U.S. Fish and Wildlife Service

Evaluation of Larval Pacific Lamprey Rearing in Mainstem Areas of the Columbia and Snake Rivers Impacted by Dams
Study Code: LMP-P-11-2

FY 2014 Annual Report

Jeffrey C. Jolley, Gregory S. Silver, Joseph J. Skalicky, Julianne E. Harris, and Timothy A. Whitesel

U.S. Fish and Wildlife Service
Columbia River Fisheries Program Office
Vancouver, WA 98683

On the cover: *USFWS personnel conducting mainstem lamprey survey at the downstream end of the Hanford Reach on the Columbia River. Photo taken in October 2015 by Jeff Jolley.*

The correct citation for this report is:

Jolley, J.C., G.S. Silver, J. J. Skalicky, J.E. Harris, and T.A. Whitesel. 2016. Evaluation of Larval Pacific Lamprey Rearing in Mainstem Areas of the Columbia and Snake Rivers Impacted by Dams. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA. 33 pp.

Evaluation of Larval Pacific Lamprey Rearing in Mainstem Areas of the Columbia and Snake Rivers Impacted by Dams
Study Code: LMP-P-11-2

Study funded by

U.S. Army Corps of Engineers

and authored by

Jeffrey C. Jolley
Gregory S. Silver
Joseph J. Skalicky
Julianne E. Harris
Timothy A. Whitesel

U.S. Fish and Wildlife Service
Columbia River Fisheries Program Office
1211 SE Cardinal Court, Suite 100
Vancouver, WA 98683

Final
February 11, 2016

Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

The mention of trade names or commercial products in this report does not constitute endorsement or recommendation for use by the federal government.

Evaluation of Larval Pacific Lamprey Rearing in Mainstem Areas of the Columbia and Snake Rivers Impacted by Dams Study Code: LMP-P-11-2

Jeffrey C. Jolley, Gregory S. Silver, Joseph J. Skalicky, Julianne E. Harris, and Timothy A. Whitesel

U.S. Fish and Wildlife Service
Columbia River Fishery Program Office
1211 SE Cardinal Court, Suite 100
Vancouver, WA 98683

Abstract – Pacific lamprey *Entosphenus tridentatus* are declining in the Columbia River Basin and larval lamprey use of large, mainstem river habitats is understudied. Information on their use of shallow depositional areas in the mainstem associated with tributary inputs and non-tributary shallow-water areas is equally lacking. We used a unique deepwater electrofisher to explore occupancy, detection, and habitat use of larval Pacific lamprey and *Lampetra* spp. in John Day and McNary pools and associated river mouths of the John Day, Umatilla, Walla Walla, and Yakima rivers, as well as shallow-water pool margins in John Day and McNary pools. We used a generalized randomized tessellation stratified (GRTS) approach to select sampling quadrats in a random, spatially-balanced order. Shallow-water strata in John Day and McNary pools were delineated to indicate the areas that are most susceptible to dewatering by hydropower operations. Larval lamprey occupied all strata surveyed except the Walla Walla River mouth and Yakima River mouth, where they were not detected. We calculated strata-specific detection probabilities which ranged from not detected to 0.06. In strata where lampreys were found, detection was lowest in the John Day shallow-water and McNary Pool strata and highest at the mouth of the John Day River in the John Day Pool. Relatively higher detection rates in tributary mouth areas may indicate the prevalence of rearing in these habitats, but these rates were much lower than those for comparable river mouths downstream in the Columbia River Basin. The effect of water level management and potential stranding in these shallow habitats on larval lamprey should be considered when conserving these important species.

Page intentionally left blank

Table of Contents

List of Tables iv
List of Figures iv
Introduction 5
Study Area 8
Methods 14
Results 18
Conclusions 20
Acknowledgements 24
Literature Cited 25

List of Tables

Table 1. Total number of quadrats delineated, visited, sampled, and occupied and species of larval lamprey present in 2014-2015. Unidentified larval lampreys are noted as "Unid"..... 18
Table 2. Mean percent organic content in sediment and large substrates in John Day and McNary pools and river mouths in 2014-2015. 19
Table 4. Summary of detection rate for all Columbia River mainstem larval lamprey work to date. 23

List of Figures

Figure 1. John Day Pool sampled quadrats in 2014-2015. 7
Figure 2. John Day River backwater mouth sampled quadrats in 2014. 9
Figure 3. Umatilla River mouth sampled quadrats in 2014. 10
Figure 4. McNary Pool sampled quadrats in 2014-2015. 11
Figure 5. Walla Walla River mouth sampled quadrats in 2015. 12
Figure 6. Yakima River Mouth sampled quadrats in 2014-2015..... 13
Figure 7. John Day Pool shallow-water strata (A), detail of a shallow-water area (B), and sampled quadrats in 2015..... 16
Figure 8. McNary Pool shallow-water strata (A), detail of a shallow-water area (B), and sampled quadrats in 2015. 17
Figure 9. Mean percent, by weight, of sediment in different size categories (mm) in river strata in 2014 and 2015. Large cobble and bedrock categories not included. 20

Introduction

Pacific lamprey *Entosphenus tridentatus* in the Columbia River Basin and other areas have experienced a great decline in abundance (Close et al. 2002). They are culturally important to Native American tribes and are ecologically important in inland food webs (Docker et al. 2015). Information is lacking on basic biology, ecology, and population dynamics required for effective conservation and management. In 2003, the Pacific lamprey was petitioned for listing under the Endangered Species Act, and Oregon and Idaho list Pacific lamprey as a species of concern. Managers lack critical information about the life history and basic biology of Pacific lamprey that is necessary to develop effective conservation strategies and management actions. Knowledge of Pacific lamprey status (e.g., occupancy and abundance) and knowledge of biology and ecology of Pacific lamprey were deemed important data gaps (Mesa and Copeland 2009; Luzier et al. 2011). Furthermore, determining the effects of Federal Columbia River Power System (FCRPS) water management operations on Pacific lamprey larvae rearing in mainstem Columbia and Snake Rivers was deemed a top study objective by Columbia Basin researchers at a series of workshops hosted by the U.S. Army Corps of Engineers (Juvenile and Larval Lamprey Passage Workshop, Facilitator's Summary, 2012).

Pacific lampreys have a complex life history that includes larval (i.e., ammocoete), migratory juvenile (i.e., macrophthalmia), and adult marine phases (Scott and Crossman 1973). Larvae and juveniles are strongly associated with stream and river sediments. Larvae live burrowed in stream and river sediments for multiple years (i.e., 2-7) after hatching, where they filter feed detritus and organic material (Sutton and Bowen 1994). Larvae metamorphose into juveniles from July to December (McGree et al. 2008) and have a protracted migration season (Mesa et al. 2015; Moser et al. 2015); major migrations are made downstream to the Pacific Ocean in the spring with some beginning migration in the fall (Beamish and Levings 1991; Moser et al. 2015). The sympatric western brook lamprey *Lampetra richardsoni* does not have a major migratory or marine life stage although adults may locally migrate upstream before spawning (Renaud 1997). In addition, the river lamprey *L. ayresii*, paired-species to the western brook lamprey (Docker 2009), has a similar migratory parasitic life-history as the Pacific lamprey. The river lamprey has been reported to occur in the lower Columbia River (Weitkamp et al. 2012, 2015) and a putative migratory juvenile was recently reported at the John Day Dam smolt bypass facility (Jolley et al. *in press*). The majority of information on habitat preference, occupancy, and distribution of larvae comes from shallow, wadeable tributaries of the Columbia River Basin (Moser and Close 2003; Torgersen and Close 2004; Stone and Barndt 2005; Stone 2006) and coastal systems (Farlinger and Beamish 1984; Russell et al. 1987; Gunckel et al. 2009).

Lamprey larvae are known to occur in sediments of shallow streams but only recently has their use of larger river (i.e., >5th order [1:100,000 scale]) habitats in relatively deeper areas become more apparent. These areas include the mainstem of the Columbia and Willamette rivers (Jolley et al. 2012c; 2014) as well as larger, mainstem portions of tributaries to the Columbia River and Puget Sound (Torgersen and Close 2004; Hayes et al. 2013; Jolley et al. 2013b; Hughes et al. 2014; Moser et al. 2015). Sea lamprey *Petromyzon marinus* larvae have been documented in deepwater habitats in tributaries of the Great Lakes, in proximity to river mouths within the lakes (Hansen and Hayne 1962; Wagner and Stauffer 1962; Lee and Weise 1989; Bergstedt and Genovese 1994; Fodale et al. 2003*b*), and in the deepwater habitats of the St. Marys River, a large river that connects Lake Superior to Lake Huron (Young et al. 1996).

Larval densities in the St. Marys River are considered high enough for the Sea Lamprey Control Program of the United States and Canada to actively reduce their numbers (Schleen et al. 2003). References to other species occurring in deepwater or lacustrine habitats are scarce (American brook lamprey *L. appendix*; Hansen and Hayne 1962).

Knowledge of patterns in occupancy, abundance, habitat use, and movement by Pacific lamprey in regulated-rivers is generally lacking, but needed for management. Downstream movement (or dispersal) of larvae within and out of tributary systems occurs year-round as the result of both passive displacement and active relocation (Nursall and Buchwald 1972; Gadomski and Barfoot 1998; White and Harvey 2003; Moser et al. 2015; Mesa et al. 2015). The numerous hydroelectric dams on the Columbia River have transformed this river into a series of low velocity pools. Anecdotal observations exist regarding larval lamprey occurrence in large river habitats mainly at hydropower facilities or in downstream bypass reaches (Hammond 1979; Moursund et al. 2003; Dauble et al. 2006; CRITFC 2008; Mesa et al. 2015), impinged on downstream screens, or through observation during dewatering events. Occurrences at hydropower facilities are generally thought to be associated with downstream migration and specific collections of presumably migrating lampreys have been made in large river habitats (Beamish and Youson 1987; Beamish and Levings 1991). However, patterns of occupancy, abundance, and habitat use by larval Pacific lamprey in pools created by and influenced by dams, and associated tailwater areas have been given only cursory attention. Understanding whether and the extent to which larval lampreys utilize mainstem habitats for rearing, as well as passage through hydroprojects may be paramount to the conservation of Pacific lamprey.

