Evaluation of changes in abundance and methods for salvage of larval lamprey during a “slow” water drawdown and dewatering in Leaburg Reservoir, OR

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On the cover: Biologists convened at Leaburg Reservoir (near Leaburg, Oregon) to assist in the evaluation of research and salvage techniques for larval lampreys during a scheduled drawdown in March 2018 (Photo credit: Patrick Cooney, Smith-Root).

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EVALUATION OF CHANGES IN ABUNDANCE AND METHODS FOR SALVAGE OF LARVAL LAMPREY DURING A “SLOW” WATER DRAWDOWN AND DEWATERING IN LEABURG RESERVOIR, OR

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Abstract

Similar to other lampreys, Pacific Lamprey Entosphenus tridentatus is of cultural importance and increasing management concern. Larval lamprey naturally reside and burrow in fluvial sediments making them especially vulnerable to stranding and mortality during dam operations that dewater their nursery habitats, such as the drawdown of Leaburg Reservoir (McKenzie River, OR) in March 2018. Our study objectives were to: 1) identify changes in larval distribution, abundance, and density due to the drawdown; 2) evaluate techniques (excavation, liquefaction, and electrofishing) to sample and salvage larvae in dewatered habitats; and 3) examine larval emergence from burrows during dewatering. We assessed changes in distribution, abundance, and density by deepwater electrofishing before and after the drawdown. We evaluated techniques and examined emergence by sampling in 1-m² quadrats during the drawdown. The estimated number of larvae in the study area (1,142 m²) was substantially higher before the drawdown (~12,300; 95%: 10,893–14,011) than after re-watering (~2,600; 95%: 2,196–3,206). As water receded, 45% of burrowed larvae (65 fish) emerged from the eight excavated quadrats; the remaining 55% (80 fish) were collected by excavation. In eight observation quadrats, 34 larvae emerged during dewatering and six emerged after the quadrat was fully dewatered. Thus, about 53% of larval lamprey volitionally emerged during the drawdown, with 85% of emergence occurring as the surface of the sediment was dewatering. Liquefaction was not successful due to the high flow level of the pump and further study is required to evaluate its efficacy. Excavation was useful for research, but too time-consuming and disruptive to sediment for use in salvage. Electrofishing dewatered sediments was effective at removing burrowed larvae and may aid salvage during future drawdowns. Similar to laboratory dewatering studies, our field results suggested that about 50% of larval lamprey in the study area of Leaburg Reservoir emerged during the drawdown, resulting in changes in abundance and distribution. This work suggests that drawdowns could negatively affect Pacific Lamprey and other lamprey populations in regulated rivers. Future studies to identify fates of larval lamprey that remain burrowed and those that emerge could help clarify population-level impacts of drawdowns.
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Introduction

Pacific Lamprey *Entosphenus tridentatus* is an anadromous species that has experienced declines in distribution and abundance in many freshwater areas including the Columbia River Basin (CRB; Close et al. 2002; Wang and Schaller 2015; Clemens et al. 2017). The species is culturally important to Native American tribes and ecologically important in freshwater and marine ecosystems (Close et al. 2002; Wang and Schaller 2015; Clemens et al. 2017, 2019). Pacific Lamprey is an indicator species whose decline provides insight into the impacts of human actions on ecological function (Close et al. 2002; Wang and Schaller 2015). However, much information on biology, ecology, population dynamics and responses to anthropogenic impacts is lacking and required for effective conservation of Pacific Lamprey and management of regulated rivers (Clemens et al. 2017).

Pacific Lamprey has a complex life history that includes a multiple year larval stage, a juvenile marine stage, and an adult stage that returns to freshwater to spawn and die (Clemens et al. 2010, 2019). Larvae and juveniles are strongly associated with fluvial sediments. Larvae live burrowed in stream and river sediments for multiple years after hatching where they filter feed on detritus and organic material (Sutton and Bowen 1994; Dawson et al. 2015; Evans and Weber, In Press). The sympatric Western Brook Lamprey *Lampetra richardsoni* also burrows in fluvial sediment as larvae, but does not have a marine life stage (Renaud 2011). For both species, the majority of the information on biology, distribution, and habitat preferences of larvae comes from the CRB (e.g., Moser and Close 2003; Torgersen and Close 2004; Stone and Barndt 2005; Stone 2006) and coastal basins (e.g., Farlinger and Beamish 1984; Russell et al. 1987; Gunckel et al. 2009; Starcevich et al. 2014).

