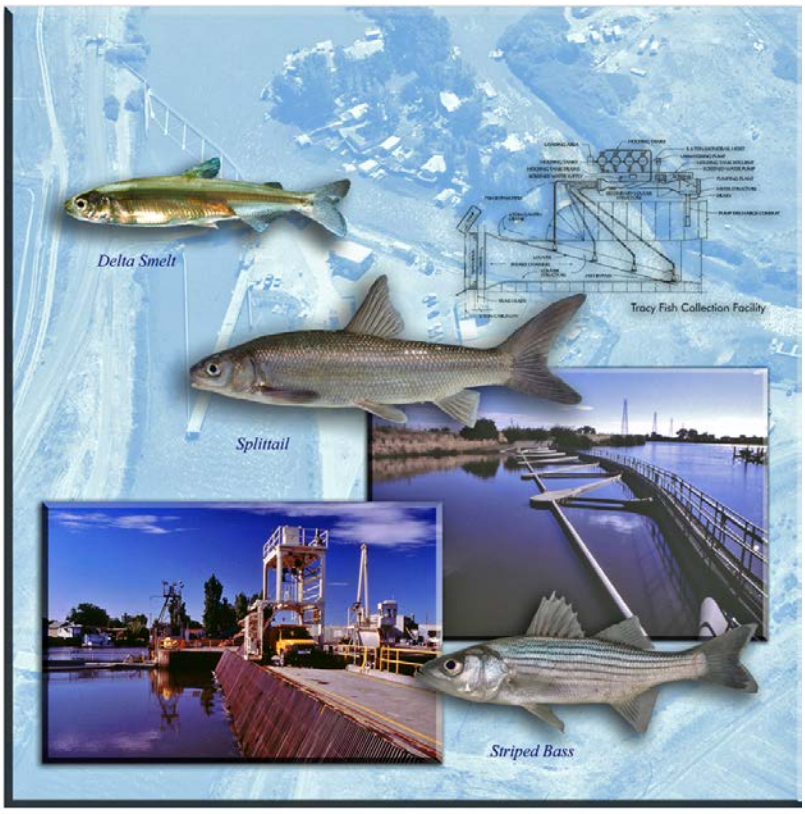
RECLAMATION

Managing Water in the West

Tracy Series Volume 54

Pacific Lamprey Macrophthalmia Louver Efficiency at the Tracy Fish Collection Facility



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14. ABSTRACT

The Bureau of Reclamation's Tracy Fish Collection Facility (TFCF) in Byron, California, uses a system of behavioral barriers called louvers designed to divert fish entrained by pumps at the C.W. "Bill" Jones Pumping Plant (JPP) to holding tanks. The louver system was specifically designed for capturing juvenile Striped Bass (*Morone saxatilis*) and outmigrating Chinook Salmon (*Oncorhynchus tshawytscha*) and is currently used to salvage over 50 other fish species from the Sacramento-San Joaquin River Delta. For many of these species, including Pacific Lamprey (*Entosphenus tridentatus)*, little information is known about the effectiveness of louvers. In 2012, TFCF secondary channel louvers were tested at different diel period (day vs. night) and water velocities using Pacific Lamprey macrophthalmia, the outmigrating life stage of the species. Diel period did not have a significant effect on secondary channel louver efficiency (Tukey's Test, $P > 0.05$); however, when averaged across diel period, louver efficiency of macrophthalmia exposed to a velocity of 0.3 m/s (mean ± SD) were significantly greater than those exposed to a velocity of 0.9 m/s (mean ± SD; Two-Way ANOVA, Tukey's Test, $P < 0.05$). Participation increased with increasing water velocity and was higher at night (89.4 ± SD% at 0.3 m/s).

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by

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Fish photography by René Reyes, Tracy Fish Collection Facility, Tracy, California.
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Executive Summary

The Bureau of Reclamation (Reclamation) Tracy Fish Collection Facility (TFCF), part of the Central Valley Project, is located in the southern region of the Sacramento-San Joaquin River Delta (Delta) and was designed to remove fish entrained in water exported from the Delta by the C.W. "Bill" Jones Pumping Plant. The TFCF uses behavioral louver arrays to divert fish into bypasses and into collection (holding) tanks and then transported by truck to release sites near the confluence of the Sacramento and San Joaquin Rivers. The TFCF salvages over 50 Delta fish species including Pacific Lamprey (*Entosphenus tridentatus)*.

Lampreys are observed at the TFCF year round and louver efficiency (*i.e.,* proportion of fish that encounter the louver array that are successfully guided into a holding tank) is likely lower for smaller bodied Pacific Lamprey macrophthalmia, the outmigrating life stage often encountered at the TFCF, than for adult lamprey. The goal of this study was to measure louver efficiency of macrophthalmia in relation to water velocity and diel period and to provide data to estimate lamprey entrainment loss. Because this was the first attempt to collect macrophthalmia louver efficiency data, the first objective was to develop a method to capture, hold, tag, and test macrophthalmia. The second objective was to quantify louver efficiency in the secondary channel because this closed system allows control of hydraulics and recapture of released fish. The third objective was to estimate lamprey macrophthalmia whole facility efficiency (WFE).

For the study, macrophthalmia were transported more than three hours from Red Bluff, CA with no mortality recorded. They were held at the TFCF for three days to acclimate before they were photonically marked (tagged). The base of the second dorsal fin was used for the marks for ease of tagging and color retention. A total of 816 macrophthalmia were photonically tagged with each tagged group showing no significant difference in body size.

Macrophthalmia secondary louver efficiency was tested at three velocities (0.3 m/s, 0.6 m/s, and 0.9 m/s) during day and night. Velocity had a significant effect on macrophthalmia participation for both day and night with more participating at night (mean = 72.6–89.4%) and at higher velocities (day mean = 72.3%, night mean = 89.4%). Higher night time participation was expected since macrophthalmia are known to be nocturnal and more active at night (Quintella *et al.* 2005, Dauble *et al.* 2006; Moser and Mesa 2009). Higher macrophthalmia participation at higher velocity was similar to other fish species tested at the TFCF. At lower water velocities, macrophthalmia were likely swimming out, lost through the louvers, or experienced higher rates of predation since more time was spent drifting and exposed.

The secondary louver system was not effective in guiding entrained Pacific Lamprey macrophthalmia at the TFCF. Macrophthalmia secondary louver efficiency was generally low across the three velocities tested with better efficiencies occurring at the slowest velocity (day mean = 23.6%, night mean = 28%) than at the highest velocity (day mean = 3.9%, night mean = 16%). Diel period did not have a significant effect on secondary channel louver efficiency but when averaged across diel period, efficiency was significantly greater at the slowest velocity than at the highest velocity (Two-Way ANOVA, Tukey's Test, $P < 0.05$).

During three days of whole facility efficiency (WFE) tests, few macrophthalmia released at the trashrack were recovered (mean = 5%) in the holding tank. Unlike the secondary louver channel, a net cannot be placed behind the primary louver to collect macrophthalmia that swim through the primary louvers and predators within the much larger primary channel were not removed before the tests. Furthermore, non-participation may be attributed to macrophthalmia swimming out of the TFCF or the ability of macrophthalmia in maintaining themselves within the TFCF. With the replacement of the secondary channel louvers with a traveling screen in 2014, the WFE is expected to improve; however, macrophthalmia loss will continue to occur since louvers are still used in the primary channel and no regularly occurring predator removal occurs at that location. Furthermore, since the greatest number of macrophthalmia are observed at the TFCF between December and March coinciding with high water exports, loss of macrophthalmia through the primary louver will continue to occur.