Here, we investigated and documented larval lamprey occupancy and habitat use in two pools of the Columbia River, John Day and McNary pools. We also examined occupancy in shallow-water and tributary mouth strata nested within respective pools, as these areas may be particularly vulnerable to changing water conditions due to dam operations. Fish and invertebrates can be influenced by flow regimes, tailwater levels, and other abiotic conditions related to dam operation (Scheidegger and Bain 1995; Clarkson and Childs 2000; Vinson 2001) and larval Pacific lamprey have been specifically mentioned as susceptible to stranding by dam operations (Peterson Lewis 2009). Understanding larval lampreys usage of areas above and below dams may be critical in assessing the contribution of these areas to long-term population viability. This life-history information could be used to help inform how pool and tailwater elevations are regulated and, in turn, help to minimize negative impacts to lamprey. Our study nests into a larger effort that includes understanding the effects of dewatering and stranding on larvae (Liedtke et al. 2015) and the effects of changing pool elevations on available rearing habitat (Mueller et al. 2014).

Our specific objectives were to: 1) evaluate whether pools are occupied by larvae, 2) within pools, evaluate strata-specific larval occupancy of pools (e.g., shallow areas potentially subject to dewatering, river mouth areas), and 3) evaluate the size of larvae rearing in the pools. The long-term objectives of the project are to: 1) determine if occupancy and detection of larval lamprey decline with distance upstream and increasing number of migratory obstructions, 2) identify habitats that may be positively related to larval lamprey detection, and 3) determine effects of pool and water management operations on larval lamprey. Overall, information from this study can be used to help inform how pool and tailwater levels might be regulated to minimize negative impacts to lamprey. Understanding if and how larval Pacific lampreys use mainstem habitats is essential to the conservation of this species.

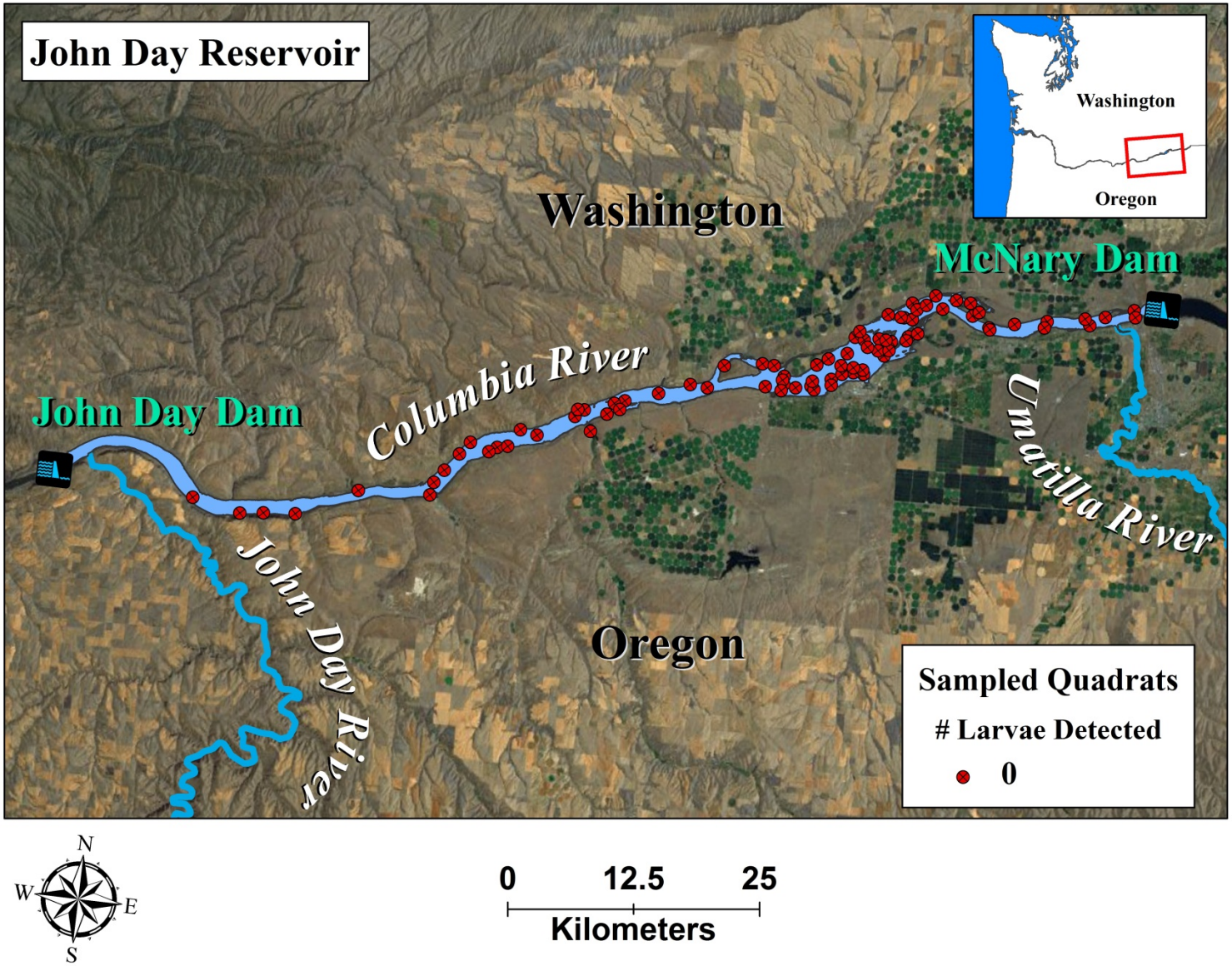

Figure 1. John Day Pool sampled quadrats in 2014-2015.

Study Area

John Day Pool is an impoundment of John Day Dam (Rkm 348; operational 1971) and is bounded on the upstream end by McNary Dam (Rkm 470). The pool is 103 km long and 22,257 -ha at full pool. John Day Pool was sampled from 11 August 2014 to 27 August 2014, from John Day Dam to McNary Dam (Figure 1).

The mouths of two major tributaries that enter the Columbia River within John Day Pool were sampled, the John Day River and the Umatilla River. The John Day River (6th order; 1:100,000 scale) originates in the Blue Mountain Range of eastern Oregon. The basin covers 20,980 $km^2$and enters the mainstem Columbia River at Rkm 352 (Figure 1). The John Day Pool impounds the lower 15 km of the John Day River, upstream to the base of Tumwater Falls (Figure 2). The Umatilla River (6th order; 1:100,000 scale) also originates in the Blue Mountain Range of eastern Oregon. The basin covers 5,931 km^2, and enters the mainstem Columbia River at Rkm 466 (Figure 3). The rivers have fine sediments originating from the Blue Mountains that provide rearing habitats for larval lamprey (Torgersen and Close 2004; Jackson and Moser 2012). The tributary mouths were sampled from 13 August 2014 to 9 September 2014 (Figure 2, 3). The John Day River mouth was sampled at the base of Tumwater Falls and the Umatilla River mouth was sampled at the confluence with the Columbia River.

McNary Pool is an impoundment of McNary Dam (Rkm 470; operational 1954) and bounded on the upstream portion by the free-flowing Hanford Reach beginning north of Richland, Washington (Rkm 549; Anglin et al. 2006) and also by Ice Harbor Dam (Rkm 16) on the Snake River. Priest Rapids Dam (Rkm 639) is the next upstream hydropower project on the Columbia River. The pool is 82 km long and 15,702 -ha at full pool. McNary Pool was sampled from 29 September 2014 to 25 June 2015 from McNary Dam to the downstream terminus of the Hanford Reach (Figure 4).

The mouths of two major tributaries that enter the Columbia River within McNary Pool were sampled, the Walla Walla River and the Yakama River. The Walla Walla River (6th order; 1:100,000 scale) originates in the Blue Mountain Range of eastern Oregon and Washington. The basin covers 4,553 km^2 and flows into the mainstem Columbia River at Rkm 506 (Figure 5). The Yakama River (7th order; 1:100,000 scale) originates on the eastern slopes of the Cascade Mountain Range in Washington. The basin covers 15,900 km^2 and enters the Columbia River at Rkm 539 (Figure 6). The rivers have fine sediments originating from the Blue and Cascade ranges that provide rearing habitats for larval lamprey (Wydoski and Whitney 2003). The tributary mouths were sampled from 30 September 2014 to 22 May 2015 (Figure 5, 6). Both river mouths were sampled at the confluence with the Columbia River.