Water drawdowns are often required for repair and routine maintenance of dams in regulated rivers and dewatering during drawdowns can cause stranding of burrowed larval lamprey (Figure 1). To our knowledge, no studies have assessed or quantified the effects of dewatering on larval lamprey behavior and biology in the wild; however, in a controlled laboratory setting, Liedtke et al. (2015) examined effects of dewatering on the burrowing behavior and survival of larval lamprey. They examined two dewatering rates (7.6 and 50.8 cm/hr) during daylight conditions over a 10% slope. They observed that about 50% of larvae emerged from burrows regardless of the dewatering rate, but that the faster rate stranded more lamprey. They observed no response to changing head pressure on emergence timing and larger lamprey were more likely to regain access to water following the dewatering event than smaller larvae. Also, exposure time (i.e., the amount of time the area was dewatered) over 24 hours significantly reduced survival of both emerged and burrowed larvae. Controlled experiments like those by Liedtke et al. (2015) are essential, but in situ studies on larval behavior are needed to corroborate laboratory results to aid conservation of Pacific Lamprey and other lampreys, develop best management practices, and inform stream management in regulated environments.

The goals of this study were to assess effects and examine potential salvage methods of larval lamprey during a drawdown in Leaburg Reservoir on the McKenzie River, OR. In March 2018, Eugene Water & Electric Board (EWEB) planned a partial drawdown of Leaburg Reservoir to conduct dam related maintenance. Observations during a previous Leaburg Reservoir drawdown in 2015, at the same site we assessed, showed perhaps thousands of larval lamprey were stranded
in dewatered areas (Figure 1). Because of the silt accumulation behind the Leaburg Dam and discovery of high lamprey densities, EWEB wanted to implement best management practices for conservation of lamprey larvae during subsequent drawdowns. Based on the laboratory experiments by Liedtke et al. (2015), it was hypothesized that a relatively “slow” (e.g., ≤ 7.62 cm/hr) ramping rate may decrease the proportion of stranded larvae during dewatering, potentially minimizing population-level impacts of a drawdown. Our specific study objectives were to: 1) identify changes in abundance, density, and spatial distribution due to dewatering; 2) assess sampling methods (liquefaction, “dry” electrofishing, and excavation) for study and salvage during a drawdown; and 3) examine the proportion and timing of larval emergence from burrows during the drawdown using observation and excavation.

**Study Area**

Leaburg Reservoir is a 0.28 km² impoundment located on the McKenzie River in western Oregon (Figure 2). The McKenzie River originates in the Cascade Mountains of Willamette National Forest and drains an area of about 3,400 km² to the Willamette River, in the CRB. Three dams exist on the mainstem of the McKenzie River and the most downstream is Leaburg Dam (RMK 62.4). Leaburg Dam was built in 1929, is approximately 3-m tall, and is owned and operated for hydroelectric power generation by EWEB. Passage efficiencies of Pacific Lamprey at the two fishways on Leaburg Dam are unknown, but areas upstream of the dam are occupied. Our study took place in a 1,142 m² area along the shoreline, just upstream from Leaburg Dam that was expected to be completely dewatered during the drawdown (Figure 2).

**Methods**

**Objective 1: Evaluation of effects of dewatering on larval lamprey abundance and distribution**

**Field Assessment**

To evaluate changes in larval lamprey density, abundance, and spatial distribution in the 0.91 m drawdown zone (i.e., dewatered area), we collected 40 samples both the day before the drawdown started on March-21 and the day after re-watering finished, March-25, using a deepwater electrofisher (Figure 3). Deepwater electrofishing techniques were first developed for collecting larval lamprey by Bergstedt and Genovese (1994) and have since been used in the Great Lakes (Fodale et al. 2003), and CRB (Jolley et al. 2012; Harris and Jolley 2017). The deepwater electrofisher was comprised of a modified AbP-2 electrofisher (ETS Engineering, Madison, WI) which delivered electrical stimulus to river bottom substrates at electrodes mounted to a fiberglass bell that was 0.65 m² in area (i.e., “deepwater shocker”; Figure 3 Inset;). The electrofisher delivered three pulses DC per second at a 25% duty cycle, with a 2:2 pulse train (i.e., two pulses on, two pulses off). Output voltage was adjusted for each sample to maintain a peak voltage gradient between 0.6 and 0.8 V/cm across the electrodes. The electrofisher bell was coupled by a 76 mm vinyl suction hose to a gasoline-fueled hydraulic pump. The hydraulic pump was started approximately five seconds prior to shocking to purge air from the suction hose. Suction was produced by directing flow from the pump through a
hydraulic eductor, which allows larvae to be collected in a mesh basket (27 x 62 x 25 cm; 2 mm wire mesh) while preventing them from passing through the pump. A 60 second pulse delivery was followed by an additional 60 seconds of pumping only to further allow displaced larvae to cycle through the hose and into the collection basket. The deepwater electrofisher, as currently configured, can sample in depths from 0.25 to 18 m. In an experimental setting, Harris and Jolley (2017) estimated that capture probability of the deepwater electrofisher (i.e., probability that a larval lamprey is collected within the bell) is approximately 0.70.

