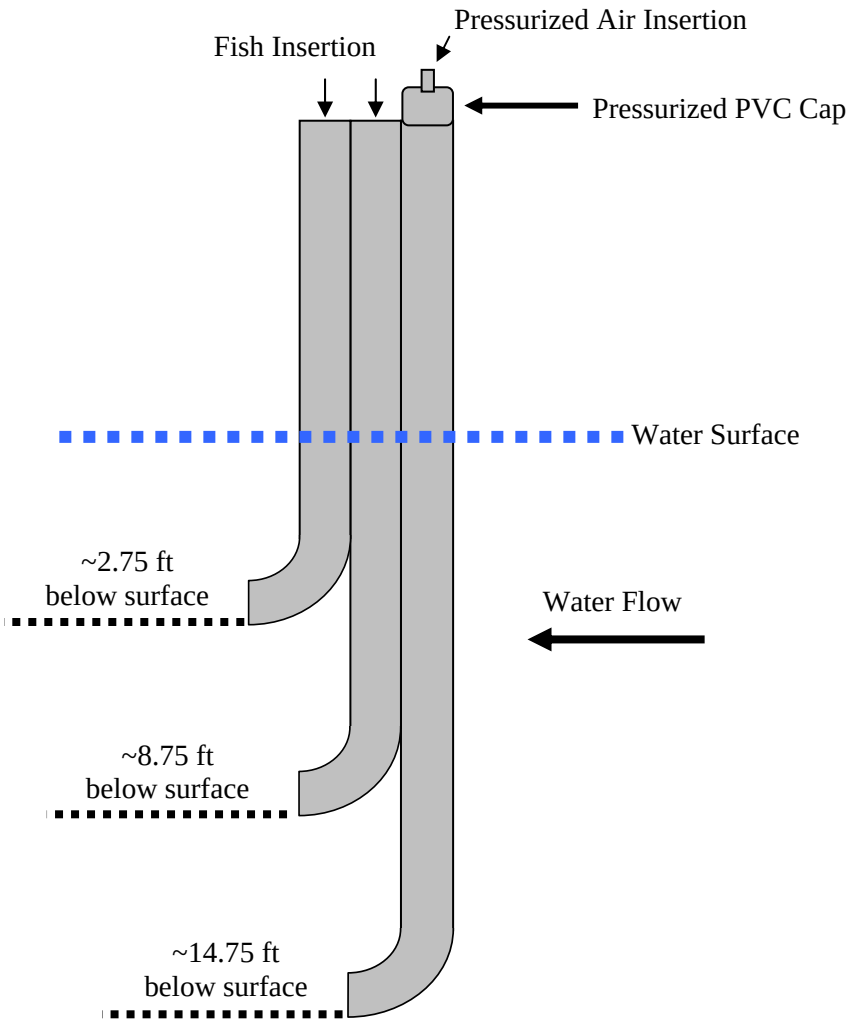


FIGURE 3.—Drawing of insertion tubes used for the insertion of fish.

Test fish were randomly assigned a treatment and placed into separate holding tanks (198 gal [750 L]) for tagging. Tags were applied to fish so that treatment groups could be identified by tag location and tag color. Fins (dorsal, anal, and caudal) were tagged with fluorescent microbeads (*BMX*™ biobead colors pink, yellow, blue, white; New West Technology, Arcata, California) three weeks prior to insertions, allowing the selection of test fish within a limited size range (50–60 mm FL) ensuring uniformity among treatments. However, fish lengths were not recorded prior to experimentation, as it was important to minimize handing stress prior to insertion. Test fish were acclimated (< 0.5 °C/day) to experimental water temperatures (16 °C) one week prior to insertion experiments.

Hydraulics

TFCF flow meters were used to establish appropriate BR for each replicate. These meters measured primary channel discharge and bypass No. 4 discharge, and average primary velocity was calculated by dividing primary channel discharge by primary channel depth and width (84 ft). Average bypass mouth velocity was calculated by dividing bypass No. 4 discharge by depth and width of the paypass opening (0.5 ft).

More precise channel water velocity measurements were taken inside and outside of the entrance to bypass No. 4 using a portable electronic flow meter (Marsch-McBirney, model 201D, Frederick, Maryland) and was calibrated internally prior to each treatment. The flow meter was attached to a 20-ft (6.7-m) by 0.5-in (1.25-cm) diameter steel rod during flow measurements. Water velocity was recorded at 1 ft intervals from 1 ft (0.3 m) under the surface downward to 15 ft (4.6 m). Deeper measurements were not possible with our equipment due to the length of the cord on the velocity meter. Some velocity profiles are only reported down to 9 ft, because at elevated water velocities measurements were not steady below this depth. In addition, higher velocities near the bypass entrances could not be collected due to problems with the flow meter support structure. Therefore, after the fisheries evaluation was complete a new support structure was built, and the flow meter was attached to an aluminum sled that was guided down a stationary guide beam anchored to the louvers in front of bypass No. 4. Three additional profiles were measured with the new equipment at BR = 6.1, 8.3, and 10.5 so missing velocity profiles could be estimated. Vertical velocity profiles were measured at 0, 1, 2, 3, 6, and 9 ft (0, 0.3, 0.6, 0.9, 1.8, and 2.7 m) upstream from bypass No. 4 in the center of the channel.

Fish Insertion Experiments

In all, 96 treatment and 24 control replicates were completed at TFCF primary bypass No. 4, between May 12 and May 20, 2005, to measure the effects of primary BR on Chinook salmon and Sacramento splittail capture efficiency. Twelve treatment (four replicates at three different depths in front of the bypass) and three control replicates (inside the bypass near the surface) were completed at each BR (1.1, 2.5, 5.3, 7.2).

Tagged fish were counted and transferred via water-to-water into 5-gal (18.9-L) buckets, with approximately 3 gal (11.4 L) of oxygen-saturated water, and transported to the insertion point (Figure 2). All fish were swimming and appeared healthy prior to insertion. Treatment groups were randomly selected, poured into the top of the insertion tube, and fish were forced out the bottom using compressed air supplied by a portable air compressor (Figure 4). A needle valve and flow meter allowed regulation of the speed at which the air entered each tube, so all tubes would evacuate at approximately the same rate. Each air ejection required 20 to 30 seconds depending on tube length.

FIGURE 4.—Reclamation fishery biologists transferring Chinook salmon into insertion tubes in front of bypass No. 4 at the Tracy Fish Collection Facility.

Control groups were inserted approximately 3 ft (0.9 m) into the bypass opening and approximately 3 ft (0.9 m) below the surface, 10 minutes (min) after the final treatment trial to verify fish in the bypass could be recovered with the collection equipment and flush. This was important, as it validated our experimental method and equipment. In addition, the control group indicated if fish could swim against a given velocity, out of the bypass, and into the primary channel. Compressed air was not used on control groups, and the insertion pipe was removed from the water once the insertion was complete.

Ten minutes was given between trials so fish had the opportunity to approach the bypass entrance prior to encountering a second group of fish. The sieve net was emptied 60 min after the final insertion at each BR tested (treatment and control groups). Once fish were removed from the net, primary bypass No. 4 valve was opened and closed, two additional times, in an attempt to flush fish residing in primary bypass No. 4 into the sieve net. Fish captured during these procedures were identified for marks, measured for FL (mm), kept separate, and labeled as flush group No. 1 or No. 2. For insertion experiments, capture efficiency was defined as the percentage of fish released that were recovered in the sieve net. Since the net was emptied three times it was possible to report the efficiency for first flush (treatment or control) and all flushes pooled together (treatment + flush or control + flush).

Water quality, operational, and hydraulic information was recorded 10 min before and 60 min after fish injections. Recorded data included primary BR, water temperature (°C), primary and secondary channel discharge, depth, and primary bypass flows in individual bypass tubes. Water temperature was measured with a YSI Model 85 oxygen meter (YSI Inc., Yellow Springs, Ohio), operational flow data was recorded using Accusonic (Accusonic Technologies, Wareham, Massachusetts) and Marsh-McBirney (Hach/Marsh-McBriney, Inc., Frederick, Maryland) flow meters, and primary water depth was recorded using a fiberglass tape measure (Keson, Waterville, Illinois).

Data Analysis

Hydraulic Analysis

As a means to demonstrate how different BR's, and the subsequent change in water velocity going into bypass No. 4, could be detected by fish at different distances upstream from the bypass entrance, vertical velocity profile graphs were developed for hydraulic flows associated with each BR gradient. A quantitative analysis using linear regression was performed on the vertical velocity field in the bypass entrance to measure if velocities were uniform from surface to bottom. Regression techniques were also used to estimate missing bypass mouth velocities at BR 5.3 and 7.2 during fish injections.

Fish Insertion Experiments

Prior to analyzing treatment effects, fish lengths were compared across treatments to test for size dependent differences. Fish lengths were not normally distributed based on an Anderson–Darling test ($P < 0.05$); therefore, lengths were compared using a nonparametric test (Kruskal-Wallis, $\alpha = 0.05$).

Control and treatment capture efficiency were analyzed separately as there were large differences in the number of replicates, the number of fish injected, their release location and release depth. Capture efficiency in control and control + flush groups for salmon and splittail were transformed using arcsine (sqrt[X]) and then compared with a one-way ANOVA (analysis of variance) and a multiple means comparison test (Tukey's test, $\alpha = 0.05$).