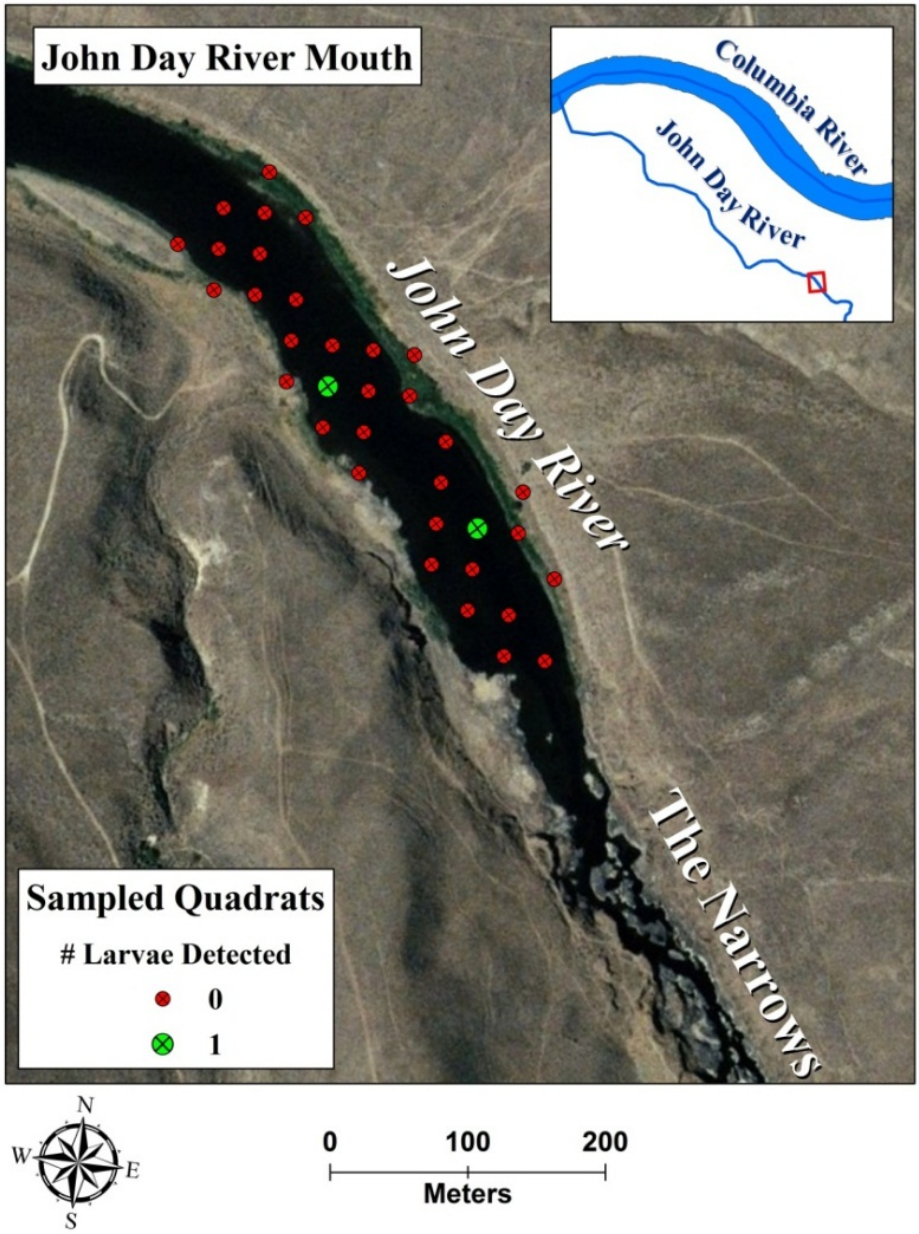

Figure 2. John Day River backwater mouth sampled quadrats in 2014.

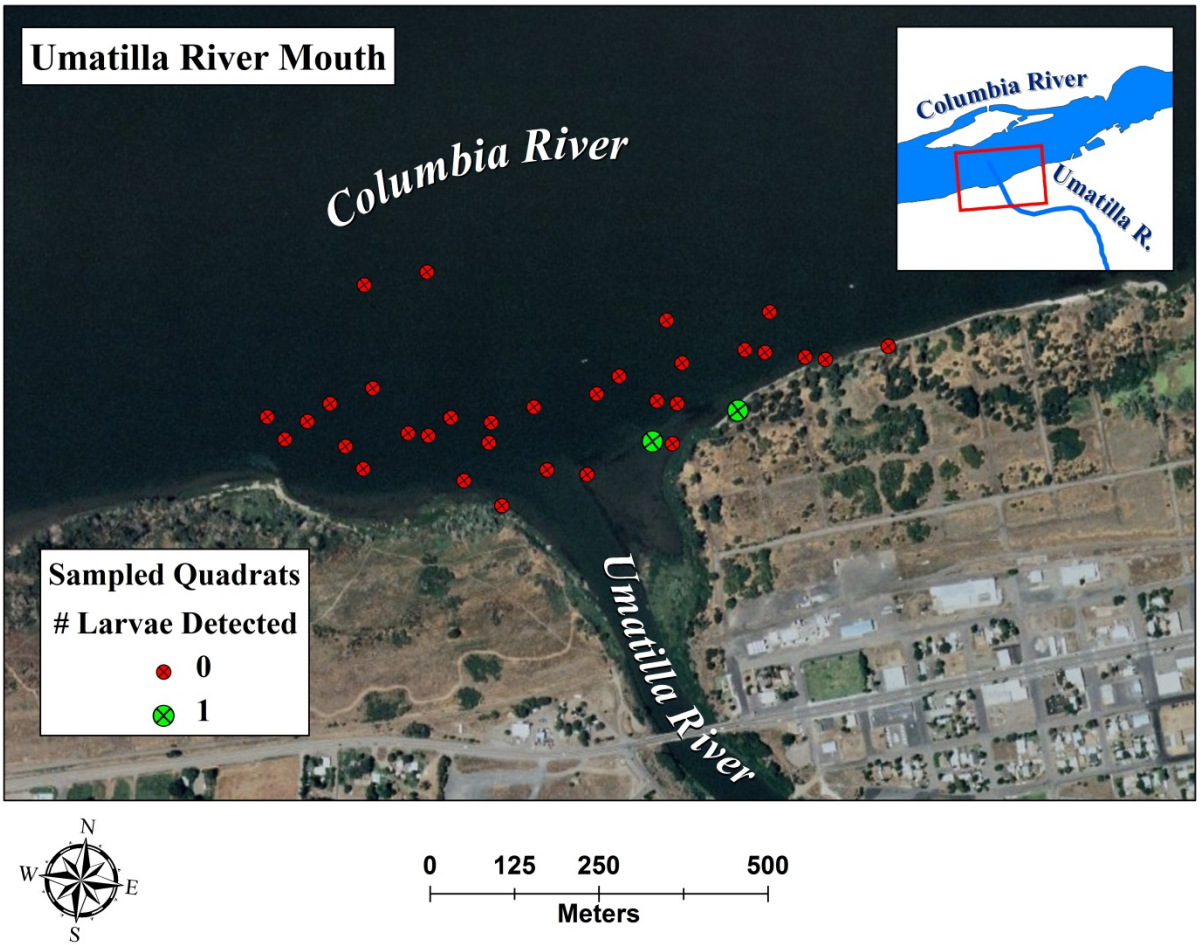

Figure 3. Umatilla River mouth sampled quadrats in 2014.

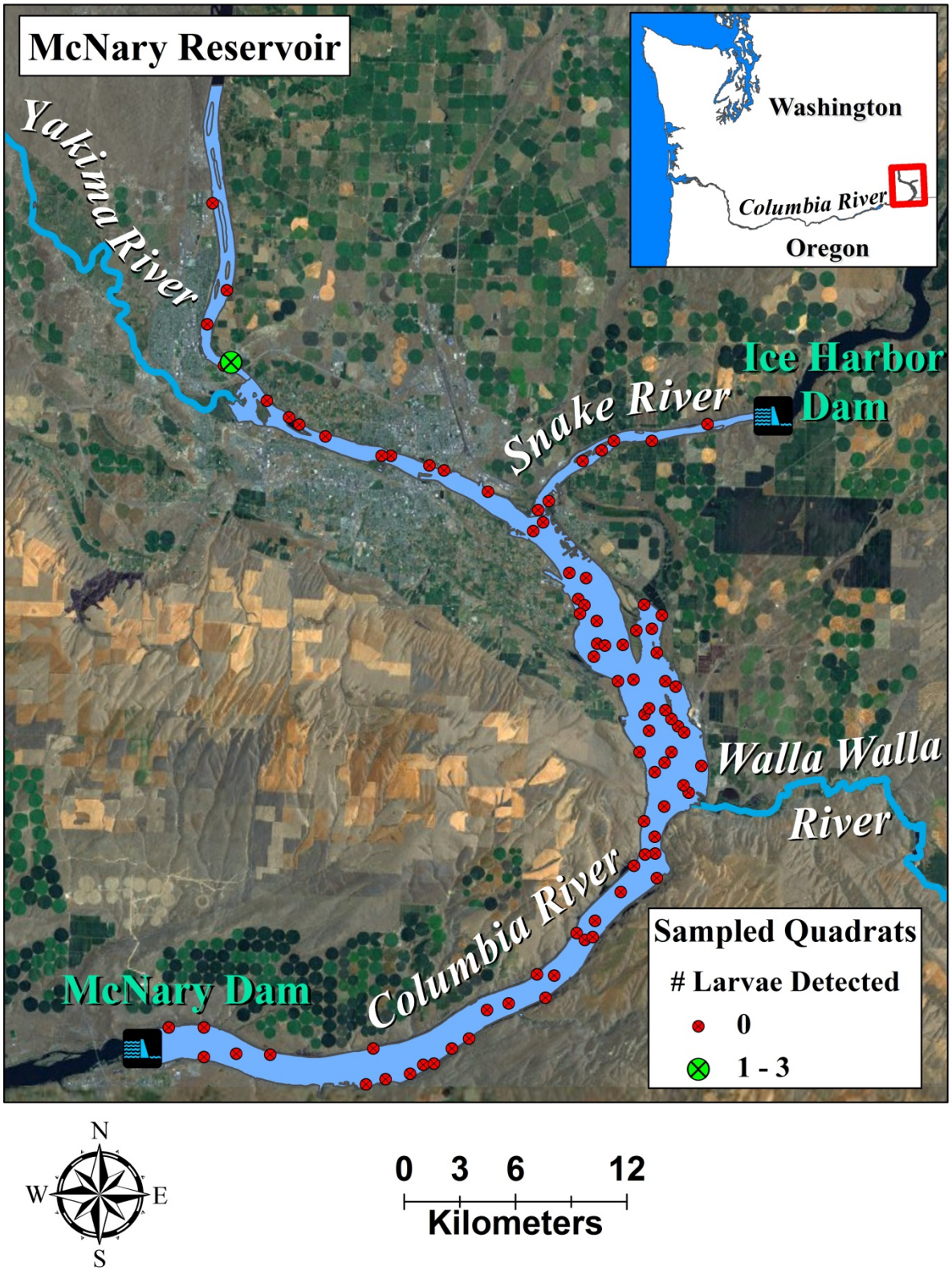

Figure 4. McNary Pool sampled quadrats in 2014-2015.