Locations of the 40 samples collected before dewatering and after re-watering were selected randomly using a GIS algorithm and located by boat using a Trimble GPS for navigation. Once at the location for each sample, we collected data on water depth and velocity. We visually estimated percent vegetation and visually categorized sediment type as: fines dominant (mix of fine sands and silt); mixed; and fines minimal. Sediment was characterized by fines, since larval lamprey species, including Pacific Lamprey (Torgersen and Close 2004; Stone and Barndt 2005), appear to prefer burrowing in fine sediments (Slade et al. 2003; Smith et al. 2011; Ferreira et al. 2013; Aronsuu and Virkkala 2014). We measured all collected larvae for total length (TL in mm). We identified larvae greater than 60 mm TL to genus (i.e., *Entosphenus* [Pacific Lamprey] or *Lampetra* [Western Brook or Western River Lamprey *L. ayresii]*) according to visual evaluation of caudal fin pigmentation patterns (Goodman et al. 2009; Docker et al. 2016). Upon resuming swimming behavior, larvae were released outside the 0.91 m drawdown zone.

**Analysis**

We used a modified N-mixture model (Harris and Jolley 2017) to estimate abundance of larval lamprey, and logistic regression to estimate the probability of collecting at least one larval lamprey both before de-watering and after re-watering as a function of sediment type (i.e., fines dominant, mixed, or fines minimal) and minutes dewatered. Other collected covariates were not included in analyses due to high correlations among the covariates values.

The first level of the hierarchical N-mixture model assessed spatial variability in local abundance from count data across the 40 samples. The second level incorporated independent data from a capture probability experiment (in Harris and Jolley 2017) to correct abundance estimates for the potential that the deepwater electrofisher missed some larvae in the sample area (i.e., potential for uncaptured individuals within the perimeter of the bell area; Figure 3). For the first level, the unobserved true abundance ($N_i$) in a sample ($i$) was estimated using a Poisson distribution:

$$N_i \sim \text{Poisson} (\lambda_i)$$

where $\lambda_i$ is the expected value for larval abundance in sample ($i$). We used the log link function to evaluate the relationship between expected abundance at a site $\lambda_i$ and the number of minutes the sample location was dewatered ($D_i$: continuous and scaled) and sediment type ($S_i$: fines dominant, mixed, and fines minimal):

$$Log(\lambda_i) = b_0 + b_1 D_i + b_2 [S_i]$$
where $b$ values indicate estimated coefficients. For the second level, each count ($y_i$) was a function of the true abundance ($N_i$) and capture probability of the deepwater electrofisher ($p$):

$$y_i \sim \text{Binomial}(N_i, p)$$

Capture probability ($p$) was estimated using data from an experimental tank study (n=23 tanks) described in Harris and Jolley (2017). Capture probability ($p$) was estimated as a function of the total number of individual larvae captured by the deepwater electrofisher in each tank ($C_i$) and the total number of larval lamprey available for capture in that tank ($A_i$):

$$C_i \sim \text{Binomial}(A_i, p)$$

This level accounts for less than 100% detection during the sampling process (Kéry and Schaub 2012). We calculated the expected mean density (i.e., mean # of larval lamprey per m$^2$) both before dewatering and after re-watering separately as the mean of all $N_i$ divided by the number of square meters in one sample (i.e., 0.65). We calculated total expected abundance ($T$) in the 0.91 m drawdown zone both before dewatering and after re-watering, as mean density multiplied by the total number of square meters in the zone (i.e. 1,142).