Treatment and treatment + flush capture efficiency at each depth, and all depths combined did not display normality (Anderson–Darling test, $P < 0.05$) or homogeneity of variance (Levene's test, $P < .05$), and was therefore, analyzed using a nonparametric alternative (Kruskal Wallis, $\alpha = 0.05$). For comparing multiple medians, Dunn's test was used, setting the experimental-wise error rate at 0.05, and Bonferroni individual alpha at 0.002 (α /n).

To predict how an increase in bypass mouth water velocity affected capture efficiency of both species, a least squared linear regression analysis was performed using treatment and treatment + flush capture efficiency data. A one-way ANOVA was used to assess the affect of increasing water velocity (slope) as well as the difference between linear regression lines for each species and treatment type (slope and y-intercept). Residuals

were inspected and coefficient of determination (R^2) were developed for each linear regression relationship as tools to aid in determining how well the equation of the regression line fit our data set.

RESULTS

Hydraulic Analysis

Vertical water velocity profiles in the primary channel at all seven BR values tested (1.1, 2.5, 5.3, 6.1, 7.2, 8.3, and 10.5) indicate as distance away from the entrance to bypass No. 4 increases, water velocities throughout the water column tend to be more uniform from top to bottom (Figures 5 and 6). Over all BR's tested primary channel depth ranged from 19.1 to 20.9 ft (5.8–6.4 m). Mean water velocity, for each vertical velocity profile, gradually increased the closer measurements were made to the bypass entrance (Figure 7). The closer measurements were taken to the bypass entrance and the faster water entered the bypass, the greater velocities were skewed from top to bottom, with velocities generally increasing with depth. This was most evident with the vertical velocity profile inside the mouth of the bypass (Figure 8). The slopes of water velocity profiles in figure 8 are significantly different ($P < 0.005$), and except at a BR of 2.5 ($P = 0.106$), are not uniform from top to bottom ($P < 0.05$) because the slope progressively increased as more water passed through the bypass.

Vertical velocity profiles in the mouth of the bypass for BR = 5.3 and 7.2 were not complete due to equipment failure; these velocity profiles were estimated based on the five vertical velocity profiles in Figure 8. Slopes and y-intercepts from each of the five linear regression lines were plotted vs. bypass flow (Figure 9). This allowed us to estimate slope and y-intercept of the two regression lines missing for BR = 5.3 and 7.2 (Figure 10). It is interesting to note in Figure 10, BR = 7.2 is at the top of the graph; however, this is not a mistake as average channel velocity (0.73 ft/s [0.22 m/s]) was highest during this experiment.

To better understand how BR affects capture efficiency, bypass mouth velocities were estimated at the depth of each fish insertion. This was accomplished by using regression lines in Figure 10 and knowing the exact depth fish were inserted after correcting for tidal influence. These data were incorporated into a regression analysis predicting fish capture efficiency in the fisheries section below. This evaluation assumes that test fish remained at their insertion depth when entering the bypass.

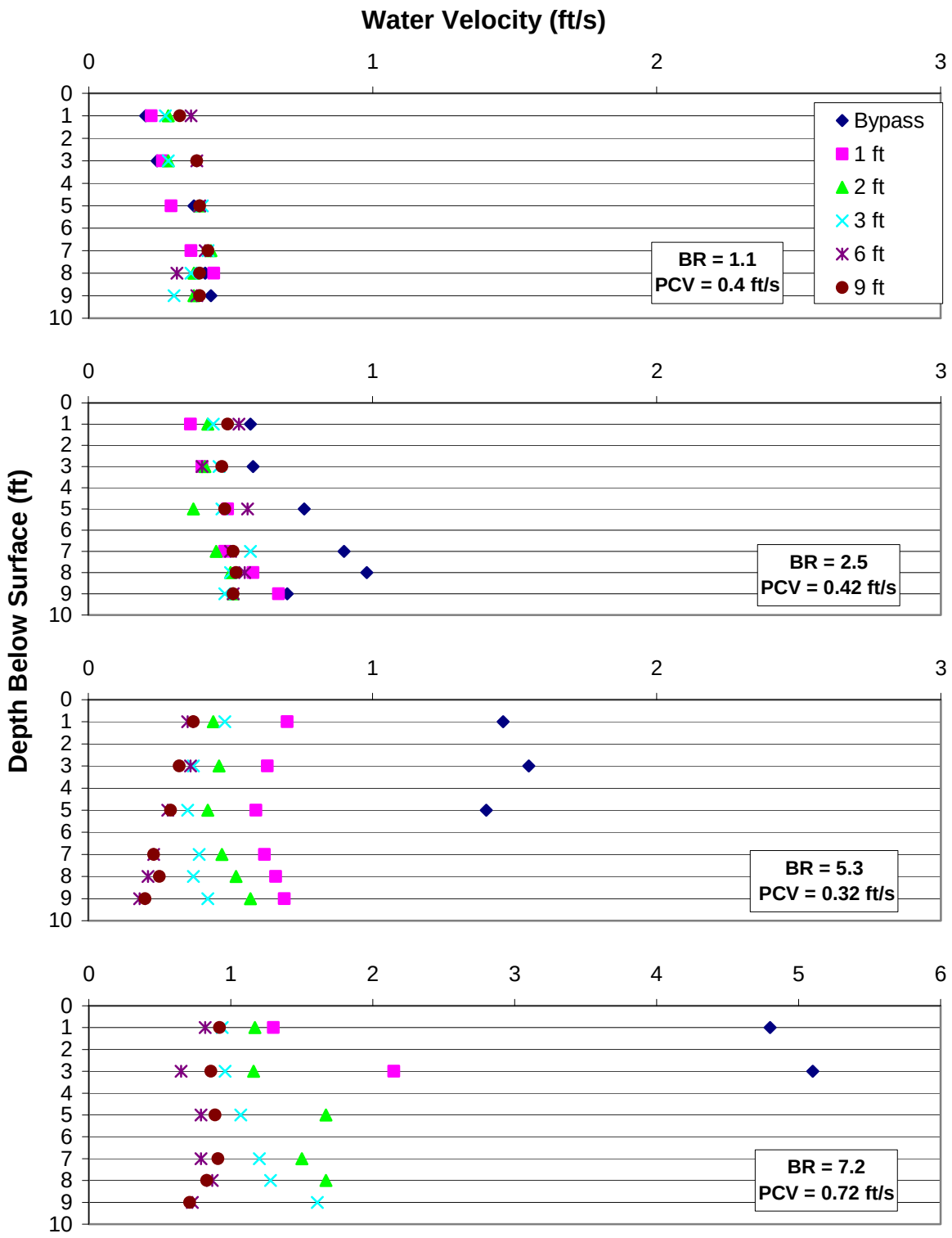


FIGURE 5.—Vertical velocity profiles measured prior to fish releases at various distances upstream from the bypass opening and across the front of the bypass opening under four unique bypass ratios (BR): 1.1, 2.5, 5.3, and 7.2, and primary channel velocities (PCV). Measurements were taken midway between the cement guide wall and the primary louver panel.