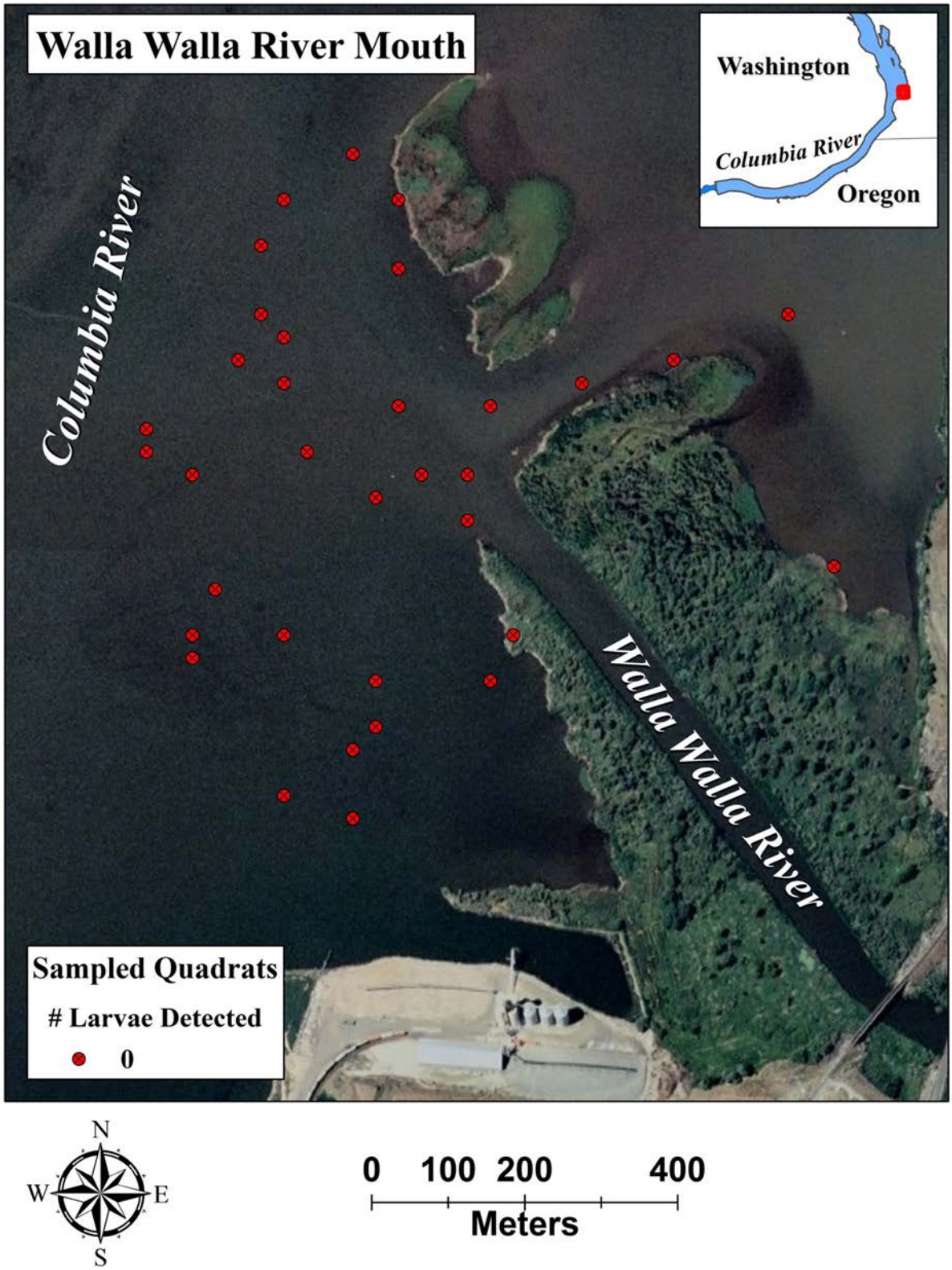

Figure 5. Walla Walla River mouth sampled quadrats in 2015.

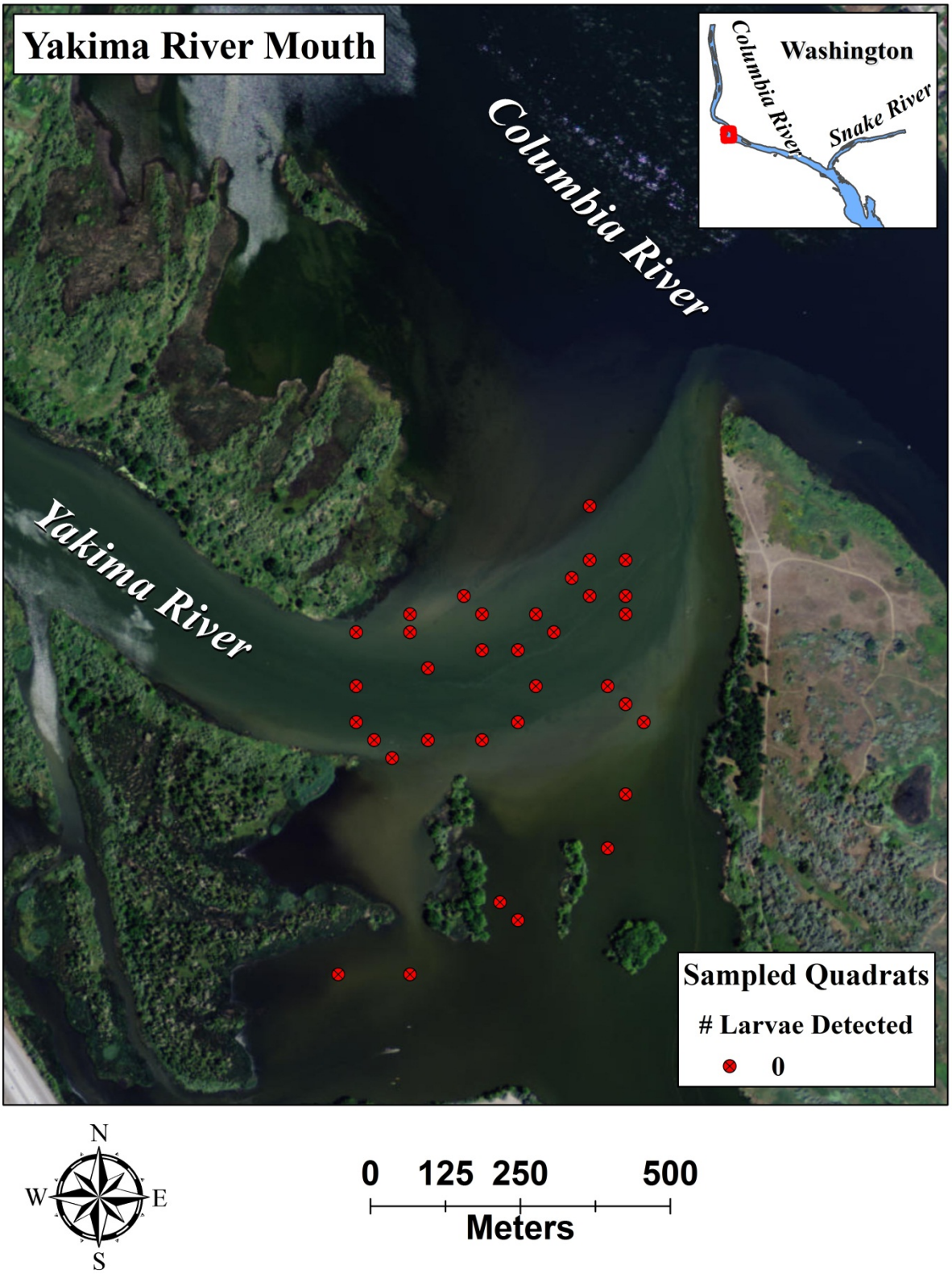

Figure 6. Yakima River Mouth sampled quadrats in 2014-2015.

Methods

We used a Generalized Random Tessellation Stratified (GRTS) approach (Stevens and Olsen 2004) to select sampling sites for our study. The GRTS approach orders all potential sample sites within an area of interest in a random, spatially-balanced manner and the number picked for sampling can be varied. This approach results in an unbiased sampling design allowing quantification of detection probability (i.e., the probability that presence is detected in at least one sampling site given that the area of interest is occupied). First, we developed a layer of 30 m x 30 m quadrats (i.e., sampling sites) using ArcMap 9.3 (Environmental Systems Research Institute, Redlands, California) which was overlaid on each area of interest. There were 225,998 potential quadrats in the John Day Pool, and 165,215 quadrats in the McNary Pool (Table 1). Universal Transverse Mercator (UTM) coordinates representing the center point of each quadrat were determined and used to navigate the boat to the sampling location within each quadrat during sampling. Quadrats were ordered sequentially as selected by the GRTS approach and the lower numbered quadrats were given the highest priority for sampling. Quadrats that could not be sampled feasibly due to dewatered conditions or depth less than 0.3 m, excessive velocity, or excessive depth (>21 m) were eliminated and subsequent quadrats were increased in priority (Table 1). River mouth areas were defined as the area contained by a 0.5 km semi-circle from the point where the center of the tributary channel meets the respective pool.

A sampling event consisted of using a deepwater electrofisher (Bergstedt and Genovese 1994) in a 30 m x 30 m quadrat. This quadrat size was selected based on the previous experience of sea lamprey researchers in the Great Lakes (M. Fodale, USFWS, personal communication) as their sampling approach evolved from a systematic to adaptive approach (Fodale et al. 2003*a*). A description of the complete configuration of the deepwater electrofisher is given by Bergstedt and Genovese (1994). The bell of the deepwater electrofisher (0.61 cm^2) was lowered from a boat to the river bottom. The electrofisher delivered three pulses DC per second at 10% duty cycle, with a 2:2 pulse train (i.e., two pulses on, two pulses off). Output voltage was adjusted at each quadrat to maintain a peak voltage gradient between 0.6 and 0.8 V/cm across the electrodes. Suction was produced by directing the flow from a pump through a hydraulic eductor, prohibiting larvae from passing through the pump. Suction began approximately 5 seconds prior to shocking to purge air from the suction hose. Shocking was conducted for 60 seconds, and the suction pump remained on for an additional 60 seconds after shocking to ensure collected larvae passed through the hose and emptied into a collection basket (27 x 62 x 25 cm; 2 mm wire mesh). The sampling techniques are described in detail by Bergstedt and Genovese (1994) and were similar to those used in the Great Lakes region (Fodale et al. 2003*b*) and the Willamette River (Jolley et al. 2012c).