We used statistical simulation to examine how the number of deepwater electrofishing samples (20-50 by 10) could affect bias and precision of abundance estimates using data from before the drawdown and after re-watering analyzed separately. Each simulated dataset of counts was produced by randomly sampling with replacement from true counts (i.e., $y_i$) either from before the drawdown or after re-watering. We simulated 1,000 replicates of 20, 30, 40, and 50 random counts from each true dataset to examine bias and precision at different sample sizes both before dewatering and after re-watering. We simplified the N-mixture model to estimate one $\lambda$ for all samples (i.e., we did not include covariates) and used that $\lambda$ to estimate total abundance ($M_i$) for each simulated ($i$) dataset. To assess bias by sample size, we calculated percent error ($100 \times (M_i - T)/T$) for each simulation ($i$) of abundance assuming expected abundance ($T$; either before dewatering or after re-watering, as appropriate) was unbiased. To assess precision, we calculated the coefficient of variation ($100 \times \sigma_i/N$) for each simulation ($i$) using the model estimated standard deviation ($\sigma_i$). We used boxplots to examine expected bias and precision for each sample size (i.e., 20, 30, 40, and 50) before dewatering and after re-watering.

We used logistic regression to estimate the probability that at least one larval lamprey was collected and to relate the probability to environmental variables both before and after the drawdown. Specifically, we used the logit link function to examine if the probability that a sample contained at least one larval lamprey ($O_i$) was a function of the number of minutes the sample location was dewatered ($D_i$) and sediment type ($S_i$: fines dominant, mixed, or fines minimal):

$$\text{Logit}(O_i) = a_0 + a_1 D_i + a_2 [S_i]$$

where $a$ values indicate estimated coefficients. Actual samples ($x_i$) either contained or did not contain at least one larval lamprey:
We calculated expected proportions of occupied samples both before drawdown and after re-watering as the mean of all \( O_i \).

**Objectives 2 and 3: Assessment of salvage methods and volitional emergence timing by larvae**

**Field Sampling**

To assess impacts of dewatering on larval lamprey emergence in the wild and to assess the potential to collect larval lamprey during a drawdown (i.e., March 22-23) for research and salvage, we sampled during the drawdown in Leaburg Reservoir. Sampling was conducted in eight 3-m² plots randomly selected within the drawdown zone. Each of the 3-m² plots were further subdivided into nine 1-m² quadrats by fiberglass stakes set in the corners. Within each plot, we randomly assigned each corner quadrat to one of four techniques: excavation, “dry” electrofishing, liquefaction, and observation (Figure 4). Sampling began in a 1-m² quadrat when it began to de-water. During the first \(~15\) minutes, each quadrat was observed as it became fully de-watered, and all larvae that emerged were counted. Following the 15-minute dewatering period, in excavation quadrats, all sediment down to 15 cm substrate depth was excavated and sieved in a 2 mm mesh basket to locate and count all larvae. In “dry” electrofishing quadrats, backpack electrofishing was conducted for multiple passes with each pass defined as 90 s of electrofishing followed by a 15 min rest interval (Harris et al. 2016). Electrofishing settings were 125 V, 3 Hz pulse frequency, with a 25% duty cycle and a burst pulse train of 3:1. Repeated passes were made until 0 lamprey emerged for two consecutive passes. In liquefaction quadrats, a 0.5 m² 15-cm deep bottomless cylinder was placed over the substrate to contain lamprey. A Lifan 2.5 HP pump with a metal wand was inserted into the sediment within the cylinder and water pumped in at various depths. Any emerging lamprey were documented. In observation quadrats, all larvae that emerged were counted and recorded in 15-minute intervals.

**Analysis**

We estimated the timing and proportion of larvae to exit their burrows volitionally and larval abundance in the dewatered area using information from multiple sampling techniques (Figure 4). To examine timing of volitional emergence, we observed eight quadrats for 60-105 minutes post dewatering and noted the number of individuals to emerge during the de-watering period and within each subsequent 15-minute interval (i.e., “Observation” quadrats). To estimate the proportion of larvae that emerged volitionally during dewatering (i.e., during the period when the water was receding), we observed quadrats during de-watering then excavated the sediment down to 15 cm depth (i.e., “Excavation” quadrats). We assumed all larval lamprey in excavation quadrats (\( q \)) were detected: either they emerged volitionally during dewatering and were seen on the surface (\( V_q \)) or they were detected in the sediment by sieving (\( E_q \)). We estimated the proportion to emerge volitionally during dewatering (\( v \)) as:

\[
V_q \sim \text{Binomial} \left( (V_q + E_q)_q, v \right)
\]
We assumed that \( v \) from excavation quadrats was also appropriate for observation and “dry” electrofishing quadrats; thus, we divided the total number to initially emerge from observation and “dry” electrofishing quadrats by \( v \) to estimate the expected total number in those quadrats. After estimating the total number in observation quadrats, we could calculate the proportion to emerge later during the drawdown in the observation quadrats. For “dry” electrofishing quadrats, we compared the total number collected by electrofishing to the total number expected in the quadrats based on emergence during dewatering. No analysis was completed for liquefaction quadrats, because the technique was unsuccessful.