Introduction

The Bureau of Reclamation (Reclamation) Tracy Fish Collection Facility (TFCF), a component of the Central Valley Project (CVP), commenced operation in 1957 and is located at the head of the Delta-Mendota intake channel in the southern region of the Sacramento-San Joaquin River Delta (Delta) near Tracy, California (Figure 1). The TFCF is designed to remove fish entrained in the water exported from the Delta by the C.W. "Bill" Jones Pumping Plant (JPP). The TFCF uses behavioral louver arrays to guide fish into fish bypasses for removal (Figure 2). Primary louver arrays are angled across the channel (25 m wide) at 15° to the direction of flow and consist of 2.5-cm-spaced vertical slats angled 90° to the direction of flow. Water approaching the louvers creates a turbulent wake (Figure 3) that fish sense and guides them away from the louvers in a downstream direction. Fish are then diverted into one of four 15-cm-wide bypass entrances which transition to underground 0.9-m-diameter concrete bypass pipes leading to the secondary channel. Upon entering the secondary channel, fish encounter two more louver arrays. Like the primary channel louvers, the secondary channel louver arrays are angled 15 degrees to the direction of flow, with 2.5-cm spaced vertical slats that are angled 90° to the direction of flow. Fish are guided to another 15-cm-wide bypass which transitions into a 50.8-cm metal pipe that drains into a 6.1-m-wide and 5.0-m-deep holding tank. These "salvaged" fish are removed from holding tanks daily and trucked to release sites approximately 30 km to the north near Sherman Island near the confluence of the Sacramento and San Joaquin Rivers where they are far from the influence of the Delta pumps.

There are two positively identified species of lamprey observed at the TFCF, the Pacific Lamprey (*Entosphenus tridentatus)* and River Lamprey (*Lampetra ayresi*). Adult Pacific Lamprey are the larger of the two, attaining > 40 cm total length (TL). They migrate in from the ocean starting in March and spawn in Central Valley rivers between April and June (Moyle 2002). Adult River Lampreys are much smaller than the Pacific Lamprey, averaging ~17 cm TL. They return to the rivers starting in autumn and spawn earlier, between February and May, than Pacific Lamprey (Moyle 2002). Larval lamprey (ammocoetes) of both species reside in the river for several years (White and Harvey 2003, Dauble *et al.* 2006) before transforming to juveniles (macrophthalmia). Macrophthalmia migrate from freshwater parental streams to the Pacific Ocean (Orlov *et al.* 2008) and their migration timing has been anecdotally correlated with rain or snow melt, distance from ocean, and elevation (Goodman and Reid 2012).

Lampreys have gained more ecological attention in recent years as their distribution and abundance have been evaluated (Goodman and Reid 2012). Pacific Lamprey were historically widespread along the west coast of the United States (Scott and Crossman 1973) though there is an observed decline in abundance and distribution throughout California, Oregon, Washington, and Idaho (Moyle *et al.* 2009). Threats to lamprey occur in much of their range (Goodman and Reid 2012) and include passage barriers, flow management, and water quality/habitat issues associated with high water temperatures, low flow and nutrient loading (Moyle *et al.* 2009). Pacific Lamprey, River Lamprey, Western Brook Lamprey (*L. richardsoni*), and Kern Brook Lamprey (*L. hubbsi*) have been declining in abundance throughout their range and a petition in 2003 (Nawa *et al.* 2003) to list them under the Endangered Species Act was not successful due to insufficient biological information (USFWS 2004). In the Delta, there are no requirements in the

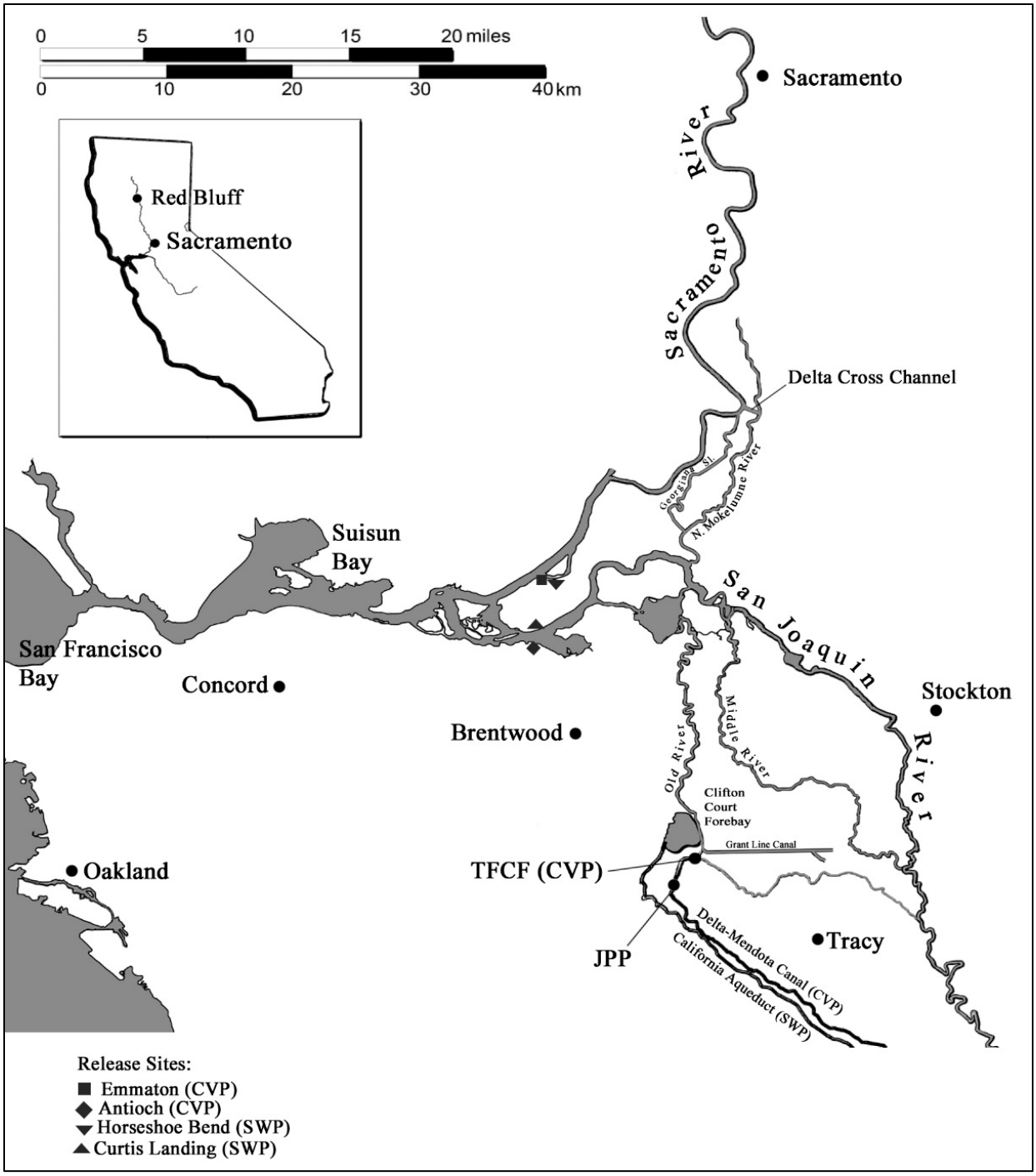

Figure 1. Map of the Sacramento-San Joaquin Delta showing the location of the Tracy Fish Collection Facility (TFCF) and C.W. “Bill” Jones Pumping Plant (JPP) in the south Delta and the release sites located near the confluence of the Sacramento and San Joaquin Rivers.