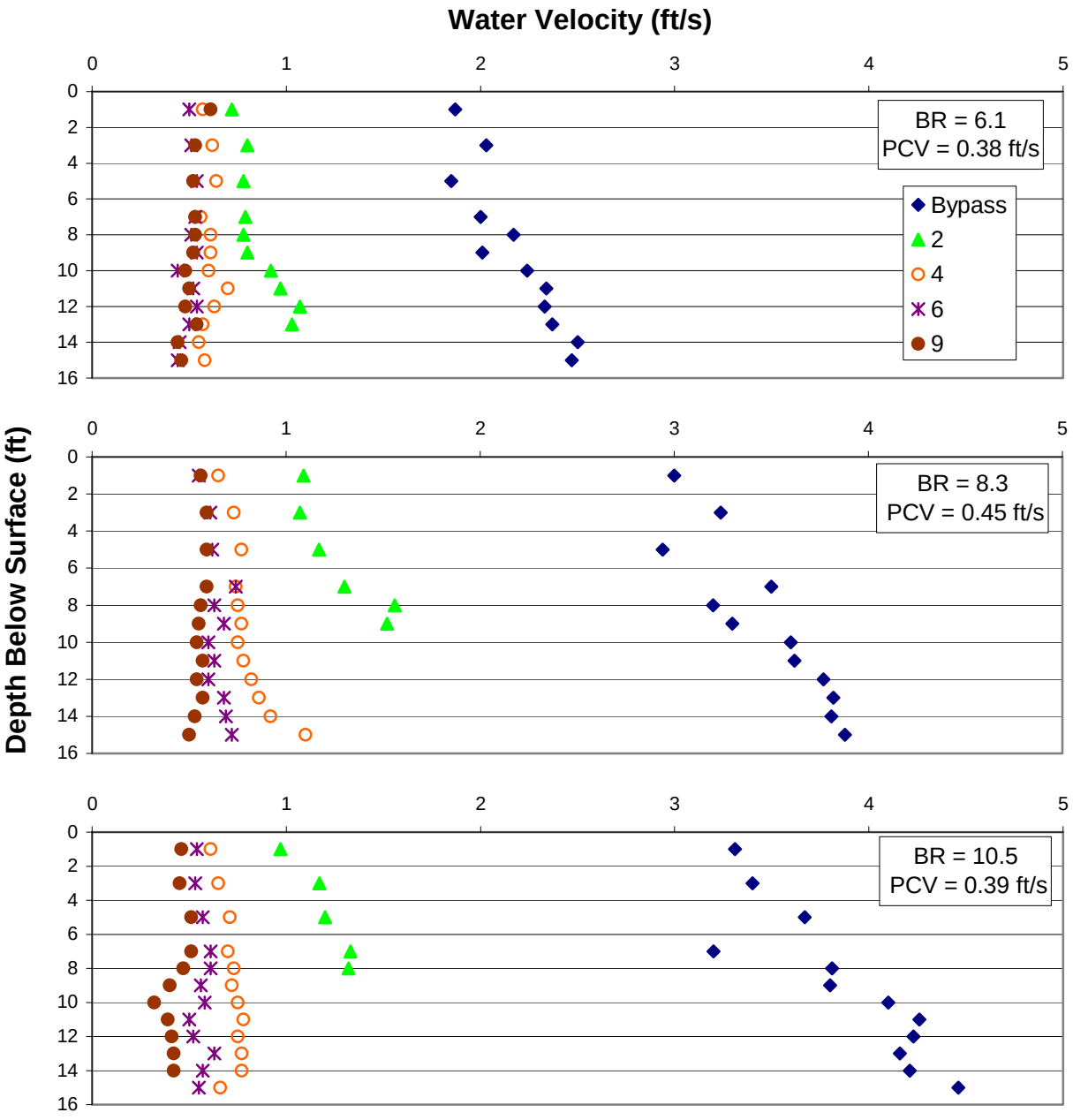


FIGURE 6.—Vertical velocity profiles measured during non-fish releases at 2, 4, 6, and 9 ft (0.6, 1.2, 1.8, and 2.7 m) upstream from the bypass opening and across the front of the bypass opening under three unique bypass ratios (BR): 6.1, 8.3, and 10.5. Measurements were taken midway between the cement guide wall and the primary louver panel when the primary channel velocity (PCV) was similar to the velocities during fish releases.

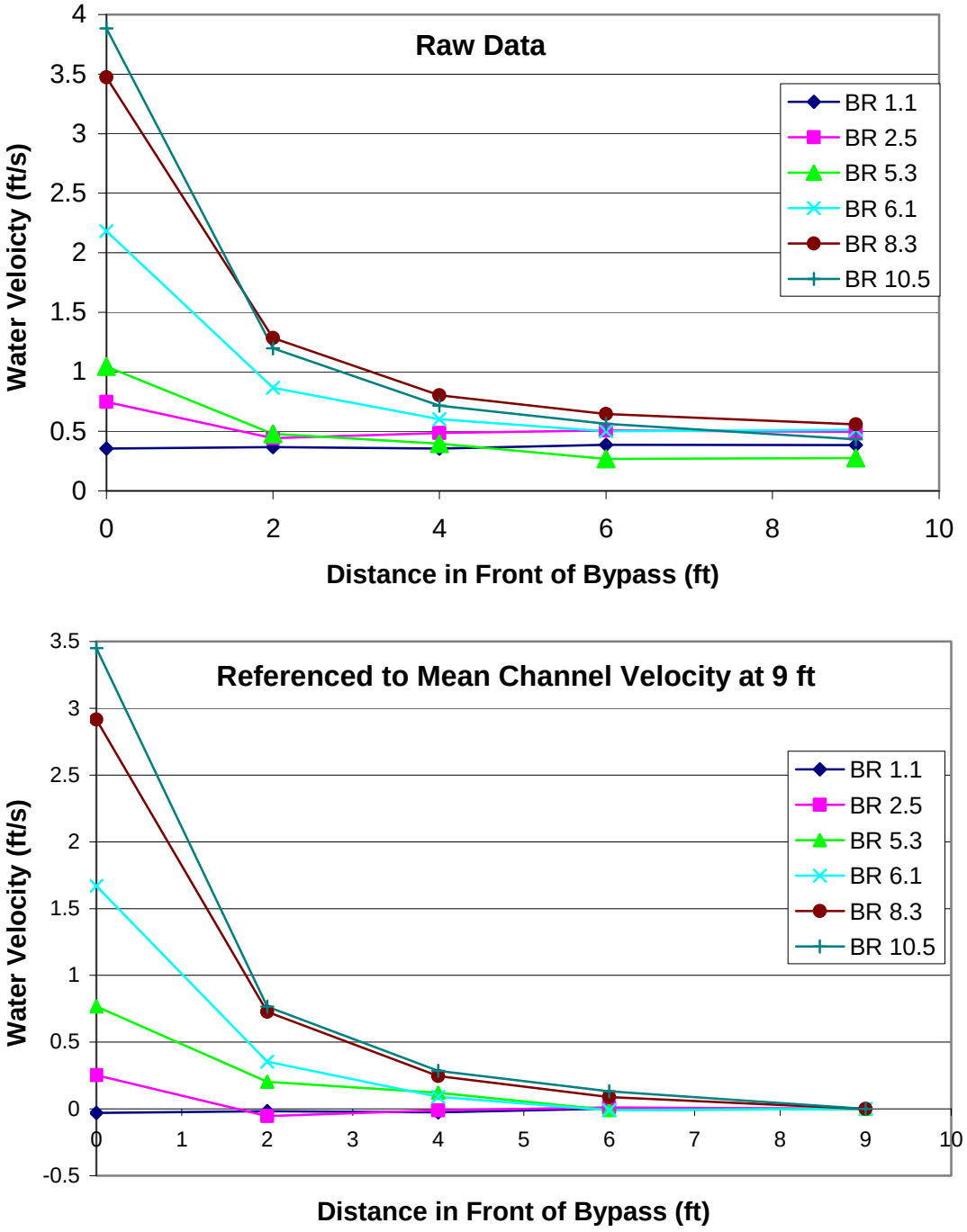


FIGURE 7.—Mean water velocities for each vertical profile taken at seven different bypss ratios (BR): 1.1, 2.5, 5.3, 6.1, 7.2, 8.3, and 10.2. Top graph shows raw data and the bottom graph show the same data that has been standardized relative to the channel velocity at 9 ft (2.7 m) in front of the bypass.

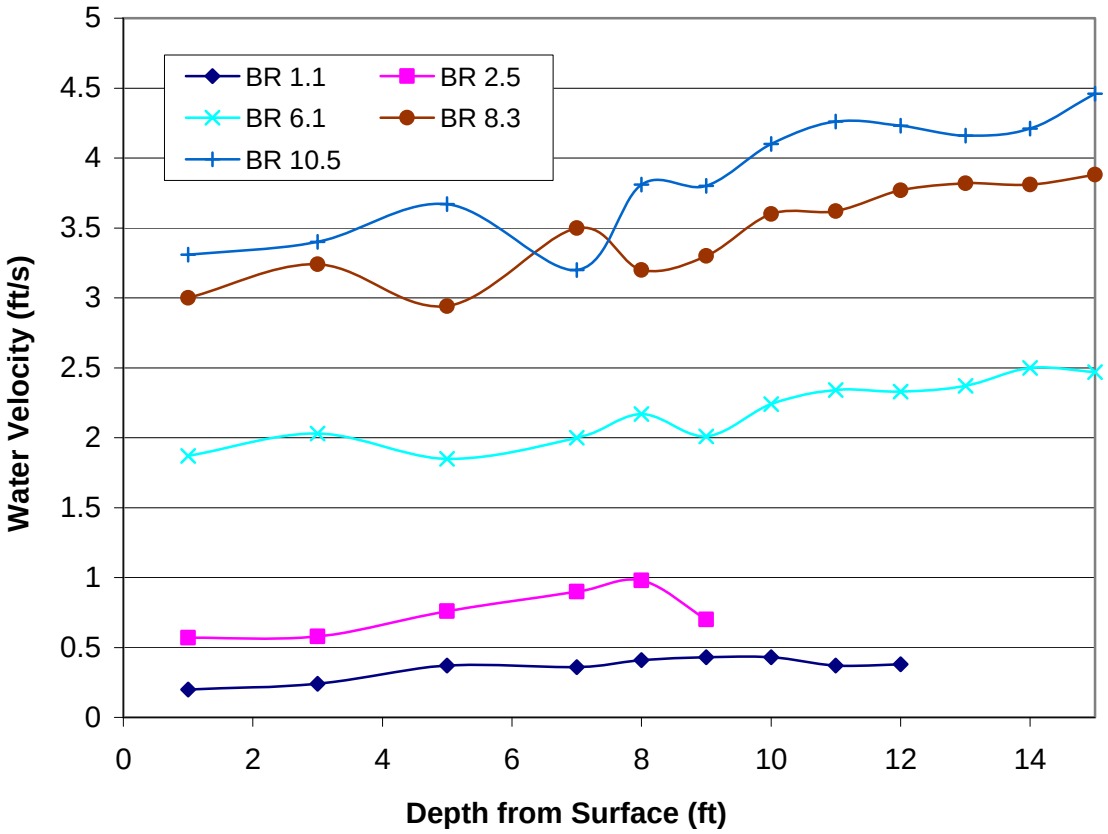
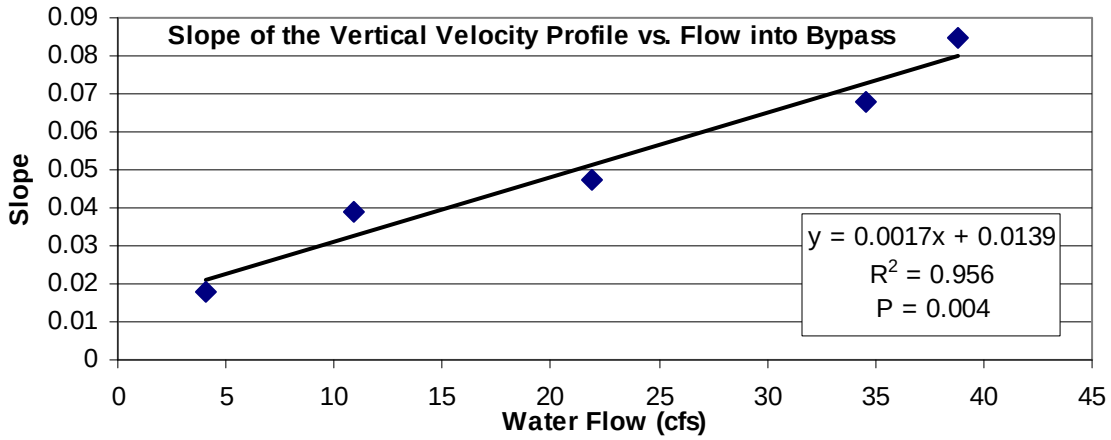