All analyses were evaluated by Bayesian methods using JAGS software (Plummer 2003) called from Program R (R Core Team 2013). We included three chains, a burn-in of 10,000, and saved 50,000 iterations. We assumed model convergence when Rhat scores were less than 1.1 for all estimated parameters (Gelman and Hill 2007; Kéry and Schaub 2012). We reported the median as the expected value and the 95% credible interval to describe precision.

Results

The drawdown at Leaburg Reservoir was conducted on 22-23 March 2018 at a rate of 4.57 cm/hr and re-watering occurred on 24 March 2018 at a similar rate (Figure 5). During the drawdown, it was cool and cloudy with some rain and sun breaks. Daytime air temperatures ranged from 1.7 to 7.8 \( ^\circ \)C. Discharge at the USGS gage 14163900 McKenzie River near Walterville, varied between 42.7 to 65.8 cubic m/s. Water temperature at the same gage varied between 4.5–7.6 \( ^\circ \)C. Observed water clarity was excellent.

Objective 1: Evaluation of effects of dewatering on larval lamprey abundance and distribution

Before the drawdown, we conducted 40 samples using the deepwater electrofisher and collected a total of 196 larval lamprey ranging in size from 12 – 144 mm TL (Figure 6). The number of larval lamprey in a sample was variable and ranged from 0 – 38. Total abundance before the drawdown was estimated at 12,255 (95%: 10,893 – 14,011) and density was estimated at 10.7 larvae/m\(^2\) (95%: 9.5 – 12.3; Figure 7). Larval counts from samples with fines dominant or mixed sediments were higher than counts in samples with fines minimal (Table 1) and 95% credible intervals did not overlap. The expected proportion of samples containing at least one larva before the drawdown was 0.60 (95%: 0.47 – 0.73). There was a higher probability of larval presence when fines were dominant compared to when fines were minimal and 95% credible intervals for those two sediment categories did not overlap (Table 1). Probability of a larval lamprey in mixed sediments was intermediate (Table 1). Median estimates suggest a slightly negative relationship between lamprey count or presence in a sample and the amount of time that the sample location was dewatered, but 95% credible intervals overlapped zero (Table 1).

After dewatering and refilling the reservoir, we completed 40 samples in the study area resulting in collection of 42 larval lamprey (0-10 in a sample) ranging in size from 15 to 95 mm (Figure 6). Total abundance after re-watering was estimated at 2,591 (95%: 2,196 – 3,206) larvae and average larval density was 2.3/m\(^2\) (95%: 1.9 – 2.8; Figure 7). Similar to before dewatering, larval counts and the probability of larvae were higher in samples with fines dominant as compared to
areas with minimal fines and 95% credible intervals did not overlap between the two sediment
categories (Table 1). Samples in mixed sediments were intermediate and 95% credible intervals
overlapped with the two other sediment categories. In addition, similarly, median estimates
suggested slightly negative relationships between the amount of time that the sample location
was dewatered, and both lamprey count in a sample and lamprey presence in a sample, but 95%
credible intervals overlapped zero for both relationships (Table 1).

Simulation results suggest that bias was likely lower and precision higher for abundance
estimates produced before the drawdown as compared to those produced after re-watering
(Figure 8). Median simulated estimates of abundance were slightly (all within 5%) lower than
expected “true” estimates (i.e., estimates that used the true counts and included covariates in the
model) and the range in simulated abundance estimates decreased with simulated sample size
both before drawdown and after re-watering (Figure 8). Simulated abundance estimates were
within 25% of the true estimate ($T = 12,298$) when 30-50 samples were selected from pre-
drawdown counts for at least 50% of the simulated datasets (Figure 8). Simulated abundance
estimates from the middle 50% of simulated datasets were within 18% of the true estimate and
all simulated abundances estimates were within 65% of the true estimate when 40 samples (i.e.,
number collected in this study) were selected from pre-drawdown counts. In contrast, simulated
abundance estimates post re-watering were within 25% of the true estimate ($T = 2,635$) for 50%
of the simulated datasets only with 50 samples (Figure 8). Also from post re-watering counts,
estimates from the middle 50% of simulated datasets with 40 samples were within 27% of the
true estimate and all simulated abundances estimates were within 135% of the true estimate
(Figure 8). Precision improved with increases in sample size for simulated datasets (Figure 8).
For pre-drawdown simulations, the median coefficient of variation ranged from 7.77 for 20
counts to 6.37 for 50 samples and all coefficients were less than 10% with 40 or 50 samples. For
post drawdown simulations, the median coefficient of variation ranged from 13.66 for 20
samples to 9.46 for 50 samples and all coefficients were less than 20.5% with 40 or 50 samples.