Near-shore, non-tributary shallow-water areas were also identified for John Day and McNary pools. We estimated depth strata most susceptible to dewatering due to normal hydrosystem operations using orthophotography. Available images were reviewed in a GIS and the best images detailing shallow-water regions were digitized to delineate the shallow-water strata. Shallow-water strata extending from the shoreline to where the river bottom was no longer discernible were digitized as a contiguous polygon. If waves, sun glare or other factors precluded shallow water discrimination, a cut-off distance of approximately 20 meters from the shoreline was used. These shallow-water strata are where lampreys have the highest probability of being vulnerable to stranding. Digitized strata were overlaid on the GRTS sample quadrats which were previously delineated. Sample quadrats that were within the shallow-water strata

polygon were sampled in the manner described for each pool proper. The estimated shallow-water strata of John Day Pool had an area of 1,941 ha which was 8.7% of the total pool area, or 21,576 quadrats (Figure 7). The estimated shallow-water strata of McNary Pool had an area of 1,248 ha which was 7.9% of the total pool area, or 13,877 quadrats (Figure 8). When visiting a predicted shallow-water quadrat, the depth was greater than 1.2 m (i.e., depth < 1.2 m considered susceptible to dewatering during normal pool management scenarios), the quadrat was abandoned (i.e., not sampled) and the next candidate quadrat was selected from the list generated by the GRTS operation.

We estimated occupancy of larval lamprey in John Day and McNary pools, tributary mouths, and shallow-water strata by adapting an approach that was applied to studies of larval lamprey in the Willamette and Columbia rivers (Jolley et al. 2012c, 2013a; 2013b; 2014). The approach has several requirements: 1) a site- and gear-specific detection probability (assumed or estimated); 2) the probability of presence at a predetermined acceptably low level (given no detection); and 3) random identification of spatially-balanced sample sites that allow estimation of presence and refinement of detection probabilities. A reach-specific probability of detection, d_{reach}, was calculated as the proportion of quadrats (i.e., 30 m x 30 m sampling quadrat) occupied (i.e., larvae captured) by larval lamprey in the Lower Willamette River, an area known to be occupied. The posterior probability of reach occupancy, given a larval lamprey was not detected, was estimated as:

$$(1)\ \mathrm{P}(F|C_o) = \frac{\mathrm{P}(C_o|F)\cdot\mathrm{P}(F)}{\mathrm{P}(C_o|F)\cdot\mathrm{P}(F) + \mathrm{P}(C_o|\sim F)\cdot\mathrm{P}(\sim F)},$$

where P(F) is the prior probability of larval lamprey presence. Although we knew the Willamette River reach was occupied with larval lamprey, P(F) of 0.5 (uninformed) was used for future study design (i.e., P[$F|C_o$]) in areas where larval lamprey presence is unknown. P(~F), or 1 – P(F), is the prior probability of species absence, and P($C_o|F$), or 1 – d, is the probability of not detecting a species when it occurs (C_0 = no detection; Peterson and Dunham 2003). Patterns of occupancy by river were compared using the Chi-square test for differences in probabilities (Conover 1999).

To pick the number of quadrats sampled at river mouths, we drew on information from previous occupancy sampling in other river mouths, with detection rates ranging from 0.02 to 0.32. We assumed a relatively low to moderate detection rate of 0.08 (given an area was occupied). We estimated that a minimal sampling effort of 17 quadrats was necessary to achieve 80% certainty of lamprey absence when they are not detected (see Jolley et al. 2012c). To be conservative, we doubled that sampling rate to 34 quadrats (94% certainty of lamprey absence when not detected).

We attempted to adjust for the large spatial scale of the pool and shallow-water strata areas (e.g., pools are much larger than river mouths and we have less information on detection probability of pools). We estimated detection probability (d) as a function of an assumed proportion of sites occupied (*Prop*), an assumed density within occupied sites (*Den*), and an assumed sampling efficiency to detect one individual (E) by the following equation:

$$d = Prop * (1 - (1 - E)^{Den})$$

We wanted to ensure we could detect larvae if we assumed that at least 5% of the sample area was occupied (conservative assumption), that when occupied, a site would have a density of at least 1 individual/0.61 m^2 (i.e., at least one individual within the deepwater electrofisher frame)

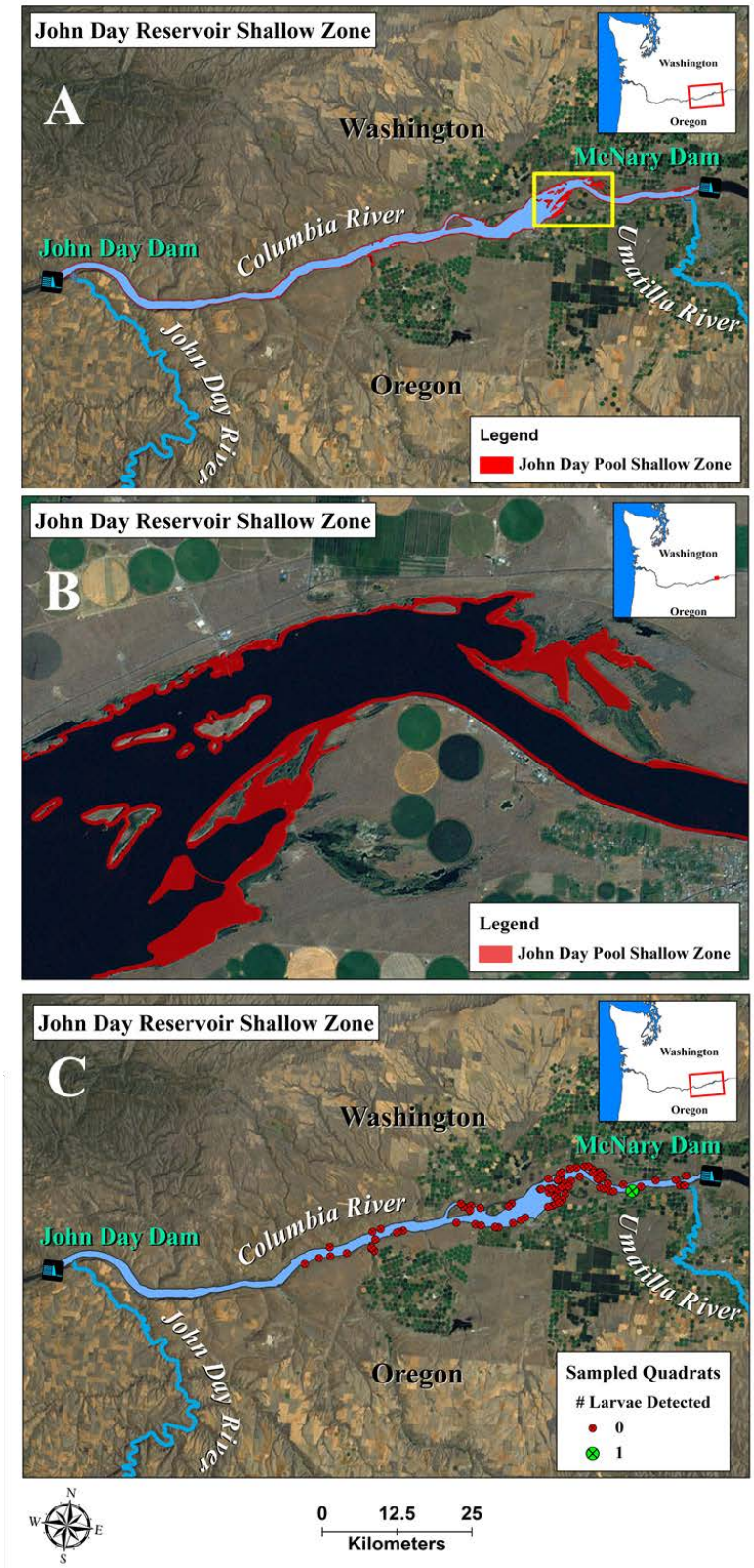

Figure 7. John Day Pool shallow-water strata (A), detail of a shallow-water area (B), and sampled quadrats in 2015.