FIGURE 8.—Vertical velocity profiles in the mouth of bypass No. 4 at five bypass ratios (BR): 1.1, 2.5, 6.1, 8.3, and 10.5. Flows through the bypass were 4.1, 10.9, 21.9, 34.6, and 38.8 ft^3/s (0.1, 0.3, 0.6, 1.0, and 1.1 m^3/s), respectively.



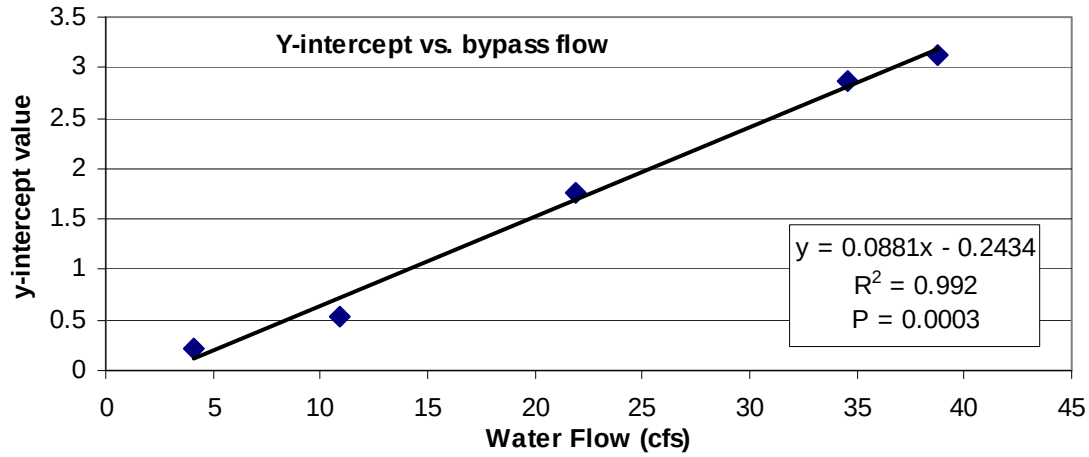


FIGURE 9.—Least squares linear regression lines generated to predict the slope and y-intercept of the missing bypass entrance velocity profiles for bypass ratios (BR) 5.3 and 7.2 during the fish release experiments.

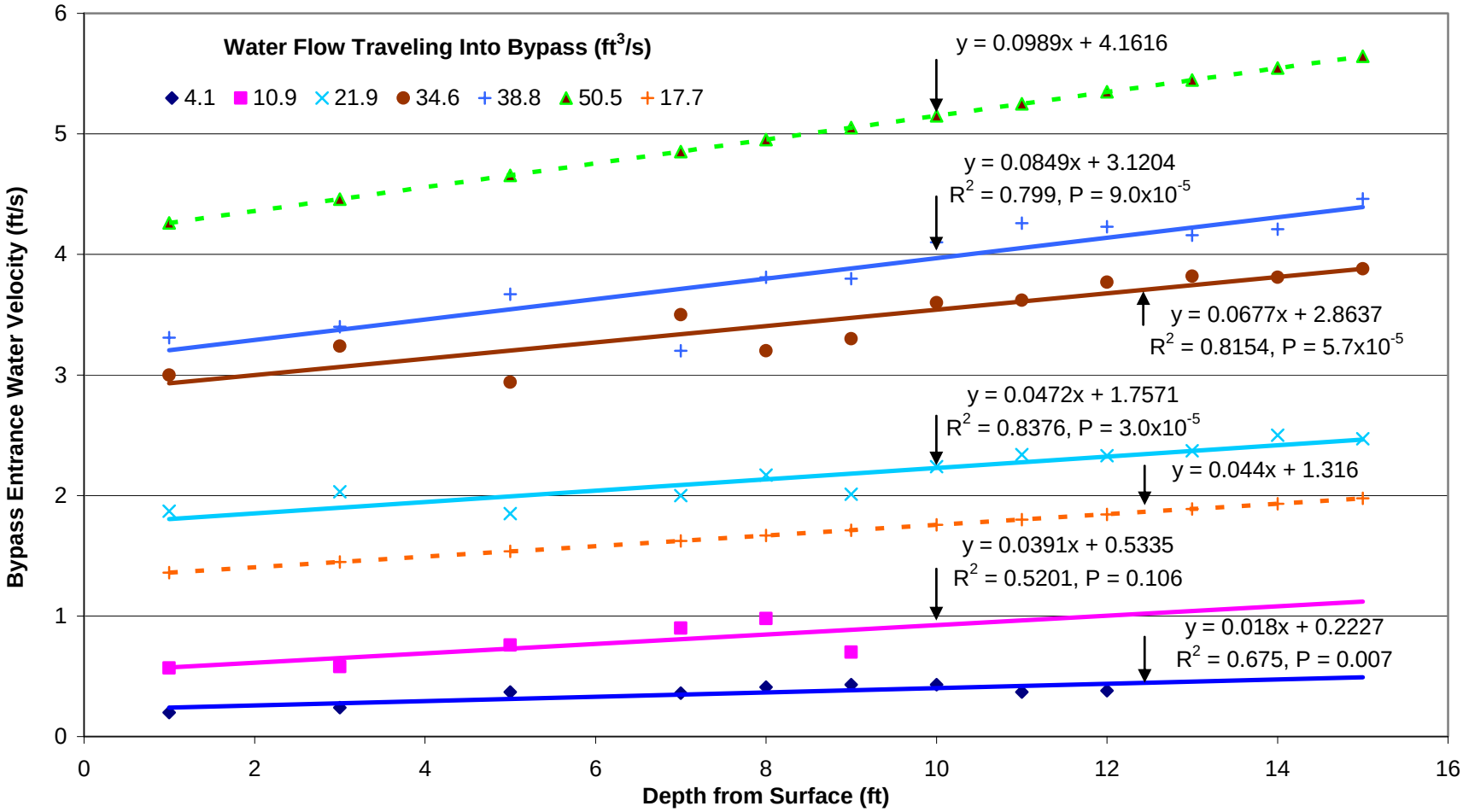


FIGURE 10.—Least squares linear regression lines for the water velocity profiles in the mouth of bypass No. 4 during the fisheries and non-fishery trials. The water flows of 4.1, 10.9, 17.7, 21.9, 34.6, 38.8, and 50.5 ft^3/s (0.1, 0.3, 0.6, 1.0, 1.1, 1.4 m^3/s) correspond with bypass ratios (BR) 1.1, 2.5, 5.3, 6.1, 8.3, 10.5, and 7.2, respectively. Dotted regression lines for BR 5.3 and 7.2 were estimated based on data from field measurements (solid regression lines).

Fish Insertion Experiments

Sacramento Splittail

There was no significant difference in the length of juvenile Sacramento splittail (2.1 ± 0.2 in, 54 ± 4.2 mm; mean ± standard deviation) comparing size classes against controls and treatments ($P > 0.05$). However, because fish measurements were conducted after each treatment, and uncaptured fish were not included in the data set, these results may be biased.

Capture Efficiency

Control Groups

Results of our splittail capture efficiency experiments indicate as BR increased, from 1.1 to 7.2, capture efficiency of control splittail increased and was different for each BR tested (Figure 11). When comparing control and control + flush groups at each individual BR, the only significant difference detected was at BR 1.1 ($P < 0.05$), and when comparing the difference in capture efficiency for control and control + flush across BR, there were no significant differences at any BR ($P > 0.05$; Figure 12). However, when exposed to BR of 5.3 and 7.2, the majority of treatment fish were captured prior to the flush.