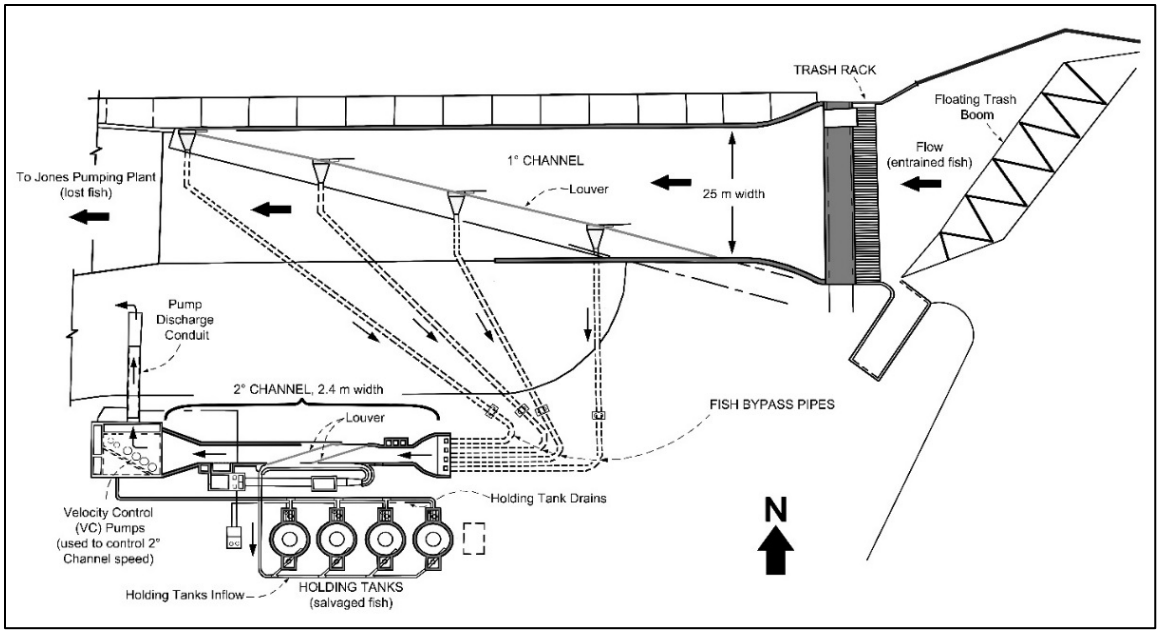

Figure 2. General schematic design of the Tracy Fish Collection Facility. Large arrows represent direction of water flow through the primary channel; the smaller arrows represent flows through the four bypasses, the secondary channel, and the bypass to the holding tanks. The louvers at the primary channel and secondary channel are angled 15° to the flow.

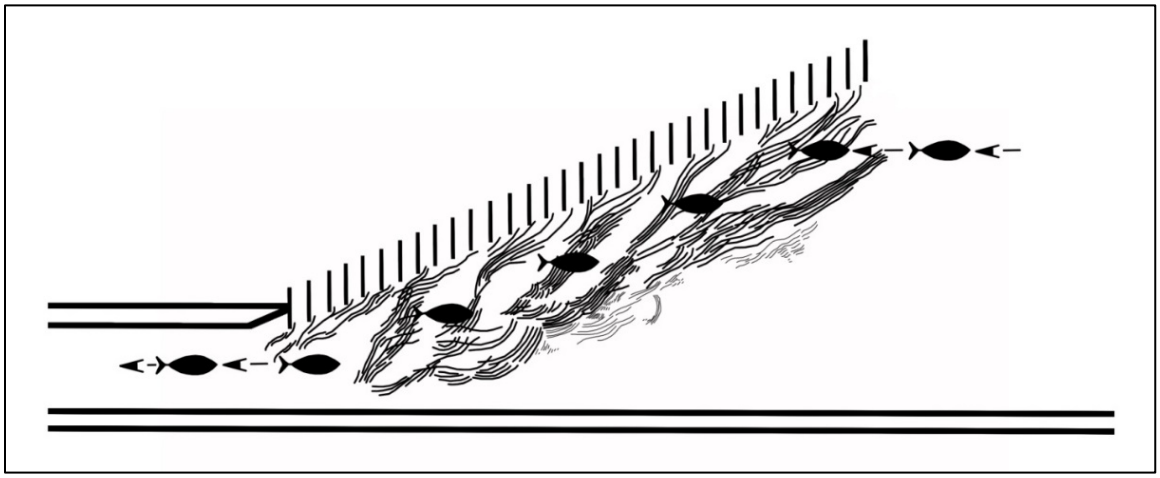

Figure 3. Fish sense turbulent wake created by water approaching the louvers. The avoidance and behavioral response to the wake guides the fish to a bypass entrance.

National Marine Fisheries Service Biological Opinions (NMFS 2009) specifying special TFCF operating conditions for lamprey or limits in the number of lamprey that the facility can capture annually.

The TFCF louver system was specifically designed for capturing juvenile Striped Bass (Morone saxatilis) and outmigrating Chinook Salmon (Oncorhynchus tshawytscha), but is currently used to salvage over 50 other Delta fish species including lamprey. Only the migrating life stages of lamprey, i.e. adult and macrophthalmia, are observed at the TFCF with most macrophthalmia (~100–150 cm) collected in January and February and adults in spring (Figure 4). For Pacific Lamprey and River Lamprey, little information is known about the effectiveness of louver systems while operated at different diel periods and water velocities. Empirical evaluations in the secondary louver channel capturing wild fish entering the facility resulted in the capture of few lamprey. In 254 paired holding tank and sieve net samples from 1993 to 1995, nine lamprey were collected, with a combined louver efficiency of 56% (Karp et al. 1993). In 1996 and 1997, 456 paired samples collected 11 lamprey (Bowen et al. 2004). Ten of these fish were over 1000 g in weight (≥ 40 cm TL), indicating they were adult Pacific Lamprey since adult River Lamprey rarely reach sizes greater than 31 cm TL (Moyle 2002). Overall secondary louver efficiency for these 11 fish was 73%. High efficiency for the adult Pacific Lamprey is expected as the large Pacific Lamprey has a body width very close to the louver slat clear opening (2.5 cm) and the louvers function as barriers to these large fish. However, macrophthalmia have a much smaller maximum width (~ 1 cm, this study) and poorer swimming ability (Dauble et al. 2006) making them more susceptible to loss through the louvers.

The efficiency of the TFCF secondary channel louvers was tested in 2012 using Pacific Lamprey macrophthalmia (hereafter called macrophthalmia) and although these louvers were replaced with traveling screens in 2014, results from this study are relevant since the primary channel still utilize louvers. The number of lamprey entrained by the JPP cannot be predicted based on the numbers salvaged at the TFCF since it is not known how many are eaten by predators, lost through the louvers, or swim out of the facility. Furthermore, macrophthalmia migrate (Moser and Mesa 2009) and are more active at night (Quintella et al. 2005, Dauble et al. 2006), therefore the influence of diel period on macrophthalmia louver efficiency should be investigated.

The goal of this project was to measure secondary louver efficiency of macrophthalmia in relation to water velocity and diel period. The first objective of this study was to develop a method to capture, hold, and mark (external tag) macrophthalmia. The second objective was to quantify louver efficiency in the secondary channel. The secondary channel was studied because this closed system allows control of the hydraulics and recapture of released fish. The third objective was to develop a rough estimate of the whole facility efficiency (WFE) for the TFCF from trashrack to holding tank.