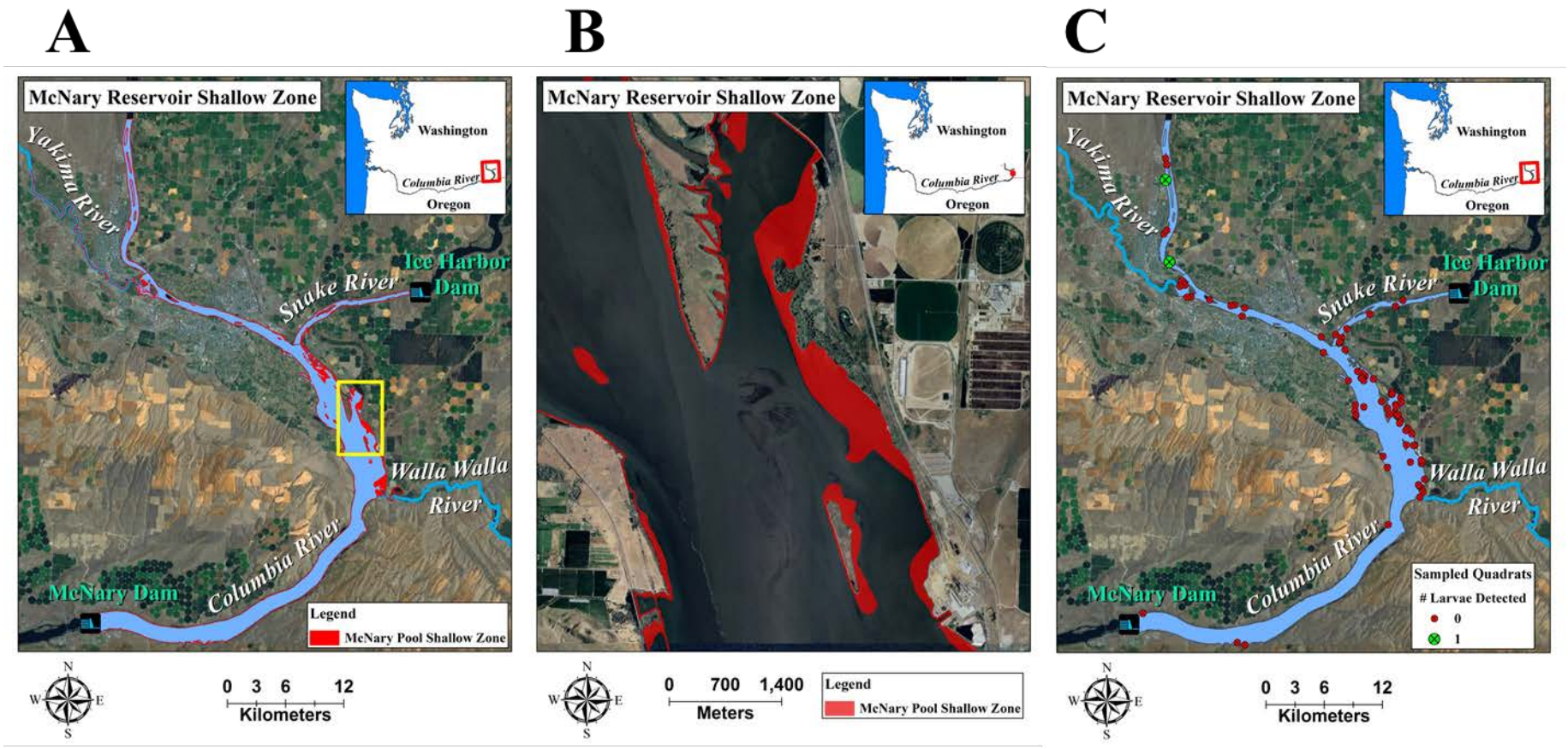

Figure 8. McNary Pool shallow-water strata (A), detail of a shallow-water area (B), and sampled quadrats in 2015.

and that we would collect individuals at 1/3 of all occupied sites. Thus, the detection probability at one random site within the area would be:

$$0.05 * (1 - (1 - 0.33)^1) = 0.0167$$

This estimate of detection probability (0.0167) was used in the model by Peterson and Dunham (2002) to estimate the number of quadrats that need to be sampled to obtain a posterior probability of area occupancy below the acceptable level, if not a single individual is detected. This exercise resulted in a target sampling effort of 83 quadrats to achieve a probability of occupancy of less than 20%, if no individuals were detected (i.e., we would be at least 80% certain the area was not occupied if no individuals were collected).

Table 1. Total number of quadrats delineated, visited, sampled, and occupied and species of larval lamprey present in 2014-2015. Unidentified larval lampreys are noted as "Unid".

		Quadrats								
Reach	Date	Total	Visited	Sampled	Occupied	*d*	Pacific lamprey	*Lampetra* spp.	Unid	Total
John Day Pool	8/11 - 8/27	225,998	125	85	0	0.00	0	0	0	0
John Day mouth	9/9	61	41	34	2	0.06	1	0	1	2
Umatilla mouth	8/13 - 8/28	442	39	34	2	0.06	1	0	1	2
John Day Pool shallow	5/6 - 5/19	21,576	110	90	1	0.01	0	0	1	1
McNary Pool	9/29 - 6/25	165,215	101	87	1	0.01	2	0	1	3
Walla Walla mouth	5/21 - 5/22	654	38	34	0	0.00	0	0	0	0
Yakima mouth	9/30 - 5/19	481	45	34	0	0.00	0	0	0	0
McNary Pool shallow	5/19 - 6/25	13,877	116	81	2	0.02	2	0	0	2

Collected lampreys were anesthetized in a solution of tricaine methanesulfonate (MS-222), and those fish >60 mm TL were identified as Pacific lamprey or *Lampetra* spp. according to caudal pigmentation (Goodman et al. 2009; Docker et al. *in review*), and classified according to developmental stage (i.e., ammocoete, macrophthalmia, or adult). Lampreys <60 mm TL were deemed "unidentified". A caudal fin tissue sample was collected from all larvae and stored in 100% ethanol (Spice et al. 2011). Lampreys were measured (TL in mm), placed in a recovery bucket of fresh river water, and released after resuming active swimming behavior. Length-frequency histograms were constructed for each species to describe size structure.

Concurrent to each sampling event a sediment sample was taken from the river bottom by using a Ponar bottom sampler (16.5 cm x 16.5 cm). A 500 mL sample was labeled, placed on ice, and returned to the lab. Samples were oven-dried for 12 hours at 100°C to remove all water. Sediment size was characterized by weighing the component portions of the sample that collected on a set of sieves (opening sizes: 37.5 mm, 19 mm, 9.5 mm, 1 mm, 0.5 mm, and remainder less than 0.5 mm). Percent organic content of replicate samples was determined using loss-on-ignition methods (Heiri et al. 2001) by combusting organic material at 500-550 C for six hours. All statistical analyses were conducted using SAS software (SAS 2002).

Results

We targeted 83 quadrats per pool and shallow-water strata and 34 quadrats per tributary mouth strata (Table 1). Some quadrats were not sampled because they were not feasible (dewatered conditions, excessive depth, excessive velocity, large boulder substrate). Feasibility of sampling a quadrat in each stratum was 68% to 89%. Larval lampreys were detected in all strata except the John Day Pool, the Walla Walla River mouth, and the Yakima River mouth

(Table 1). All occupied strata contained either Pacific lamprey or unidentifiable small larvae (genetic identification is currently ongoing). Detection probability was highest at the John Day River mouth and Umatilla River mouth (d=0.06) and larvae were not detected in the John Day Pool, the Walla Walla River mouth, and the Yakima River mouth. By definition, Pacific lamprey occupied The John Day Pool since larvae were detected in the John Day River mouth, Umatilla River mouth, and shallow-water strata, which are nested areas within the entire pool. As a whole, larval lamprey are likely at a level of abundance too low in the John Day Pool proper to be detected with our current sampling effort (there was a 20% chance that we failed to detect larvae when they actually occupied the pool). Detection probabilities did not differ among reaches (Fisher's Exact Test multivariate permutation technique, Brown and Fears 1981, P>0.05).

Lamprey larvae ranged in size from 23 to 147 mm TL. Sample sizes were too small to assess potential length differences among strata with just one or two individuals captured in many strata. Depths sampled ranged from 0.2 to 19.8 m and larvae were detected in depths from 0.6 to 3.7 m. The total number of larvae occupying any individual quadrat ranged from 0 to 3.

Analysis of river bottom sediment samples showed mean percent organic content ranged from 0.1 to 5.8% among sites and was significantly different among strata (ANOVA, F=3.51, df=7, P<0.01; Table 2). The John Day Pool shallow-water stratum had lower organic content than the McNary Pool or Walla Walla River mouth strata. By strata, river mouths on average had higher percentages of organic content (mean=1.7%) than shallow-water areas (mean=1.3%; ANOVA, F=3.57, P<0.05). Multiple differences in the relative amount of different sediment sizes were detected (Figure 7). Fine sediments were present in all reaches although the Walla Walla River mouth and Yakima River mouth had the highest relative amount of the smallest-size particles while the John Day River mouth had the least (i.e., <0.5 mm, ANOVA, F=8.31, P<0.05). The John Day River mouth had the highest relative amount of larger-sized particles (i.e., 19-37.5 mm; F=4.59; P<0.05). Large cobble/boulder or bedrock substrates (too large for the dredge) were detected at up to 29% of sites at the John Day River mouth and no sites at the Yakima River mouth.

Table 2. Mean percent organic content in sediment and large substrates in John Day and McNary pools and river mouths in 2014-2015.

Reach	Number	Mean percent organic content	Standard error	Percent boulder or bedrock
John Day pool	54	1.2	0.1	25.5
John Day mouth	7	1.1	0.1	9.2
Umatilla mouth	9	1.4	0.2	8.5
John Day shallow	72	1.1	0.1	13.5
McNary pool	52	1.7	0.2	28.7
Walla Walla mouth	33	1.9	0.2	0.3
Yakima mouth	33	1.7	0.2	0.0
McNary shallow	60	1.6	0.2	16.2

Predictions of shallow-water habitat in John Day Pool and McNary Pool were successfully estimated using orthophotography. The predictions agreed well with subsequent field sampling, although a few points (n=6; <3%) were deeper than 1.2 m.