Treatment Groups

At all BR tested, depth had no affect on capture efficiency of treatment and treatment + flush test groups ($P > 0.05$). This allowed us to combine replicates, averaging over fish insertion depth, and increase our sample size from 4 to 12. The results of pooled data for treatment splittail indicate capture efficiency of test fish tended to increase with increasing BR. However, this relationship was only significant when comparing capture efficiency at BR's 1.1 to 5.3 and 7.2, and 2.5 to 7.2 (Figure 13). There were no differences between treatment and treatment + flush groups when tested at each individual BR ($P < 0.05$). However when comparing the difference in capture efficiency for treatment and treatment + flush across BR, BR 5.3 was lower than 2.5, and BR 7.2 was lower than 1.1 and 2.5 ($P < 0.05$; Figure 14).

Data points collected from each insertion experiment were used to develop treatment and treatment + flush linear regression lines to measure the affect of increasing bypass mouth velocity on capture efficiency (Figure 15). For all linear regression relationships developed, coefficient of determination values were adequate (> 0.60) and validate modeling using a linear relationship. Linear regression lines for splittail treatment and treatment + flush groups had significantly different slopes ($P < 0.05$) and y-intercepts ($P < 0.05$). However, both linear regression lines suggest as bypass entrance water velocity increases, capture efficiency of juvenile splittail in both treatment and treatment + flush group's increase (Figure 15).

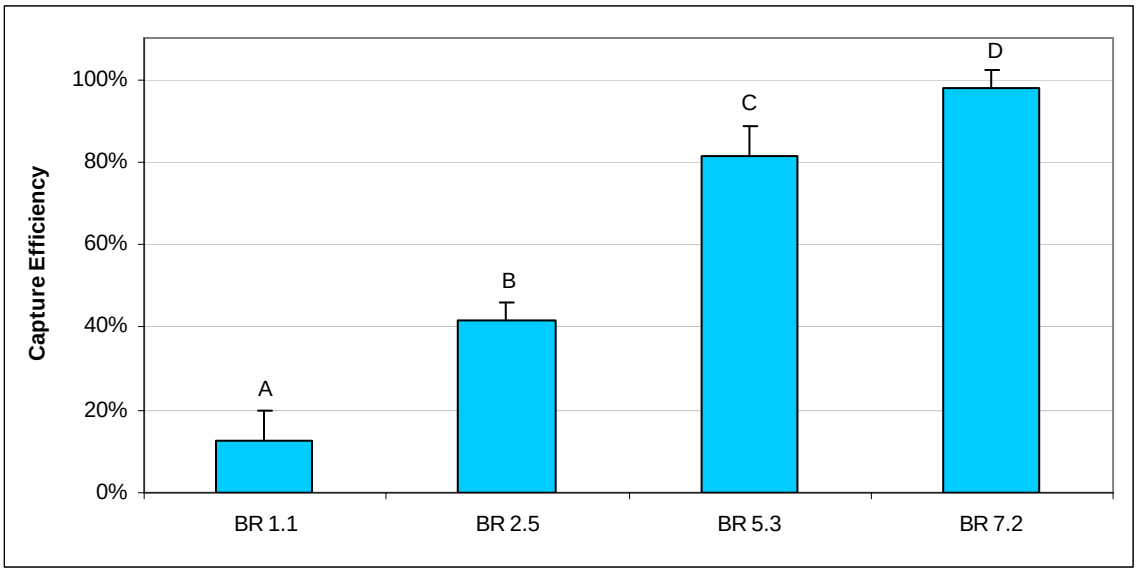


FIGURE 11.—Capture efficiency (mean ± 2SE) of Sacramento splittail control groups (n = 3), prior to flushing bypass No. 4, at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experimental-wise error rate = 0.05).

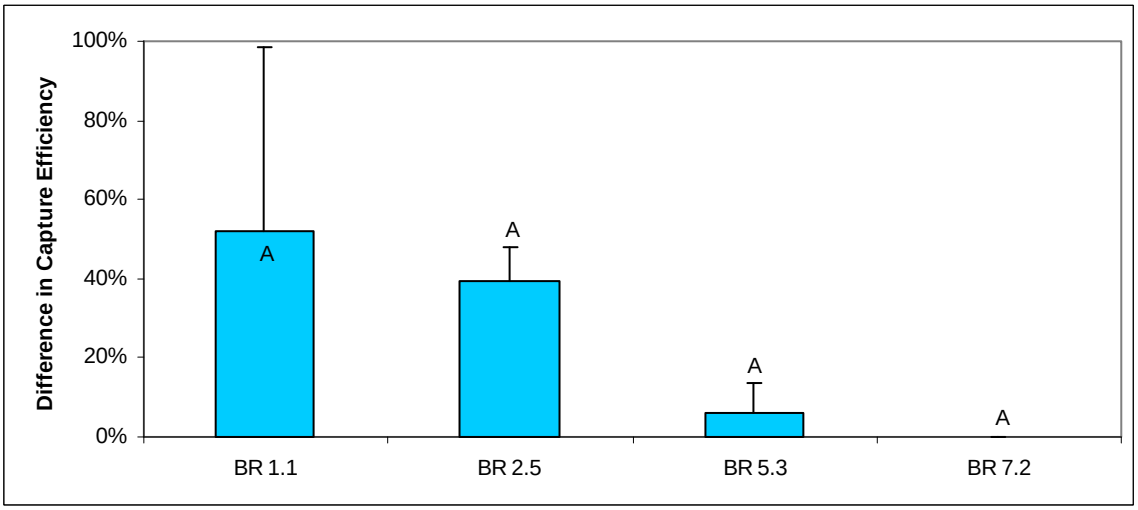


FIGURE 12.—Difference (mean ± 2SE) between Sacramento splittail control capture efficiency and control + flush capture efficiency at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experimental-wise error rate = 0.05).

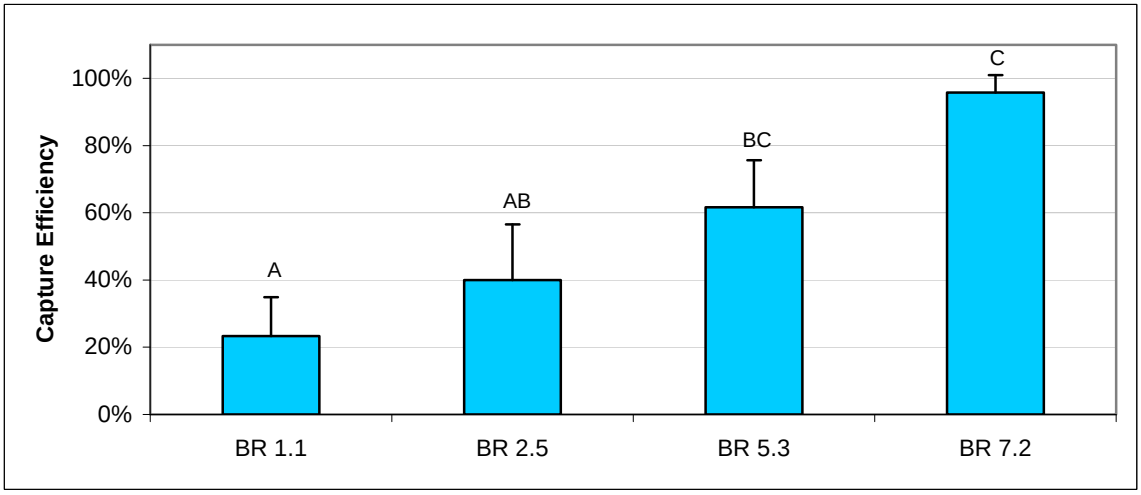


FIGURE 13.—Capture efficiency (mean ± 2SE) of Sacramento splittail treatment groups (n = 3), prior to flushing bypass No. 4, at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experimental-wise error rate = 0.05).

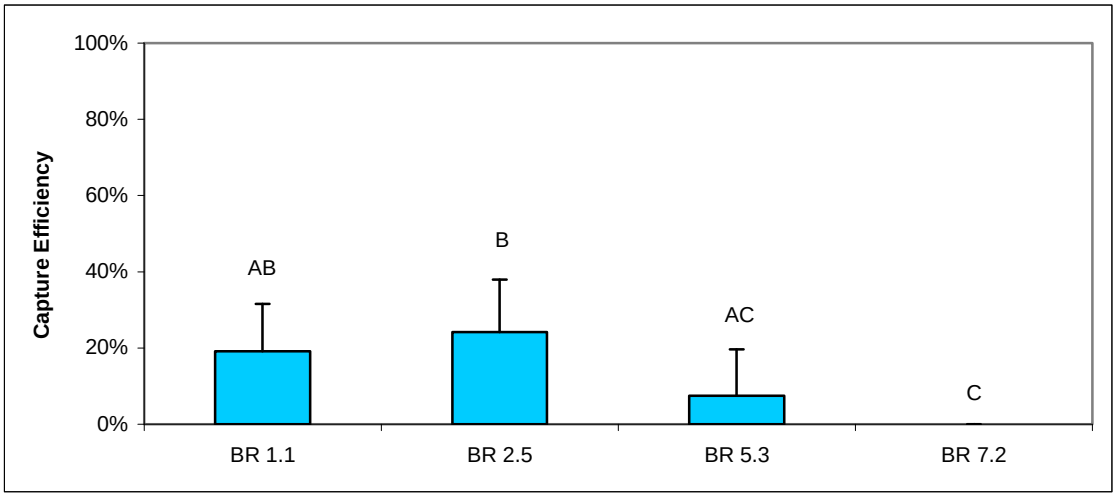


FIGURE 14.—Difference (mean ± 2SE) between Sacramento splittail treatment capture efficiency and treatment + flush capture efficiency at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experimental-wise error rate = 0.05).