Objectives 2 and 3: Assessment of salvage methods and volitional emergence timing of larvae

Eight 1-m² excavation quadrats were observed while water was receding (i.e., “dewatering
period” of ~15 minutes) and then immediately excavated to collect any remaining larval
lamprey. During the dewatering period, 65 individuals emerged volitionally from excavated
quadrats. An additional 80 individuals were collected through excavation, for a total of 145
individuals in excavated quadrats or a density of 18.1 larvae/m². Data from one quadrat had to be
removed for analysis of proportion to emerge volitionally (i.e., $v$) since no individuals were
detected in that quadrat. The expected value for $v$ (i.e., proportion to emerge during dewatering)
was 0.45 (95%: 0.37 – 0.53).

Thirty-four individuals emerged volitionally during dewatering from observation quadrats. After
the dewatering period ended, six additional larvae volitionally emerged, two in the first 15-
minute interval. Thus, 85% of all larvae to emerge did so as water was receding through the
quadrat. Assuming our estimate of $v$ (estimated above), we estimated 76 (95%: 64 – 92) larvae
in the eight observation quadrats for an overall estimated density of 9.5 larvae/m² (95%: 8.0 –
11.5). The total proportion of larval lamprey to volitionally emerge from observation quadrats
during the drawdown at Leaburg Reservoir was estimated to be 0.53 (95%: 0.43 – 0.62).
From the eight electrofishing quadrats, 54 individuals were observed volitionally emerging during dewatering and an additional nine were observed volitionally emerging during a 15-minute window after dewatering and before electrofishing started. Assuming $v$ (estimated above), we estimated that the total number in electrofishing quadrats would be 120 larvae (95%: 102 – 146) for an expected density of 15.0 larvae m$^2$ (95%: 12.8 – 18.3). A total of 69 larvae were collected during electrofishing (1 to 10 passes/quadrat), for a total number of 132 larvae observed or collected from electrofishing quadrats. Thus, more larvae were collected in electrofishing quadrats (i.e., 132) than were expected (i.e., 120), but not more than potentially expected, as suggested by 95% credible intervals (i.e., 102 – 146).

Liquefaction did not prove effective in sampling lamprey from dewatered test quadrats conducted just prior to the fieldwork. No lamprey were collected. Liquefaction was likely unsuccessful due to high flow level of the pump and further study is required to determine its efficacy. The pump was effective at delivering water into the substrate but at too high of a flow rate. Because of high flow rate and the likelihood of affecting adjacent quadrats, we abandoned liquefaction from further use during this study.

**Discussion, Conclusions and Management Implications**

To the best of our knowledge, this is the first study to examine the effects of dewatering on larval lamprey during a drawdown. Drawdowns are common for construction and maintenance of water control structures, hydroelectric power operations, and for habitat restoration projects. Drawdowns can result in dewatering of areas used by larval lampreys, including larval Pacific Lamprey; thus, understanding the effects of drawdowns, on larvae specifically and lamprey populations more generally, is essential for identifying best management practices during these operations. In this study, we quantified effects of dewatering on larval lamprey emergence and distribution in an affected area, and we evaluated potential field techniques for use in future study and salvage efforts during drawdowns and other operations that would result in dewatering of larval lamprey habitat.

Our results suggest that most larval lamprey will either 1) emerge almost immediately due to habitat dewatering, or 2) remain in their burrows and not emerge at all. About 85% of all larvae that emerged did so while water was receding from the quadrat. Larvae may emerge almost immediately because some sediments quickly become compacted after dewatering, making it difficult to emerge any later. For burrowing fishes, the water layer just above the sediment is important for burrowing behavior (Tatom-Naecker and Westneat 2018); thus, we could speculate that the process of dewatering likely immediately affects both emergence and burrowing behaviors. Liedtke et al. (2015) found emergence after dewatering was 44% for trials where emergence was recorded 1-hour post-dewatering, and was actually lower (35%) in trials where emergence was recorded 4-hours post-dewatering. Since they did not detect burrowing behavior in dewatered areas, this also suggests that most emergence occurs soon after dewatering, if emergence is going to occur. Our field results suggest that just over half of the larvae volitionally emerged during the drawdown. It is unclear why some larvae emerged and others did not, but it may partially be due to larval burial depth, size (e.g., potential differences in mobility; Liedtke et al. 2015) or habitat conditions (e.g., differences in sediment type). Diversity of movement patterns within a species, such as “movers” and “stayers”, is common for some fish and likely
provides population resilience in changing or unstable environments (Grant and Noakes 1987; Moore et al. 2014; Schroeder et al. 2016). Diversity in emergence may be adaptive and potentially reduce impacts of natural events such as tides and anthropogenic dewatering events on lamprey populations.