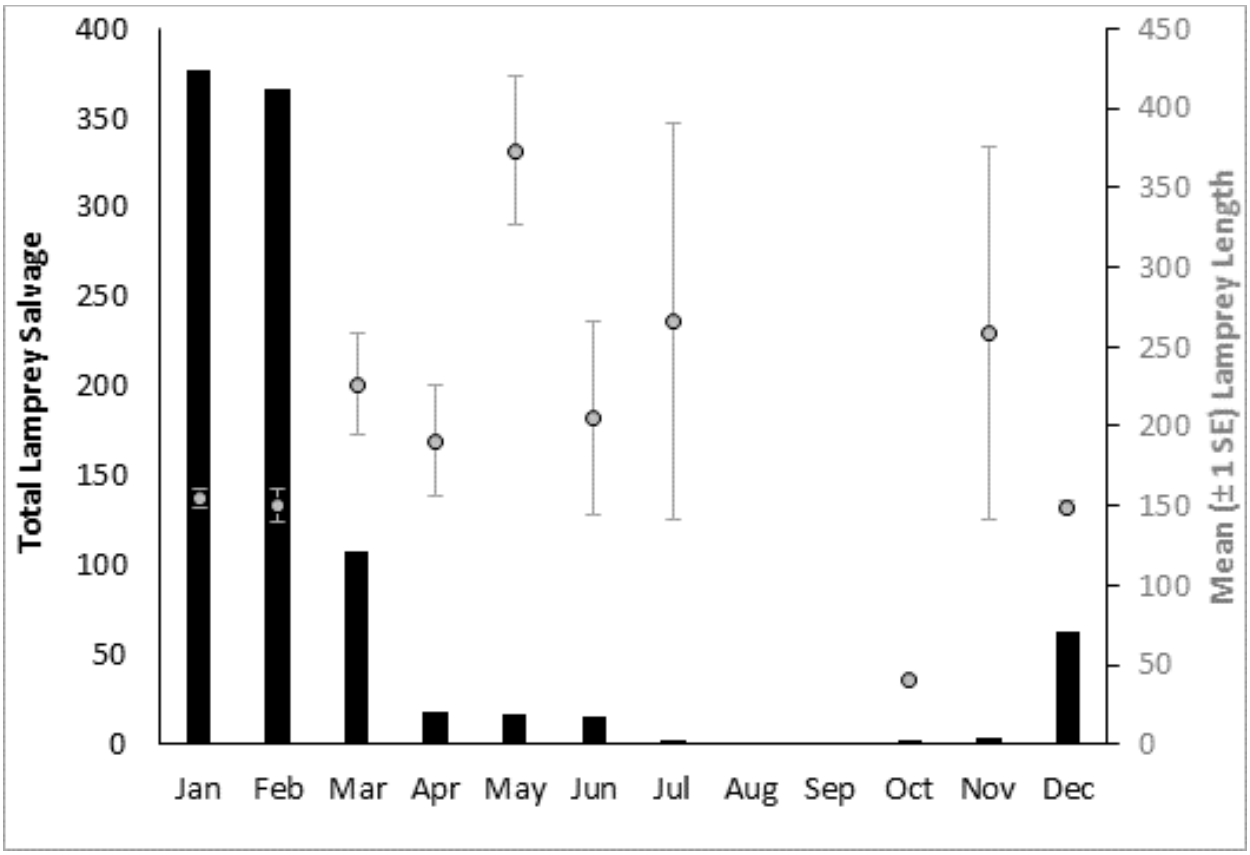

Figure 4. Total salvage (black bars) and mean length (grey circles) in mm of Pacific and River Lamprey at the Tracy Fish Collection Facility between 1993–2006.

Methods

In March 2012, rotary screw traps were used to collect macrophthalmia from the upper Sacramento River at the Red Bluff Diversion Dam (Red Bluff, Tehama County). Approximately 830 macrophthalmia were transported to the TFCF and were divided evenly among two black, 890-L (1.2 m diameter, 0.8 m deep), circular tanks with flow-through ozonated Delta water (12.1–15.0 °C) and approximately 1 L/min aeration through a Sweetwater® medium pore diffuser (8 cm long x 4 cm wide, Aquatic Ecosystems, Inc., Apopka, Florida). Each tank was covered with netting (3-mm mesh) and housed four cinder blocks (39 cm long, 19 cm wide and 19 cm deep) to provide cover and substrate. Lampreys do not feed exogenously during this juvenile life stage (McGree *et al.* 2008) and therefore were not fed during the holding period. Fish were maintained under these conditions for 3–5 days until they were photonically marked (tagged) and separated into distinct groups.

Macrophthalmia were externally tagged (Figure 5) on the posterior dorsal fin to differentiate them from wild lamprey and between replicate releases. Prior to tagging, macrophthalmia were anesthetized in 10-L of ozonated Delta water containing 200 mg/L of FINQUEL® Tricaine

methanesulfonate (MS-222, Argent Chemical Laboratories, Redmond, Washington) and a subset of fish were measured for total length (mm TL). Temperature of the anesthetic bath was maintained within the same range as holding conditions by adding ice packs.

A high-pressure, CO_2 powered tagging gun (POW'R-JECT BMX-1000, NewWest Technologies, Santa Rosa, California) was used to tag the dorsal fin. The gun was set at 200 psi and dispensed approximately 0.1 mL of marking paint (BMX-1000 photonic marking formulation) per trigger pull. Subcutaneous injections of colored paint (pink, blue, yellow, violet, orange, green, brown, and white) or color combinations (white/green, pink/white, blue/white, orange/blue, blue/yellow, yellow/pink, pink/blue, and white/violet) were injected. Sixteen unique groups were tagged and held outside in separate black, 174-L (0.8 m diameter, 0.4 m deep), circular tanks with flow-through ozonated Delta water (12.7–16.4 °C) and approximately 1 L/min of aeration through a Sweetwater® medium pore diffuser (5.0 cm long, 2.5 cm wide). Each of the 16 holding tanks were covered with heavy black sun screen fabric (Easy Gardener Products, Ltd., Waco, Texas) to provide shade and prevent predation by birds. Fish were held for 2–13 days before release in the secondary louver channels. Mortality of each tag group was recorded daily to verify that mortality was uniformly distributed across all tag groups. After the secondary louver evaluation was complete, recovered macrophthalmia were held for two weeks in outdoor tanks to recover before they were used again in the whole facility efficiency (WFE) evaluation.

Secondary Channel Louver Evaluation

The TFCF secondary channel louver efficiency and participation of macrophthalmia was investigated at three water velocities, 0.3, 0.6 and 0.9 m/s (1, 2 and 3 ft/s) during day and night periods. These treatments cover the full velocity range of normal operations. Day replicates were performed between 0800 and 1700, while night replicates were completed between 2000 and 0100. Since there was a limited number of macrophthalmia available for the study, the number of replicates available for testing each treatment was affected. Since this was the first known louver experiment with macrophthalmia, there was no past estimate of variance nullifying our ability to employ a power analysis to estimate suitable sample size

Macrophthalmia released during each day and night period were based on a randomized block design for water velocity. The release point was upstream of the first (secondary) louver array close to the north side of the channel wall (Figure 6). Prior to each fish release, water flow was initiated in an empty holding tank and two sieve nets (2.7 m high, 2.5 m wide, 7.6 m long, 3.2 mm mesh) downstream of the secondary louvers were lowered to capture any macrophthalmia lost through the louvers. The effectiveness of the sieve nets at capturing and retaining macrophthalmia was determined at an earlier time by injecting groups of 10 fish directly in front of the sieve net and verifying that they could be recovered. The desired secondary channel water velocity was obtained by adjusting the number of velocity control (VC) pumps at the end of the channel (see Figure 6). Water flowing to the holding tank was controlled by running either one or both holding tank pumps. Two pumps must be operated when the primary depth is above 5.3 m (17.5 ft).