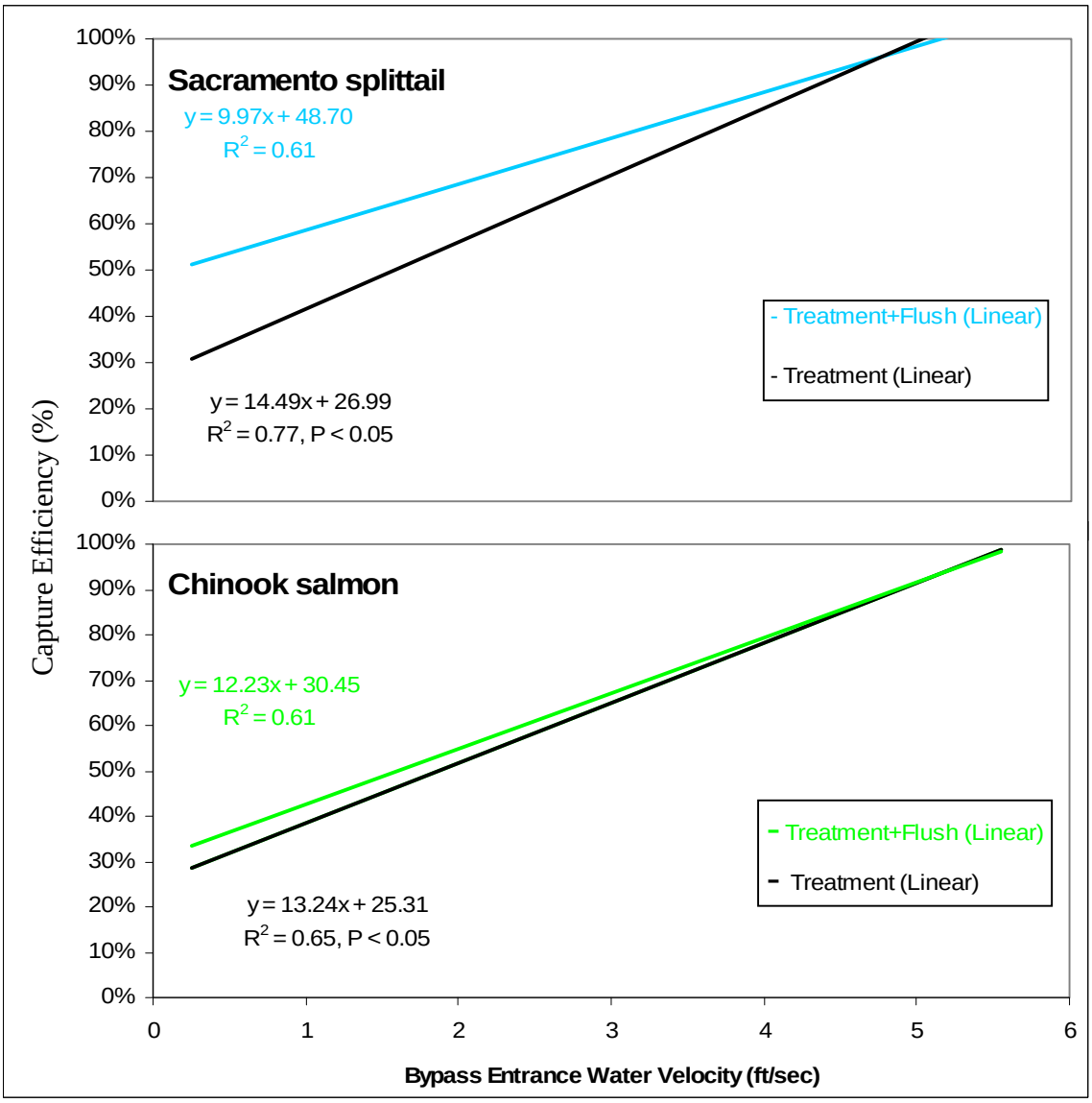


FIGURE 15.—Capture efficiency of Sacramento splittail and Chinook salmon treatment and treatment + flush groups plotted in relation to bypass entrance water velocity. Least squares regression lines indicate bypass mouth water velocity explains a significant amount of variance in capture efficiency scores for all groups. Splittail regression lines show different y-intercept and slope ($P < 0.05$), while salmon regression lines do not have significantly different y-intercepts or slopes ($P > 0.05$).

Chinook Salmon

There was no significant difference in the length of juvenile Chinook salmon (3.2 ± 0.2 in, 81 ± 6.2 mm; mean ± standard deviation) comparing size classes against controls and treatments ($P > 0.05$). However, because fish measurements were conducted after each treatment, and uncaptured fish were not included in the data set, it should be taken into consideration these results may be biased.

Capture Efficiency

Control Groups

Results of the Chinook salmon experiments indicate capture efficiency was higher for control groups at the two highest BR, 5.3 and 7.2, compared to BR of 1.1 and 2.5 ($P < 0.05$; Figure 16). When testing the effects of flushing the bypass on our salmon capture efficiency, there were no differences comparing control and control + flush at each individual BR. Similarly, our comparison of the difference in capture efficiency between control and control + flush across BR indicated BR had no affect on these rates ($P > 0.05$; Figure 17).

Treatment Groups

At all BR tested, capture efficiency of treatment and treatment + flush groups was not affected by fish insertion depth ($P > 0.05$). This allowed us to combine replicates and increase sample size from 4 to 12. Pooled data from Chinook salmon treatment and treatment + flush groups indicate, in general, as BR increases, capture efficiency of salmon increases ($P < 0.05$; Figure 18). However, there were no differences between treatment and treatment + flush groups at each individual BR, as well as the differences in the capture efficiency of treatment and treatment + flush groups across BR ($P > 0.05$; Figure 19).

Data points collected from each insertion experiment were used to develop treatment and treatment + flush linear regression lines to measure the affect of increasing bypass mouth velocity on capture efficiency (Figure 15). For all linear regression relationships developed, coefficient of determination values were adequate (> 0.61) and validate modeling the data using a linear relationship. There was no significant difference between Chinook salmon treatment and treatment + flush slopes ($P > 0.05$) or y-intercepts ($P > 0.05$), and both linear regression lines suggest as bypass entrance water velocity increases, capture efficiency of juvenile Chinook salmon in both treatment and treatment + flush groups increases (Figure 15).

There was no significant difference between treatment linear regression lines slope ($P < 0.05$) or y-intercept ($P < 0.05$) when compared between species. Given these results, and because the species tested were similar in size, life-stage, and were tested on the same days and under the same environmental conditions, we felt it was justifiable to combine capture efficiency data for both species (Figure 20). Combining capture

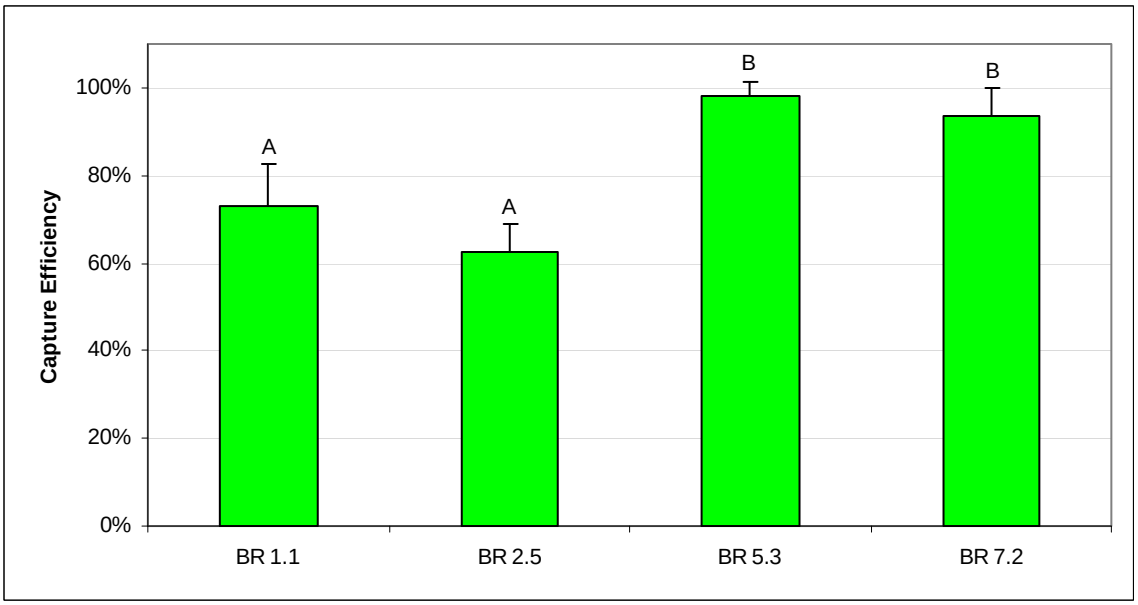


FIGURE 16.—Capture efficiency (mean ± 2SE) of Chinook salmon control groups (n = 3), prior to flushing bypass No. 4, at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experimental-wise error rate = 0.05).