The 0.91 m drawdown at Leaburg Reservoir reduced abundance of larval lamprey in the dewatered area, but fates of missing individuals are unknown. We detected a substantial decline in estimated abundance of larvae in the study area from 12,255 (95%: 10,893 – 14,011) individuals before the drawdown to 2,591 (95%: 2,196 – 3,206) individuals after re-watering. Although we know that many emerged, we do not know what proportions of these individuals moved and re-burrowed outside the study area, re-burrowed within the study area after re-watering, or perished due to exposure to desiccation or predation by birds and land mammals. Liedtke et al. (2015) found limited mobility of larvae stranded on the sediment surface, especially for smaller individuals, suggesting that emergence could increase the probability of mortality from exposure or predation. Lampreys are soft-bodied and high in lipid content; thus, they may be optimal prey for many animals (Roffe and Mate 1984; Close et al. 2002) and they may be especially vulnerable when stranded. We also do not know the fates of burrowed larvae; burrowed larvae may also have higher mortality, as found by Liedtke et al. (2015), making them unavailable to electrofishing after re-watering. Our simulation results suggest some imprecision in abundance estimates, but not enough to suggest that low sampling effort could explain the observed change in abundance. Regardless of the magnitude of change in abundance, more research into the fates of larval lamprey subjected to dewatering are needed to better identify the impacts of drawdowns on lamprey populations.

Larval lamprey display a patchy distribution in freshwater habitats, but appear closely associated with fine sediments. Multiple studies in shallow streams and deepwater habitats suggest that larval lamprey distribution and density vary considerably within and among systems at multiple spatial scales (Torgersen and Close 2004; Stone and Barndt 2005; Schultz et al. 2016; Harris and Jolley 2017). Similarly, results from multiple sampling methods suggested that larval density in the study area at Leaburg Reservoir was highly variable among samples, averaged 9.5 – 18.1 larvae/m², and was positively associated with fine sediments. Fine sediments are important nursery habitat for larval lampreys (Dawson et al. 2015). Future projects that require dewatering in areas accessible to anadromous and resident lampreys should consider the extent of fine sediment deposits to better assess the potential impact of dewatering on them.

Liquefaction may prove useful if the flow rate into the sediment could be adjusted, but tests are needed to evaluate flow rates in different sediments. Excavation can successfully estimate density of burrowed larvae (Ojutkangas et al. 1995), but it is time-consuming and disturbing to sediments, and therefore not ideal for use in salvage. We also collected burrowed larvae by “dry” electrofishing. A similar technique has been used to collected larval lamprey from salvage previously (Beals and Lampman 2018). Additional research is needed to evaluate lethal and sub-lethal effects of “dry” electrofishing compared with leaving burrowed individuals in the
sediment. Electrofishing under water is used commonly to sample larval lamprey (Moser et al. 2007) and appears to show minimal negative effects and low mortality at least in the short-term (Jolley et al. 2017). However, effects of “dry” electrofishing have not been examined. It is possible that the costs of repeated “dry” electrofishing to remove individuals will outweigh benefits, especially when the dewatering period is short (e.g., <24 hrs). Our results also improved understanding of bias and precision in density estimates generated by deepwater electrofishing. Due to the patchy distribution of larval lamprey within and across habitats, estimating density and abundance in particular areas can be challenging. Our simulation results suggest minimal systematic bias, but some imprecision; thus, even with 40 samples, abundance estimates from deepwater electrofishing may be incorrect by >50%. Deepwater electrofishing shows great promise to estimate abundance and density, but a more extensive study in multiple habitats would help assess how and when estimates from samples can be scaled up to abundance estimates in varied habitat.

In conclusion, we identified effects a drawdown on larval lamprey abundance and behavior in a dewatered area and examined potential methods to assess drawdown effects and to aid salvage. The purpose of this work was to aid conservation of Pacific Lamprey during operations in which nursery habitat may be dewatered. Our focus was on Pacific Lamprey, since they are of high cultural and ecological value in freshwater and marine ecosystems and are currently in decline due to anthropogenic factors, including dams and other water control structures (Close et al. 2002; Wang and Schaller 2015; Clemens et al. 2017, 2019). However, considering the similar sediment preferences of multiple species of larval lamprey (Slade et al. 2003; Smith et al. 2011; Ferreira et al. 2013; Aronsuu and Virkkala 2014), we suggest that this work could also inform potential effects and aid future studies and salvage efforts for many species of lamprey.