Figure 5. Externally tagged Pacific Lamprey macrophthalmia. A single or double tag (photonic mark) was injected on the posterior dorsal fin.

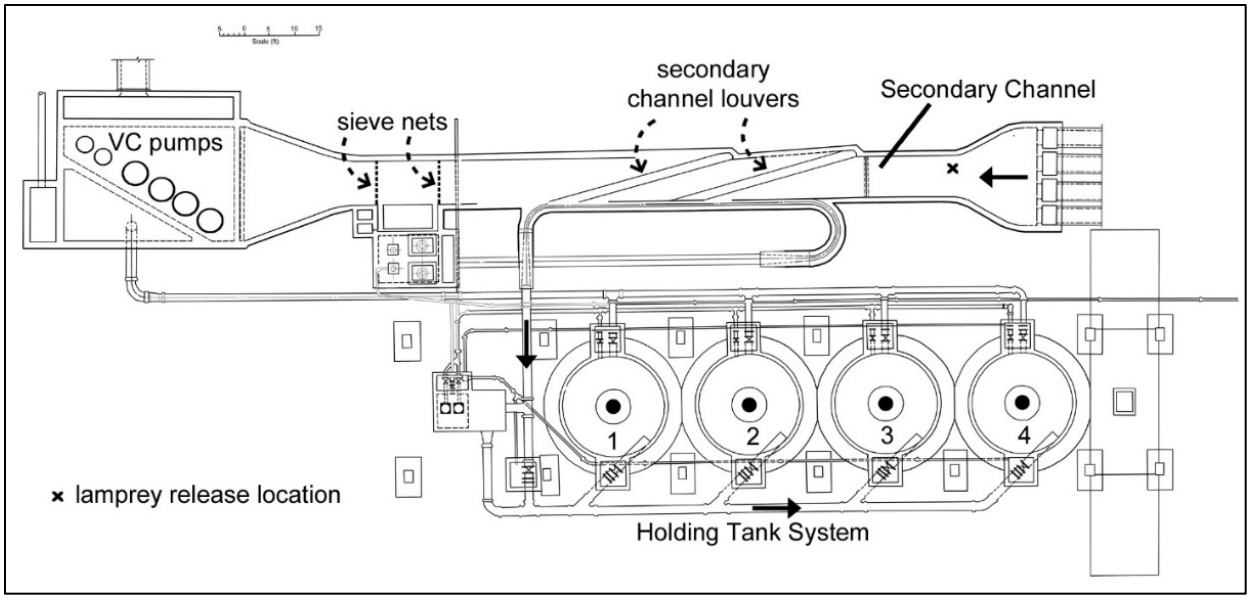

Figure 6. Schematic of the secondary channel and holding tank systems showing location where test fish were released (x), 2 sets of secondary channel louvers, 2 sieve nets located downstream of the secondary channel louvers, and the velocity control (VC) pumps. Arrows represent direction of water flow.

Hydraulic measurements were recorded at the start of each replicate. Measurements of secondary channel depths were provided by HydroRanger 200 level indicators (Siemens AG, Munich, Germany) while measurements of secondary channel and holding tank flows were obtained from Panametrics DF868 flow meters (General Electric Company, Fairfield, Connecticut). Light levels and the turbidity of the water in the secondary channel were measured using a model LI-250 light meter (LI-COR, Lincoln, Nebraska) and a 2020 turbidity meter (LaMotte Company, Chestertown, Maryland).

At each velocity, six to seven replicates were completed during day and night. For each replicate, 20 fish were counted into a 19-L black bucket containing approximately 10 L of ozonated Delta water, lowered near the northern wall of the secondary channel, and released via water-to-water transfer. Ten Sacramento Splittail (*Pogonichthys macrolepidotus*) were simultaneously injected into the holding tank as control fish to verify that the holding tank screen was seated appropriately and the bucket valve did not fail during each repetition.

Each release group was allowed 20 minutes to participate in the test. After 20 minutes, water flow to the holding tank was stopped and the tank was drained to an approximate depth of 0.6 m. The 343-L fish count bucket was inserted into the holding tank drain pit and the center holding tank screen lifted to allow collection of the holding tank sample into the fish count bucket. The fish count bucket was then hoisted out of the holding tank using an R&M LOADMATE LM20, 460V, 3 ton, two-speed electric chain hoist (R&M Materials Handling, Inc., Springfield, Ohio) and the sample was released into the fish count station for processing.

The front sieve net was also lifted at the end of every 20-minute period in order to remove and process macrophthalmia that passed through the louvers. Fish from the holding tank and sieve net were used together to calculate secondary louver efficiency (SLE, Equation 1). The rear

sieve net remained down for the entire duration of the day or night repetitions and served to catch fish while the front sieve net was being lifted and emptied. Fish collected in the front sieve net were used to measure percent of fish participating in the secondary louver experiment (SLP, Equation 2).

$$SLE = [H/(H+S)]100 \quad \text{(Eq. 1)}$$

$$SLP = [(H+S)/I_s]100 \quad \text{(Eq. 2)}$$

Where:

H = Number of fish recovered from the holding tank

S = Number of fish recovered from the front sieve net

I_s = Number of fish inserted into the front of the secondary channel

Most of the macrophthalmia collected in the holding tank and sieve net samples were anesthetized using 200 mg/L MS-222 and a few healthy individuals were saved for reuse for the WFE test. Each macrophthalmia collected were individually inspected to record photonic tag and total length (TL). All Sacramento Splittail control fish from the holding tank were also anesthetized (75 mg/L MS-222) and measured. All wild fish were identified to species, counted, and released as part of facility salvage.

Whole Facility Efficiency Evaluation

Whole Facility Efficiency (WFE) testing was a pilot level effort to help direct future work. Since it was difficult to acquire macrophthalmia from wild stock, testing was limited to reusing macrophthalmia from the secondary louver evaluation. The authors realize this may bias the WFE estimate to some extent, as the fish already were exposed to louvers. However, by completing the WFE replicates this will help with future testing and provide some insight on data variability so the appropriate number of replicates can be estimated.