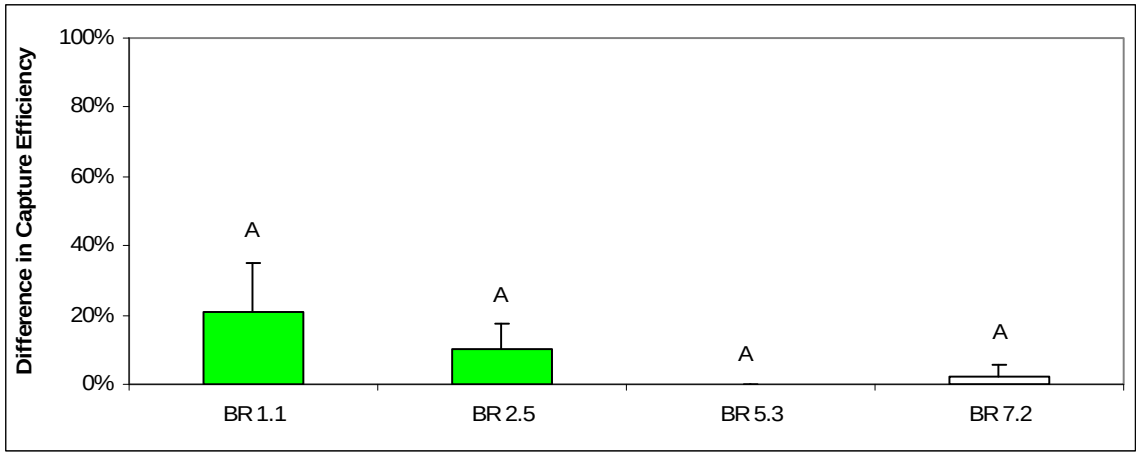


FIGURE 17.—Difference (mean ± 2SE) between Chinook salmon control capture efficiency and control + flush capture efficiency at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experiment-wise error rate = 0.05).

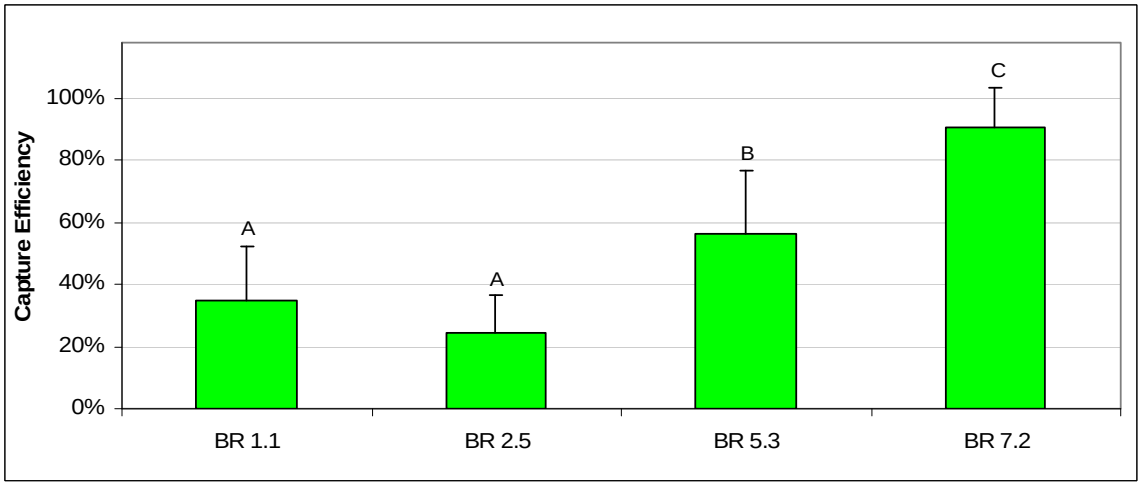


FIGURE 18.—Capture efficiency (mean ± 2SE) of Chinook salmon treatment groups (n = 12), prior to flushing bypass No. 4, at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experiment-wise error rate = 0.05).

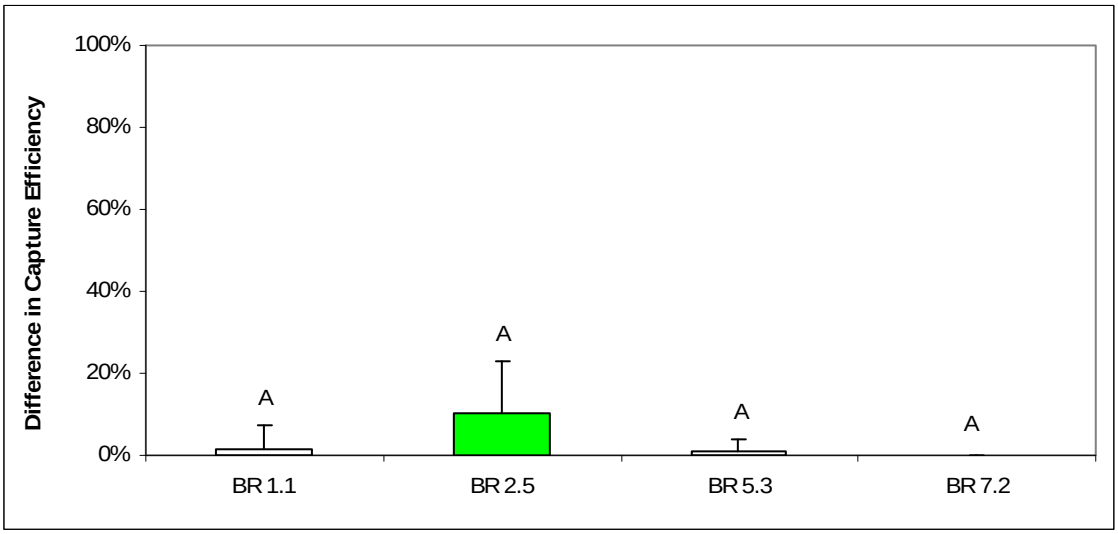


FIGURE 19.—Difference (mean ± 2SE) between Chinook salmon treatment capture efficiency and treatment + flush capture efficiency at four bypass ratios (BR) during low primary velocities. Different letters denote a significant difference between treatment medians (Dunn's Test, Experiment-wise error rate = 0.05).

efficiency data from both species increased our sample size (n = 96), therefore, improving the statistical significance of our results. After pooling data from both species, the linear regression relationship indicates capture efficiency of both splittail and Chinook salmon increased 14 percent for every 1.0 ft/s (0.3 m/s) increase in bypass entrance water velocity, and was typically > 80 percent when the water velocity was > 4.0 ft/s (1.2 m/s; Figure 20).

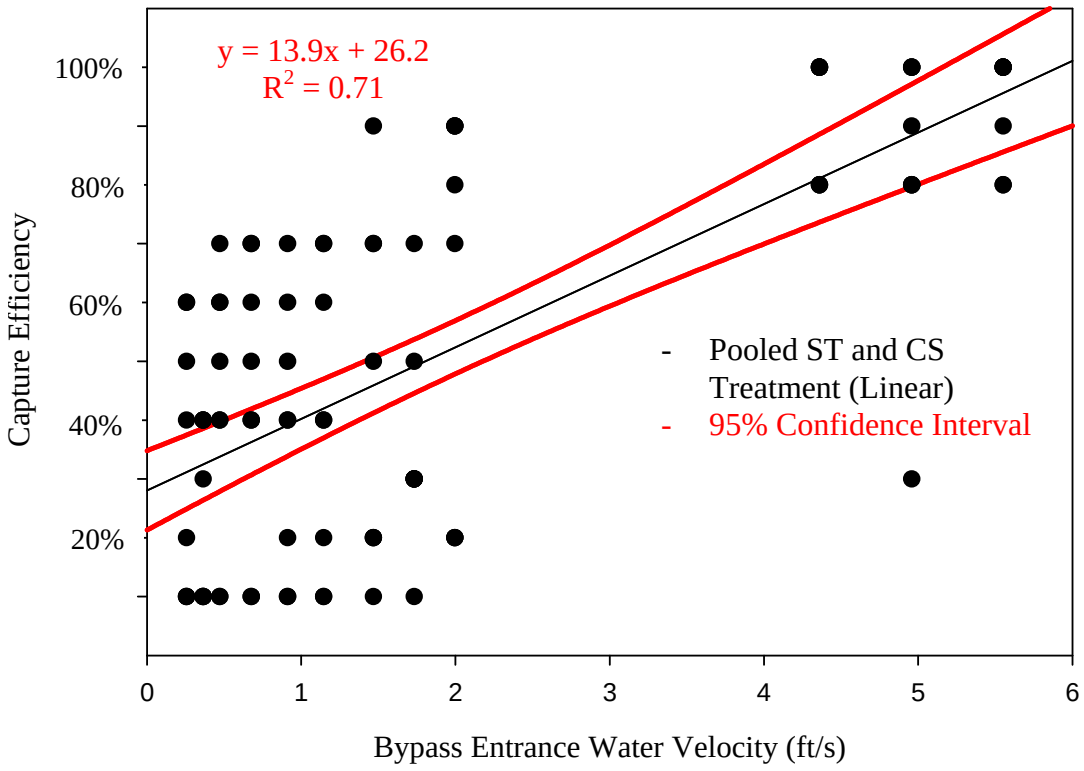


FIGURE 20.—Pooled capture efficiency for Sacramento splittail (ST) and Chinook salmon (CS) treatment groups presented using least squares linear regression relationship and 95% confidence interval. Regression line indicates bypass mouth water velocity explains a significant proportion of the variance in capture efficiency ($F = 224.8$; $P < 0.05$).