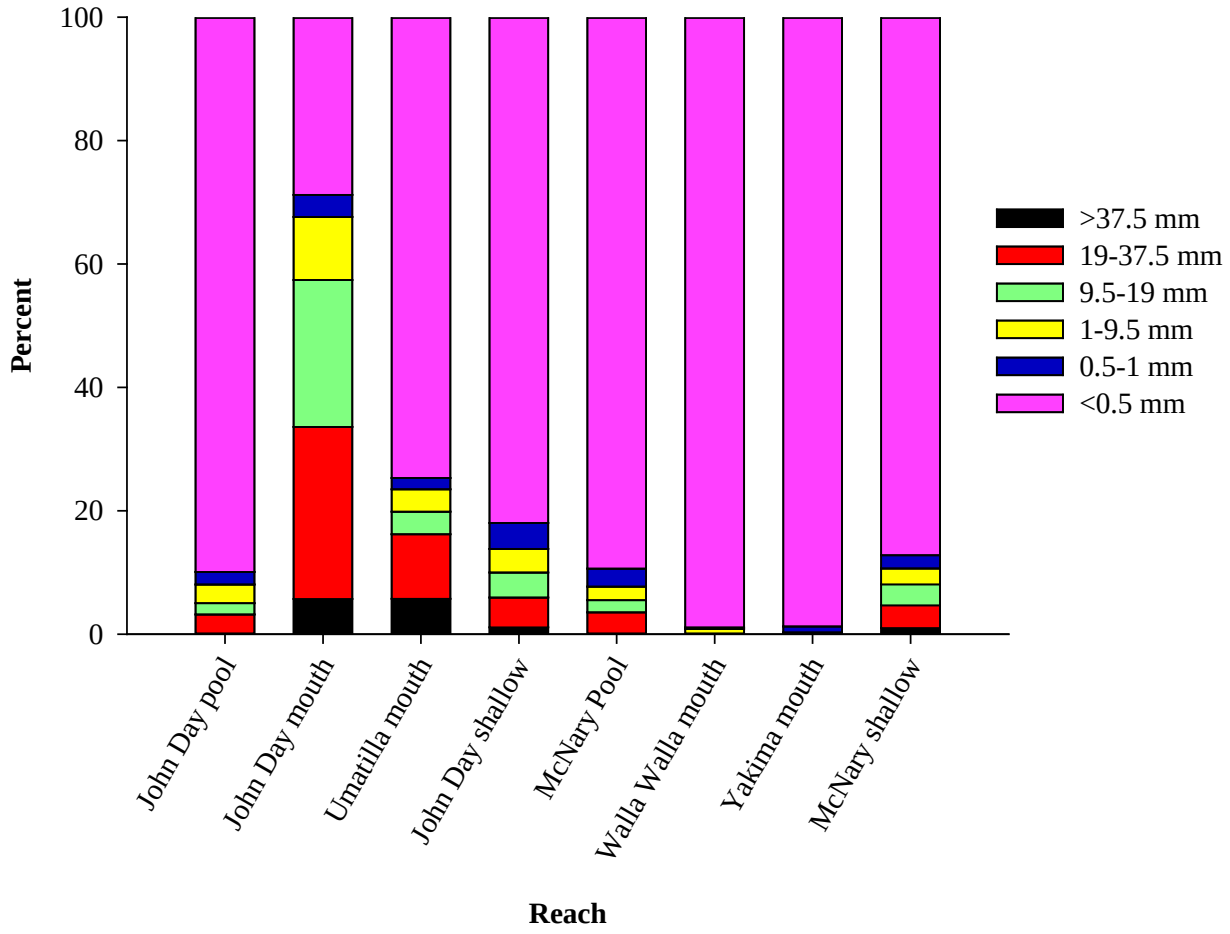

Figure 9. Mean percent, by weight, of sediment in different size categories (mm) in river strata in 2014 and 2015. Large cobble and bedrock categories not included.

Conclusions

Larval Pacific lampreys occupied all strata surveyed in the John Day and McNary pools except the Walla Walla River mouth and Yakima River mouth while *Lampetra* spp. were not detected in any strata. Higher detection rates in river mouth areas (although relatively low overall) suggest these habitats may be valuable for larval lamprey rearing. Detection rates were generally lower than those found in previous years downstream of John Day Dam (Jolley et al. 2012a; 2012b; 2013a; 2013b; 2014; Table 3). In those studies detection rates at river mouths ranged from 0.03 to 0.35. The lower detection rates in this study might be related to the increased number of mainstem dams that adults must pass (three or four dams) to access

spawning areas with consequently less spawning and larvae produced; it has been reported that up to 50% of adult lampreys approaching a dam do not pass (Moser et al. 2002). The John Day Pool was found to be occupied with larval lamprey in the shallow-water strata, as well as the mouths of the John Day River and Umatilla River, but no larvae were detected within the pool proper. The John Day Pool is wide and shallow with complex backwaters and side-channels and more sandy and silty substrates (Parsley et al 1993; Gadomski and Barfoot 1998) which may be conducive to larval lamprey rearing. Whether larvae are not rearing in the pool or they occur at a level too low to detect given our sampling effort is not known. Thus, lack of detection in the pool was unexpected.

Our findings are similar to those of studies conducted in the Great Lakes, where multiple size and age classes of larval sea lamprey and American brook lamprey *Lampetra appendix* have been found in deepwater lentic areas (Hansen and Hayne 1962), deepwater tributaries (Bergstedt and Genovese 1994; Fodale et al. 2003*b*) and large rivers (Young et al. 1996). This work also corroborates our earlier findings that Pacific and western brook lampreys inhabit relatively deep (14-16 m), mainstem areas of the Willamette and Columbia rivers (Jolley et al. 2011, 2012c; 2014). In addition, larvae collected likely comprise multiple age classes. Larvae emerge at 8-9 mm (Brumo 2006) and our smallest collections (i.e., TL<20 mm) were likely age-0 fish, although accurately estimating age based on length remains difficult (Meeuwig and Bayer 2005). The duration of occupancy of small larvae in these areas is not known, but it is likely that recruitment occurred within a relatively short time prior to being captured. Deepwater river spawning of lamprey has not been documented although lentic spawning has been observed (Russell et al. 1987). The pools created by dams on the Columbia River may produce habitats that historically didn't exist or were likely less abundant prior to dam construction. Thus, larval lamprey may use these areas at a disproportionally higher rate than pre-dam construction. Alternatively, high detection rates of larval lampreys in tributary mouths compared to other areas in our mainstem lamprey research to date (Jolley et al. 2012a; 2014), may be due to increased local density and abundance relative to other areas (Royle and Nichols 2003), enhanced rearing conditions in these areas, and/or tributaries serving as source sub-populations for larvae in the mainstem. The use of these shallow-water areas brings into questions of susceptibility to dewatering where mortality may eventually occur (Liedtke et al. 2015).

The origin of larval lampreys collected in river mouth strata in the mainstem Columbia is unknown, but is a topic that warrants further investigation. For example, these larvae may have dispersed (either actively or passively) downstream from headwater areas within the tributaries, hatched in the mouths of these tributaries, or entered tributary mouth habitats from other areas of the Columbia River mainstem (or a combination of the above). The preponderance of relatively high detection rates in river mouth areas does suggest the associated tributaries serve as the source for these detections. However, given the relative lack of suitable burrowing substrates in some mainstem areas of the Columbia River, tributary mouth habitats may serve as areas for larval recruitment from other areas. To better understand patterns of larval origin and dispersal within the mainstem Columbia River and its major tributaries, directed studies utilizing tools to identify unique genetic signatures from tributary systems may be one approach worth pursuing (Hess et al. 2014). The John Day River, Umatilla River, Walla Walla River, and Yakima River are known to have a sub-population of larval lamprey although information is scarce (NPPC 2004; Torgersen and Close 2004; Jackson and Moser 2012; Grote et al. 2014). Identifying discrete sub-populations may allow monitoring larval dynamics, spatially and temporally.

Substrate particle size and water velocity are consistently considered two of the most important fine-scale predictors of larval lamprey presence and abundance (Beamish and Jebbink 1994; Ojutkangas et al. 1995; Beamish and Lowartz 1996) but the importance of organic matter in the sediment is less clear and we found no obvious patterns relating sediment organic content to lamprey occupancy. Organic detritus is generally deposited in areas of low water velocity where accumulations of silt and sand provide suitable substrate for burrowing larvae. Potter et al. (1986) found the presence of organic material in the substrate to be an important environmental variable predicting the density of larval pouched lamprey *Geotria australis* in three of their four seasonal models (i.e., in all seasons but winter). In their habitat selection study, Smith et al. (2011) found that, after their preference for fine sand, least brook lamprey *L. aepytera* larvae exhibited a secondary preference for an organic substrate (consisting of approximately 70% decomposing leaves/stems and organic sediment particles and 30% silt/fine sand). Malmqvist (1980) suggested that the presence of organic material in the sediment is not a prerequisite for the larvae since they can ingest their food directly from the water column above the sediment.

Overall, we provide empirical evidence that lamprey larvae of multiple sizes occupy John Day and McNary pools and some tributary mouths. Multi-state occupancy models which are an extension of standard occupancy models (Nichols et al. 2007) may be particularly useful to model habitat effects on occupancy in these areas. Future work might couple thorough measures of habitat variables to be used as co-variates to the detection probability models. Management of these areas is important to conservation of these imperiled species. Continuing to document patterns of occupancy by larval lamprey further upstream in mainstem Columbia and Snake rivers is warranted for a number of reasons. It is likely that cumulative effects of multiple adult migration passage challenges are resulting in sharply declining spawning adults in these upstream areas. Larval rearing areas may be even more important to maintaining recruitment to the population, providing pheromone-based migratory cues to adults (Li et al. 2003) and preserving species subpopulations. This topic has been largely ignored and further research and monitoring is needed to address larger uncertainties in population trends, recruitment, and mortality.