The WFE for Pacific Lamprey macrophthalmia was investigated by releasing 100 photonic tagged fish at the head of the primary channel, and counting how many made it to the holding tank (Equation 3). Unlike the secondary efficiency evaluation, no sieve net was deployed behind the primary louvers to document the number of macrophthalmia lost through the louvers. Therefore, the WFE equation calculates the percent of fish released from the trashrack that make it to the holding tank. This formula does not necessarily quantify efficiency of facility components (*i.e.*, louvers). Macrophthalmia that do not make it to the holding tank have either been lost through the louvers, have been eaten by predators, swam out of the TFCF back to the Delta, or have maintained themselves within the TFCF. To minimize the impact of the last factor, recovery efforts are usually long enough to give most fish time to pass through the facility.

$$WFE = (H/I_p)100 \quad \text{(Eq. 3)}$$

Where:

I_p = Number of fish inserted into the primary channel behind the trashrack

Releases were completed at night during an incoming tide when there was one pumping unit operating at the JPP. One trial was completed each evening and the release time shifted approximately 20 minutes later each night to match the incoming tide. Fish were counted into four 19-L black buckets (25 fish/bucket) containing 10 L of ozonated Delta water and transported to the most upstream end of the TFCF primary channel. Each bucket was lowered into the primary channel downstream of the trashrack, and fish were released via water-to-water transfer. Fish were released at four equally spaced locations across the downstream side of the trashrack. Fish were given 8–10 h to travel to the holding tank. Holding tank was not checked intermittently, rather it was drained after the 8–10 h period and all collected fish were recorded. During this period, velocity in the primary channel ranged from 0.05-0.25 m/s and average primary flow was approximately 23 m^3/s. The secondary channel was operated according to the 1978 State Water Resources Control Board Water Right Decision 1485, Table 2 (*i.e.*, 0.9-1.1 m/s, 3.0–3.5 ft/sec whenever possible from February through May while salmon are present). Bypass ratio, 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 pipes and was maintained at ≥ 1 as required by Decision 1485. At high tide the faster water velocity in the secondary channel cannot be attained; therefore, velocity ranged from 0.7-1.1 m/s over the three days of testing.

WFE testing required collecting fish entering the holding tank over several days. Consequently, macrophthalmia entering the holding tanks were saved from both the salvage counts and the holding tank prior to the 0700 haul-out process. Each morning before the haul-out, all fish in the holding tanks were placed into a 356-cm-long x 734-cm-wide x 76-cm-deep fiberglass trough to sort the sample. Wild fish were placed in the fish-haul truck and all tagged macrophthalmia were euthanized in MS-222. Macrophthalmia were placed in a sealable plastic bag, labeled with the time and date, frozen, and were processed after all WFE replicates were completed.

Data Analysis

All statistical analyses were completed with Minitab 15 (Minitab Inc., State College, Pennsylvania), SigmaStat and SigmaPlot (Systat Software Inc., Richmond, California), and Excel 7.0 (Microsoft, Redmond, Washington), testing at an alpha level (α) of 0.05. Total body length was subsampled (n = 20) from the 16 tag groups to determine if there was a significant difference between mean body length between tag groups. Lengths were compared with a one-way ANOVA after testing for normality and homogeneity of variance (Levene's Test). A chi-square test was used to determine if mortalities were uniformly distributed between single vs. double tag groups.

A two-way ANOVA and Tukey's multiple comparison procedure were used to determine if measured environmental conditions, water temperature and turbidity, were significantly different between day and night replicates, as well as between secondary velocity categories. Attempts to quantify effects of velocity and bypass ratio on secondary participation using a multiple linear regression model indicated significant multicollinearity between variables, *i.e.* bypass ratio decreased in a linear relationship with velocity. It was assumed bypass ratio was dependent on velocity, and velocity was likely the most biologically relevant explanatory variable for participation, so a simple linear regression model was employed to evaluate the relationship between velocity and lamprey participation during testing. Day and night velocity × participation models were linear, did not have significantly different slopes (general linear model, velocity × diel period, $P = 0.63$), so an ANCOVA model was used to determine if there was a difference in the velocity × participation relationship by diel period. Effects of velocity on secondary efficiency, when modeled using night data, was not suitable for a linear regression model ($R^2 = 0.09$, $P = 0.2$). Because the achieved velocities were so close to target velocities, velocity categories of 0.3, 0.6, and 0.9 m/s (1, 2, and 3 ft/s) were utilized, and a two-way ANOVA and Tukey's multiple comparison procedure were used to evaluate effects of velocity and diel period on lamprey secondary efficiency.

Whole facility efficiency was evaluated under similar conditions. The mean and standard deviation were calculated for the three replicates to help aid future research.

Results and Discussion

Macrophthalmia were successfully transported more than three hours from Red Bluff, CA, and were acclimated to tanks at the TFCF using ozonated Delta water. There was no mortality before the macrophthalmia were photonically marked (tagged) three days after transport. Since the method of externally tagging macrophthalmia using the photonic method was not found in scientific literature, various fin locations were tested. The base of the second dorsal fin showed the greatest promise for ease of marking and tag retention. A total of 816 macrophthalmia were photonically tagged in two days with mean length of 135 mm TL (10.2 mm SD, n = 320; Table 1). Maximum and minimum lengths for the entire group were 111 and 168 mm TL, respectively. Body size between tag groups was not significantly different ($F(15, 304) = 0.94$, $P = 0.52$).

Mortalities were not uniform between the single and double tag types ($\chi^2(1,66) = 37.9$, $P < 0.001$). Single and double tagged groups experienced 1.1 and 7.1 mortalities on average per tag group (Table 2). Within the single tag group, mortalities were not uniformly spread among the 8 tag colors (($\chi^2(6,8) = 18.3$, $P = 0.006$). Green tagged group experienced the largest loss. The reason for the higher green tag mortality rates is unknown. For double tags, mortalities were also not uniformly spread among treatments ($\chi^2(8,58) = 77.3$, $P < 0.001$). The white/green, pink/white, and blue/white tag groups experienced the largest loss and contributed 83 % to the total loss within the double tag groups. Higher mortality rates for double tag groups using white may be attributed to the difficulty of injecting white to the dorsal fin. Because of poor retention,

the color white had to be injected several times into the dorsal fin before the color was finally retained lengthening the exposure to anesthesia.

Table 1. Pacific Lamprey macrophthalmia size of each tagged group.

Color and Fin Tagged	# Tagged	Average Fish Length (TL mm)	Std. Dev. Fish Length (TL mm)	Min. Fish Length (TL mm)	Max. Fish Length (TL mm)
Pink Dorsal	51	138	13.2	122	168
Yellow Dorsal	51	134	11.6	119	160
Blue Dorsal	51	135	12.0	116	161
Violet Dorsal	51	133	7.4	119	144
Orange Dorsal	51	135	8.2	119	151
Green Dorsal	51	134	9.4	124	159
White Dorsal	51	140	12.1	122	164
White Green Dorsal	51	132	8.9	118	150
Brown Dorsal	51	138	12.7	111	158
Pink White Dorsal	51	135	10.3	119	156
Blue White Dorsal	51	136	10.0	114	159
Orange Blue Dorsal	51	135	8.7	121	149
Blue Yellow Dorsal	51	133	9.0	114	150
Yellow Pink Dorsal	51	137	9.5	120	157
Pink Blue Dorsal	51	135	8.9	121	159
White Violet Dorsal	51	132	9.5	112	152
		135	**10.2**		

Table 2. Mortalities within each tag group.

Single Tag	Mortalities	Double Tag	Mortalities
Pink Dorsal	1	White/Green Dorsal	21
Yellow Dorsal	0	Pink/White Dorsal	13
Blue Dorsal	0	Blue/White Dorsal	14
Violet Dorsal	0	Orange/Blue Dorsal	0
Orange Dorsal	0	Blue/Yellow Dorsal	0
Green Dorsal	5	Yellow/Pink Dorsal	8
White Dorsal	2	Pink/Blue Dorsal	1
Brown Dorsal	1	White/Violet Dorsal	0
Total	**9**	**Total**	57
Mean Mortality	**1.1**	**Mean Mortality**	7.1

Six to seven secondary louver replicates were planned during the day and night for each water velocity (Table 3). Water temperature and turbidity were not significantly different between velocity categories (Tukey's Test, $P > 0.05$), but were significantly different between day and night (Two-Way ANOVA, Tukey's Test, $P < 0.05$). Tides may have influenced the turbidity since the day replicates were done during an outgoing tide and the night replicates were done at an incoming tide. Independent linear regression models suggest velocity had a significant effect on participation of lamprey during both day (regression model, $P = 0.002$, $R^2 = 0.43$) and night conditions ($P = 0.005$, $R^2 = 0.38$) with more macrophthalmia participating at faster velocity and at night (ANCOVA, $P = 0.0001$; Figure 7).