DISCUSSION

Studies have been conducted in the past to evaluate fish louvering efficiency and document velocity profiles when operating the TFCF during normal conditions (Bates *et al.*, 1960; Karp *et al.*, 1995; Bowen *et al.*, 1998; Bowen *et al.*, 2000). However, this study is the first to evaluate fish capture efficiency and approach velocity profiles over a range of elevated BR and low primary channel velocities.

Results from this study clearly show increased BR is correlated with increased capture efficiency; however, relying exclusively on BR to predict louver efficiency is unreliable. BR is generated from the ratio of two velocities: A/B (A = average bypass mouth velocity, B = average channel velocity), and both velocities must be measured and reported before a meaningful relationship can be predicted between capture efficiency and BR. For example, ratios 0.4/0.3 and 4.0/3.0 both have a BR value of 1.3, but will not equally guide fish into a bypass. In the first scenario, bypass mouth velocity is excessively slow and in the second it is at a typical operating speed. Based on the data presented in this report, the first BR will generate capture efficiencies between 30–40 percent for juvenile splittail and Chinook salmon, while previous work by Karp *et al.* (1995) indicates the second scenario will result in primary louvering efficiencies of similar sized juvenile Chinook salmon (58–90 mm FL) and striped bass (81–163 mm FL) closer to approximately 60 percent. Therefore, the two components that make up the BR, average bypass mouth velocity and average channel velocity, need to be considered when determining how to optimize capture efficiency.

Average channel velocity and an individual fishes swimming ability influences how fast a fish will approach the louver and bypass system, and how long a fish will maintain position in the primary channel prior to being forced through a bypass. The average channel velocity remained nearly constant throughout our experiments, ranging from 0.3–0.7 ft/s (0.09–0.21 m/s). Critical swimming speed (U_{crit}) is a measure of a fish's swimming performance, and can be defined as the maximum swimming speed a given species of fish can maintain for approximately the same period of time as the time interval between stepwise increases in velocities used during testing. For example, a U_{crit} of 50 cm/s, determined by exposing a fish to stepwise increases of 10 cm/s velocity every 30 min, would theoretically indicate the individual fish could swim at 50 cm/s for a 30 min duration. The swimming performance (U_{crit}) of age-1 splittail and Chinook salmon was measured by Sutphin *et al.* (2007) and Randall *et al.* (1987), respectfully. The time interval used in the experiments conducted by Sutphin *et al.* (2007) and their mean absolute U_{crit} were 10 min and 6.8 ± 0.7 (body lengths/sec), respectively. Coupling the results reported by Sutphin *et al. (*2007) and those from the current study, age-1 splittail measuring approximately 3.2 in (80.0 mm) in length, can maintain position in the TFCF primary channel at velocities < 1.8 ft/s (0.5 m/s) for up to 10 min. The time interval used in the experiments conducted by Randall *et al.* (2007) and their mean absolute U_{crit} were 60 min, and 3.2 (body lengths/s), respectively. Combining results reported by Randall *et al.* (1987) and those from the current study, age-1 Chinook salmon measuring approximately 3.2 in (80.0 mm) in length, can maintain position in the TFCF primary channel at velocities 0.9 ft/s (0.24 m/s) for up to 1 hour (h). Results presented by Sutphin *et al.* (2007) and Randall *et al.* (1987) suggest age-1 splittail and Chinook salmon should be able to swim against the channel velocities tested in the current study throughout the duration of each treatment (1-h). This would suggest, in our experiments, average channel velocity did not have a significant effect on capture efficiency. Therefore, of the two parameters that define BR, it is likely that bypass entrance velocity had greater influence on capture efficiency of splittail and Chinook salmon.

In our evaluation of bypass entrance velocity, our data suggests it is likely flow characteristics both inside and outside of the transition box had an effect on capture efficiency. Once fish enter the transition box, water flow immediately forces them to descend vertically. The transition box is triangular in shape and the water entering the front of the box is redirected approximately 90 degrees downward. The water is forced through a slot in the floor of the primary channel that transitions to an underground 3.0 ft (0.9 m) diameter tube. This underground tube is buried 7.5 ft (2.3 m) below the primary channel floor. Fish species that do not like an abrupt pressure change (~10 pounds per square inch) are likely to try to swim out of the box if the entrance velocity is slow enough. The results of our experiments suggest capture efficiency of both splittail and Chinook salmon increased 14 percent for every 1.0 ft/s (0.3 m/s) increase in bypass entrance water velocity, and was typically > 80 percent when water velocity was > 4.0 ft/s (1.2 m/s; Figure 20). This is most likely because elevated water velocities observed in the bypass entrance were at or above the velocity at which fish can maintain burst swimming. Burst swimming speed is the highest velocity that can be achieved by a fish, and is therefore the highest water velocity fish can maintain position for a short period. Fish can achieve and maintain burst swimming speeds for short periods, typically < 3–4 seconds (Beamish, 1978). Bainbridge (1958) measured the burst swimming ability of age-1 (4 in TL, 103 mm TL) rainbow trout, and reported that they were capable of burst swimming at speeds up to 3.3 ft/s (1.0 m/s). If we use age-1 rainbow trout as a surrogate for splittail and Chinook salmon, it is easy to see how capture efficiency of these species increased when they were exposed to water velocities > 4.0 ft/s (1.2 m/s), as these velocities are likely above their burst swimming abilities.

An interesting difference between the two species observed in our study is once they entered the bypass, splittail tended to hold up in the bypass and tubes at slower velocities, whereas salmon were more willing to go with the flow and descend into the bypass. This is to be expected as juvenile salmon at this size are migrating towards the ocean and are behaviorally imprinted to travel with the flow of water. This behavior was not apparent when comparing these groups and looking at BR alone, but was strongly observed in the splittail BR 1.1 control groups. This phenomenon was further supported by observations made prior to our experiments. While holding the two species in captivity, it was observed salmon preferred to swim with the direction of flow, while splittail maintained their position against the current in the circular holding tanks.

Though bypass entrance water velocity may have a significant effect on capture efficiency, flow patterns outside of the transition box are likely to influence capture efficiency as well. As we have suggested, juvenile salmon display an ocean bound migratory instinct, and are willing to descend and go with the flow more willingly than splittail. This was observed at the low BR tested, where over 62.5 percent of salmon were captured in the control group. However, in our treatment trials, when fish were inserted approximately 11 ft (3.4 m) upstream from the bypass entrance, and at low BR, salmon capture efficiency was < 35 percent. Assuming that salmon prefer to follow water flow once inside the transition box, the large drop in capture efficiency is probably due to flow patterns just outside of the transition box.

The difference between the average primary channel velocity and the bypass mouth velocity gives an indication of the distance in front of the bypass the acceleration field can be sensed by fish, and therefore, the higher the BR, the further out fish will be able to sense flow acceleration toward the bypass. However, there is a limit to the extent accelerated flows extend out in front of the bypass box, and for the conditions in this experiment the extension was approximately 8–9 ft (1.8 m; Figure 7). At the lowest BR tested (1.1 and 2.5) the acceleration field potentially sensed by fish extended out from the bypass entrance < 2 ft (< 0.6 m). Because our fish insertion tubes were placed 11 ft (3.3 m) upstream from the bypass entrance, and designed in a fashion to force fish out of the tubes downstream and in the direction of the bypass entrance (Figure 3), it is likely test fish did not sense accelerated flows at BR 1.1 and 2.5, but more likely as BR increased from 5.3 to 7.2. Therefore, at the highest BR tested (7.2), the majority of juvenile Chinook salmon sensed the accelerated downstream flow and influenced by their instinctual desire to migrate moved towards the bypass entrance and into the secondary channel sieve nets.

The results of this study provide evidence that TFCF salvage efficiency may be improved, when forced to operate the primary channel at low velocities (VAMP period; < 0.75 ft/s [< 0.23 m/s]), by maintaining secondary velocity criteria for salmon (3.0–3.5 ft/s [0.9–1.1 m/s]) and allowing primary BR to increase as high as necessary. However, results presented in this study are based upon many assumptions and limitations. Therefore, to measure the true benefit of operating the facility in this manner and to validate our results, we recommend running a full facility evaluation, using similar species and methods, during VAMP.

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