**Acknowledgements**

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**Literature Cited**


brook and river lampreys: implications for conservation and management. Biological Conservation 159:175-186.


Table 1. Estimated parameter coefficients from N-mixture model analysis ($b_{0-2}$) of larval lamprey counts and logistic regression analysis ($a_{0-2}$) of larval lamprey presence from deepwater electrofisher sampling in the drawdown area of Leaburg Reservoir both before the drawdown (“Pre-drawdown”) and after re-watering (“Post-drawdown”).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Pre-drawdown</th>
<th>Post-drawdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>Poisson intercept</td>
<td>-4.08 (-6.83 – -0.13)</td>
<td>-5.53 (-8.61 – -1.66)</td>
</tr>
<tr>
<td>$b_1$</td>
<td>minutes dewatered</td>
<td>-0.06 (-0.22 – 0.11)</td>
<td>-0.19 (-0.82 – 0.40)</td>
</tr>
<tr>
<td>$b_2[1]$</td>
<td>sediment dominant by fines</td>
<td>7.10 ( 3.15 – 9.85)</td>
<td>6.97 ( 3.03 – 9.86)</td>
</tr>
<tr>
<td>$b_2[2]$</td>
<td>mixed sediment</td>
<td>5.07 ( 1.11 – 7.84)</td>
<td>2.39 (-2.49 – 6.41)</td>
</tr>
<tr>
<td>$b_2[3]$</td>
<td>sediment with minimal fines</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$a_0$</td>
<td>Logistic intercept</td>
<td>-4.07 (-8.00 – 0.03)</td>
<td>-6.04 (-9.52 – -2.20)</td>
</tr>
<tr>
<td>$a_1$</td>
<td>minutes dewatered</td>
<td>-0.33 (-1.12 – 0.41)</td>
<td>-1.50 (-3.89 – 0.60)</td>
</tr>
<tr>
<td>$a_2[1]$</td>
<td>sediment dominant by fines</td>
<td>6.93 ( 2.19 – 9.85)</td>
<td>7.29 ( 3.02 – 9.85)</td>
</tr>
<tr>
<td>$a_2[2]$</td>
<td>mixed sediment</td>
<td>4.19 ( 0.00 – 8.20)</td>
<td>2.70 (-2.22 – 6.98)</td>
</tr>
<tr>
<td>$a_2[3]$</td>
<td>sediment with minimal fines</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 1. Photograph of stranded lamprey resulting from an accidental drawdown of Leaburg Reservoir in 2015. The boot print is approximately 30 cm long.
Figure 2. Study site depicting the location of Leaburg Dam on the McKenzie River at RMK 62.4 and the area of the 0.91 m drawdown assessed.
Figure 3. The deepwater electrofisher used in this study to collect burrowed larval lamprey both before de-watering and after re-watering. The inset illustrates the functional components of the deepwater electrofisher. Inset is Figure 1b. IN Bergstedt, R. A., and J. H. Genovese. 1994. New technique for sampling sea lamprey larvae in deepwater habitats. North American Journal of Fisheries Management 14(2):449-452.
**Figure 4.** Example of 3-m$^2$ plots setup with random assignment of 1-m$^2$ sampling quadrats. Graphic set in center depicts how the 3-m$^2$ plot would look from above.
Figure 5. Leaburg Lake drawdown and rewetting hydrograph. The 0.91 m drawdown occurred over 20 hours at a rate of 4.57 cm/hr.
Figure 6. Total length of the 196 larval lamprey collected by deepwater electrofishing before the drawdown (left panels) and after re-watering (right panels). “Larval lampreys” = those that were < 60 mm in total length, and so were not identifiable to species.
Figure 7. Results of deepwater electrofishing. Plate A depicts the number of lamprey collected on individual samples before the drawdown occurred (black circles) and Plate B depicts the number collected after the drawdown and refilling of the reservoir (white circles). The size of the circles is proportional to the number of lamprey collected.
Figure 8. Boxplots illustrating estimated abundance, percent error as a measure of bias, and coefficient of variation as a measure of precision, from simulations of 20-50 samples using the deepwater electrofisher in the affected area of Leaburg Reservoir before drawdown (“Pre-drawdown”) and after re-watering (“Post-drawdown”). The red line on the top panels illustrates the estimated abundance from the true counts and on the second panels illustrates bias of zero.