Higher night participation was expected since macrophthalmia are nocturnal, showing higher levels of activity during night (Quintella *et al.* 2005, Dauble *et al.* 2006), and downstream migration occur mostly at night (Moser and Mesa 2009). Increased participation with increased velocity is common across many species tested at the TFCF (Bowen *et al.* 2004). Similar to other fish species at lower water velocities (Karp *et al.* 2017, in press), lamprey are likely swimming out, lost through the louvers, or experience higher rates of predation since they spend more time drifting and exposed.

Though not evaluated independently due to significant multicollinearity with secondary velocity, the descriptive linear relationships between secondary participation and bypass ratio are reported in Figure 8.

Macrophthalmia secondary louver efficiency was lower (for a comparison to other Delta fish species and their louver efficiencies at the TFCF, see Appendix 1). Diel period did not have a significant effect on secondary channel louver efficiency of macrophthalmia (Tukey's Test, $P > 0.05$). However, when averaged across diel period, secondary channel louver efficiency of macrophthalmia exposed to a velocity of 0.3 m/s (1 ft/s) were significantly greater than those exposed to a velocity of 0.9 m/s (3 ft/s; Two-Way ANOVA, Tukey's Test, $P < 0.05$; Figure 9).

Few lamprey released at the trashrack were recovered in the holding tank over the three days of WFE testing. Mean (SD) percent recovered for the three days was 5%. Unlike the secondary louver channel, a net cannot be placed behind the primary louver to collect macrophthalmia that swim through the primary louvers and predators within the much larger primary channel were not removed before the tests. Therefore, loss occurring at the primary channel can be attributed to these two factors. Furthermore, non-participation may be attributed to macrophthalmia swimming out of the TFCF back to the Delta or macrophthalmia maintaining themselves within the TFCF. With the replacement of the secondary channel louvers with a traveling screen in 2014, the WFE is expected to improve; however, macrophthalmia loss at the TFCF will continue to occur since louvers are still used at the primary channel and no predator removal program is in place.

Table 3. Secondary louver channel Pacific Lamprey macrophthalmia test data. Data reported as secondary louver efficiency (SLE) or secondary channel participation (SCP) in relation to water velocity and day/night testing.

		% SLE (Day)			% SCP* (Day)	
Water Velocity (m/s)	**0.3**	**0.6**	**0.9**	**0.3**	**0.6**	**0.9**
Mean	23.6	14.8	3.9	33.4	58.1	72.3
Std. Dev.	18.9	6.8	3.7			
Replicates	6	6	7	6	6	7
Upper 95% CI	38.8	17.3	6.7	51.8	72.5	81.9
Lower 95% CI	8.5	8.3	1.1	17.4	43.0	61.6
		% SLE (Night)			**% SCP (Night)***	
Water Velocity (m/s)	**0.3**	**0.6**	**0.9**	**0.3**	**0.6**	**0.9**
Mean	28.0	20.4	16.0	72.6	88.7	89.4
Std. Dev.	16.5	18.4	11.1			
Replicates	7	6	6	7	6	6
Upper 95% CI	36.1	39.5	26.8	82.9	94.0	93.6
Lower 95% CI	8.9	9.3	11.6	60.9	82.0	84.4

* Participation data was arcsine square root transformed before analysis; therefore, confidence intervals about the mean are not symmetrical, and standard deviations are not reported.

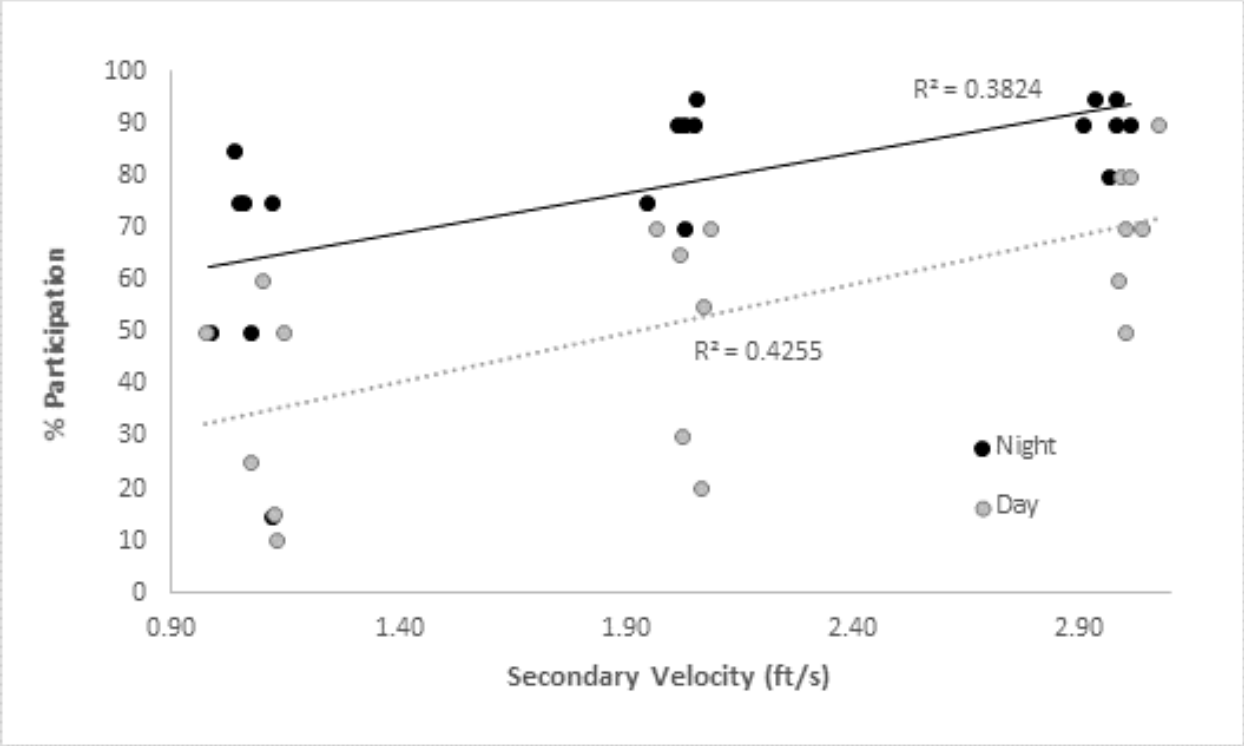

Figure 7. Secondary channel participation of Pacific Lamprey macrophthalmia as function of water velocity.

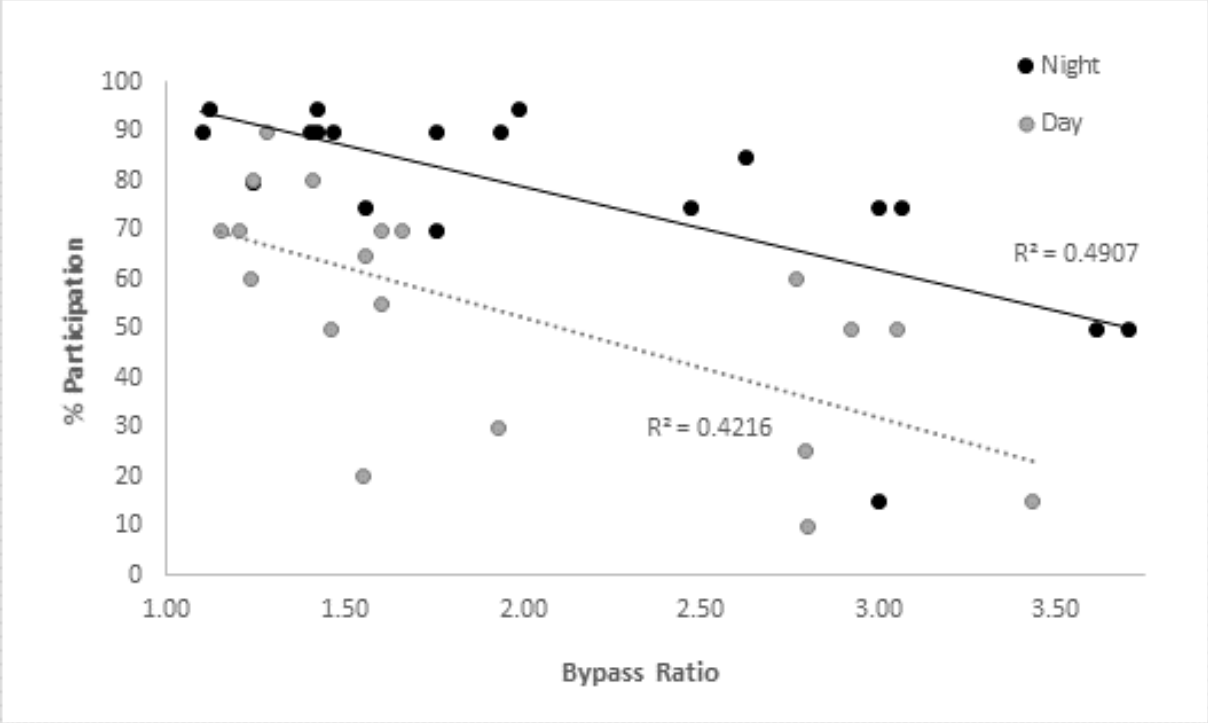

Figure 8. Secondary channel participation of Pacific Lamprey macrophthalmia as a function of bypass ratio.

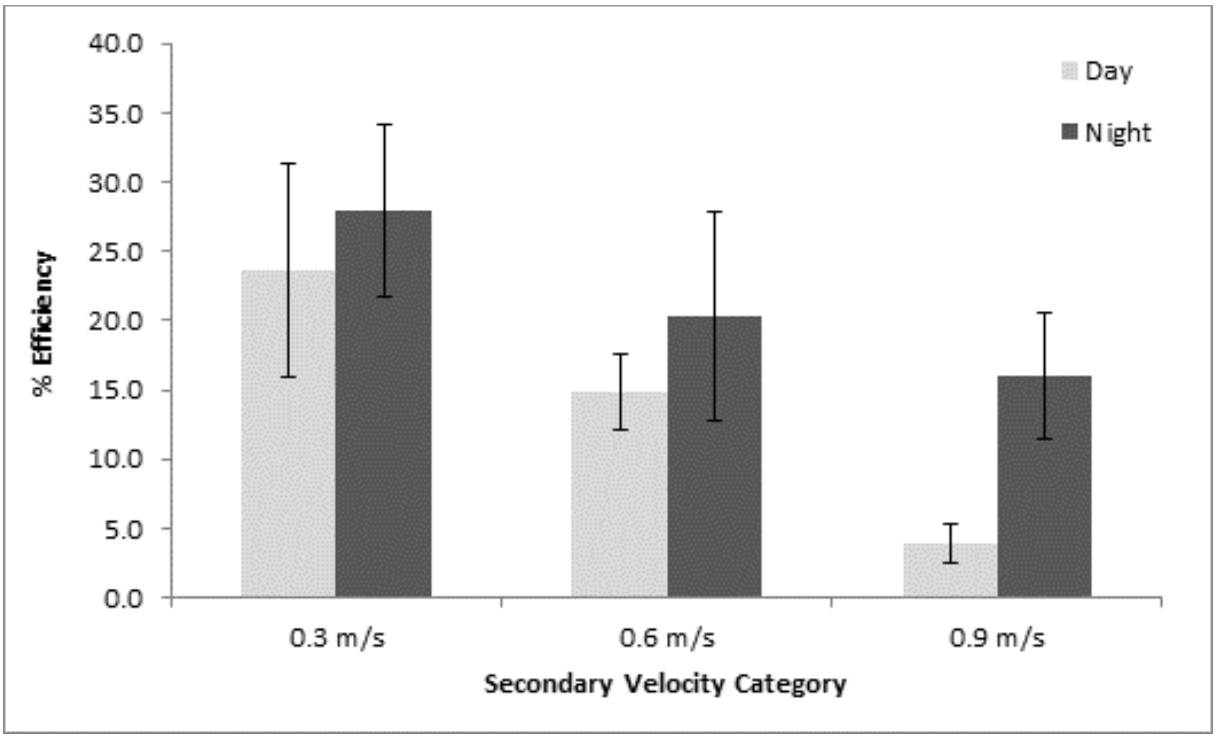

Figure 9. Secondary channel louver efficiency (mean ± SD) of Pacific Lamprey macrophthalmia as a function of diel period and water velocity.

Recommendations

The louver system at the TFCF is not effective at guiding entrained Pacific Lamprey macrophthalmia to the holding tanks for salvage. In 2014, the secondary channel louvers were replaced with a traveling screen (1.5 mm x 50 mm slit opening) thereby significantly reducing macrophthalmia loss at this location; however, macrophthalmia loss at the primary channel will continue to occur as long as louvers are in use. To minimize negative impact of Striped Bass to migrating macrophthalmia, a predator removal program should be implemented during winter which would also benefit outmigrating Chinook Salmon and adult Delta Smelt. Two integral components of the salvage process, the holding tanks and the fish haul bucket, should also be tested in the future.

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Appendix A. Louver Efficiency Results from Studies Conducted at the Tracy Fish Collection Facility

Table A-1. Louver efficiency results from studies conducted at the Tracy Fish Collection Facility.

Author	Year	Primary Efficiency (%)	Secondary Efficiency (%)	Species Tested	Size Range (mm)
Bates *et al.* (1960)	1957–1959	—	92–100	Chinook Salmon	—
		—	86–95	Striped Bass	—
		—	65–92	White Catfish	—
Hallock (1967)	1966–1967	5.4	—	Striped Bass	10–24
		76–99.4	—	Striped Bass	25–39
Hallock *et al.* (1968)	1966–1967	90	—	Chinook Salmon	70–100
		2–100	—	Striped Bass	6–19
		64.7–99.7	—	Striped Bass	10–24
		89	—	Shad spp.	—
Karp *et al.* (1995)	1993	13–82	72–100	Chinook Salmon	58–127
		40–96	30–90	Striped Bass	—
Bowen *et al.* (1998)	1993–1995	—	83.2	Chinook Salmon	—
		—	85.7	Striped Bass	—
Bowen *et al*. (2004)	1996–1997	—	85.1	Chinook Salmon	—
		—	61.6	Striped Bass	—
		—	13–82.5	Delta Smelt*	—
			60–75	Splittail	—
Bridges, unpublished	2010	—	22–63	Delta Smelt	32–40
Karp and Bridges (2015)	2009	32.2	93.3	White Sturgeon	105–265

* 13% when > 3.1 ft/s (0.94 m/s), 82.5% when < 1.09 ft/s (0.33 m/s).