Year	Reach	*d*	Pacific lamprey	*Lampetra* spp.	Unid	Total	Source
2009	Lower Willamette River	0.07	5	6	1	12	Jolley et al. 2012c
2010	Bonneville Reservoir	0.02	1	0	0	1	Jolley et al. 2011a
	Bonneville Tailwater	0.00	0	0	0	0	
2011	Bonneville Tailwater	0.03	0	1	0	1	Jolley et al. 2012a
	Hood River mouth	0.06	1	1	0	2	
	Klickitat River mouth	0.00	0	0	0	0	
	White Salmon River mout	0.00	0	0	0	0	
	Wind River mouth	0.29	22	9	6	37	
	Lower Klickitat River	0.26	13	0	2	15	Jolley et al. 2012b
	Lower White Salmon Rive	0.29	5	11	3	19	
	Lower Wind River	0.32	13	9	4	26	
2012	Klickitat River mouth	0.12	3	0	2	5	Jolley et al. 2013b
	White Salmon River mout	0.03	1	0	0	1	
	Wind River mouth	0.29	6	15	16	37	
	Lower Klickitat River	0.03	1	0	0	1	
	Lower White Salmon Rive	0.09	0	4	0	4	
	Lower Wind River	0.24	4	10	1	15	
	The Dalles Pool	0.00	0	0	0	0	Jolley et al. 2013a
	Deschutes River mouth	0.00	0	0	0	0	
2013	Deschutes mouth	0.09	5	0	2	7	Jolley et al. 2014
	Klickitat mouth	0.15	4	1	1	6	
	Klickitat mouth	0.26	49	4	0	53	
	Klickitat mouth	0.35	34	7	1	42	
	Wind mouth	0.18	4	11	1	16	
	Wind mouth	0.21	6	17	0	23	
	Wind mouth	0.24	5	20	0	25	
	Hood mouth	0.09	3	3	0	6	
	White Salmon mouth	0.15	3	4	0	7	
	Little White Salmon mout	0.09	0	4	0	4	
	Bonneville Reservoir	0.03	2	0	0	2	
	The Dalles Reservoir	0.00	0	0	0	0	
2014	Bonneville shallow	0.03	1	1	0	2	
	John Day Reservoir	0.00	0	0	0	0	Jolley et al. *in prep*
	John Day mouth	0.06	1	0	1	2	
	Umatilla mouth	0.06	1	0	1	2	
2014-15	McNary Pool	0.01	2	0	1	3	
	Yakima mouth	0.00	0	0	0	0	
2015	John Day shallow	0.01	0	0	1	1	
	Walla Walla mouth	0.00	0	0	0	0	
	McNary shallow	0.02	2	0	0	2	

Table 3. Summary of detection rate for all Columbia River mainstem larval lamprey work to date.

Acknowledgements

Funding for this project was provided by the U.S. Army Corps of Engineers through the Anadromous Fish Evaluation Program and we thank S. Tackley, S. Juhnke, and N. Zorich for valuable guidance and administrative assistance. We thank M. Kavanagh, R. Koch, B. Silver, and A. Spitzack for field assistance. D. Hines, D. Wills, and B. Haverkate provided GIS, analytical, and project guidance.

Literature Cited

Anglin D.R., S.L. Haeseker, J.J. Skalicky, H. Schaller, K.F. Tiffan, J.R. Hatten, P. Hoffarth, J. Nugent, D. Benner, and M. Yoshinaka. 2006. Effects of hydropower operations on spawning habitat, rearing habitat, and stranding/entrapment mortality of fall Chinook salmon in the Hanford Reach of the Columbia River. U.S. Fish and Wildlife Service, Technical Report, Vancouver, Washington.

Beamish, F.W.H., and J.A. Jebbink. 1994. Abundance of lamprey larvae and physical habitat. Environmental Biology of Fishes 39:209–214.

Beamish, R.J., and C.D. Levings. 1991. Abundance and freshwater migrations of the anadromous parasitic lamprey, *Lampetra tridentata*, in a tributary of the Fraser River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 48:1250-1263.

Beamish, F.W.H., and S. Lowartz. 1996. Larval habitat of American brook lamprey. Canadian Journal of Fisheries and Aquatic Sciences 53:693–700.

Beamish, R.J., and J.H. Youson. 1987. Life history and abundance of young adult *Lampetra ayresi* in the Fraser River and their possible impact on salmon and herring stocks in the Strait of Georgia. Canadian Journal of Fisheries and Aquatic Sciences 44:525-537.

Bergstedt, R.A., and J.H. Genovese. 1994. New technique for sampling sea lamprey larvae in deepwater habitats. North American Journal of Fisheries Management 14:449-452.

Brown, C. C., and T.R. Fears. 1981. Exact significance levels for multiple binomial testing with application to carcinogenicity screens. Biometrics 37:763-774.

Brumo, A.F. 2006. Spawning, larval recruitment, and early survival of Pacific lampreys in the South Fork Coquille River, Oregon. Master's thesis, Oregon State University, Corvallis.

Clarkson, R.W., and M.R. Childs. 2000. Temperature effects on hypolimnial-release dams on early life stages of Colorado River Basin big-river fishes. Copeia 2000:402-412.

Close, D.A., M.S. Fitzpatrick, and H.W. Li. 2002. The ecological and cultural importance of a species at risk of extinction, Pacific lamprey. Fisheries 27:19-25.

Conover, W.J. 1999. Practical nonparametric statistics, 3rd ed. John Wiley & Sons, Inc.

CRITFC. 2008. Tribal Pacific Lamprey Restoration Plan for the Columbia River Basin. Formal draft available: www.critfc.org/text/lamprey/restor_plan.pdf. (February 2010).

Dauble, D.D., R.A. Moursund, and M.D. Bleich. 2006. Swimming behavior of juvenile Pacific lamprey, *Lampetra tridentata*. Environmental Biology of Fishes 75:167-171.

Docker, M.F. 2009. A review of the evolution of nonparasitism and an update of the paired species concept. Pages 71-114 *in* L.R. Brown, S.D. Chase, M.G. Mesa, R.J. Beamish, and P.B. Moyle, editors. Biology, management, and conservation of lampreys in North America. American Fisheries Society Symposium 72. Bethesda, Maryland.

Docker, M.F., J.B. Hume, and B.J. Clemens. 2015. Introduction: a surfeit of lampreys. Pages 1-34 *in* M.F. Docker, editor. Lampreys: biology, conservation and control, volume 1. Springer Science, New York.

Docker, M.F., G.S. Silver, J.C. Jolley, and E.K. Spice. *In review*. Evaluation of morphological identification accuracy using a simple microsatellite marker that distinguishes North American lamprey genera *Lampetra* and *Entosphenus*.

Farlinger, S.P., and R.J. Beamish. 1984. Recent colonization of a major salmon-producing lake in British Columbia by the Pacific lamprey (*Lampetra tridentata*). Canadian Journal of Fisheries and Aquatic Sciences. 41:278-285.

Fodale, M.F., R.A. Bergstedt, D.W. Cuddy, J.V. Adams, and D.A. Stolyarenko. 2003*a*. Planning and executing a lampricide treatment of the St. Marys River using a georeferenced data. Journal of Great Lakes Research 29(Supplement 1):706-716.

Fodale, M.F., C.R. Bronte, R.A. Bergstedt, D.W. Cuddy, and J.V. Adams. 2003*b*. Classification of lentic habitat for sea lamprey (*Petromyzon marinus*) larvae using a remote seabed classification device. Journal of Great Lakes Research 29 (Supplement 1):190–203.

Gadomski, D. M., and C. A. Barfoot. 1998. Diel and distributional abundance patterns of fish embryos and larvae in the lower Columbia and Deschutes rivers. Environmental Biology of Fishes 51:353-368.

Goodman, D.H., A.P. Kinzinger, S.B. Reid, M.F. Docker. 2009. Morphological diagnosis of *Entosphenus* and *Lampetra* ammocoetes (Petromyzontidae) in Washington, Oregon, and California. Pages 223-232 *in* L.R. Brown, S.D. Chase, M.G. Mesa, R.J. Beamish, and P.B. Moyle, editors. Biology, management, and conservation of lampreys in North America. American Fisheries Society, Symposium 72, Bethesda, Maryland.

Grote, A.B., M.C. Nelson, C. Yonce, A. Johnson, D.J. Sulak, and R.D. Nelle. 2014. Passage of radio-tagged adult Pacific lamprey at Yakima River diversion dams. 2013 Annual Report. U.S. Fish and Wildlife Service, Leavenworth, Washington. 49 pp.

Gunckel, S.L., K.K. Jones, and S.E. Jacobs. 2009. Spawning distribution and habitat use of adult Pacific and western brook lampreys in Smith River, Oregon. Pages 173-189 *in* L.R. Brown, S.D. Chase, M.G. Mesa, R.J. Beamish, and P.B. Moyle, editors. Biology, management, and conservation of lampreys in North America. American Fisheries Society, Symposium 72, Bethesda, Maryland pp. 173-189.

Hammond, R-J. 1979. Larval biology of the Pacific lamprey, *Entosphenus tridentatus* (Gairdner) of the Potlatch River, Idaho. Master's thesis. University of Idaho, Moscow.

Hansen, M.J., and D.W. Hayne. 1962. Sea lamprey larvae in Ogontz Bay and Ogontz River, Michigan. Journal of Wildlife Management 26:237-247.

Hayes, M.C., R. Hays, S.P. Rubin, D.M. Chase, M. Hallock, C. Cook-Tabor, C.W. Luzier, and M.L. Moser. 2013. Distribution of Pacific lamprey *Entosphenus tridentatus* in watersheds of Puget Sound based on smolt monitoring data. Northwest Science 87:95-105.

Heiri, O., A.F. Lotter, and G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25:101-110.

Hess, J.E., N.R. Campbell, M.F. Docker, C. Baker, A. Jackson, R. Lampman, B. McIlraith, M.L. Moser, D.P. Statler, W.P. Young, A.J. Wildbill, and S.R. Narum. 2014. Use of genotyping-by-sequencing data to develop a high-throughput and multi-functional SNP panel for conservation applications in Pacific lamprey. Molecular Ecology Resources. Advance online publication. doi: 10.1111/1755-0998.

Hughes, J.S., G.A. McMichael, E.V. Arntzen, C.R. Vernon, E.S. Fischer, M.J. Greiner, R.A. Harnish, S.A. McKee, R.P. Mueller, and J.A. Vazquez. 2014. Fish presence/absence and habitat in areas affected by sediment from Mount Saint Helens, 2013-2014. U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, Washington.

Jackson, A. and M. Moser. 2012. Low-elevation dams are impediments to adult Pacific Lamprey spawning migration in the Umatilla River, Oregon. North American Journal of Fisheries Management 32:548-556.

Jolley, J.C., G. Kovalchuk, and M.F. Docker. *In press*. Putative migratory *Lampetra* spp. in the Mid-Columbia River. Northwestern Naturalist.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2011. Occurrence, detection, and habitat use of larval lamprey in Columbia River mainstem environments: Bonneville Reservoir and Tailwater. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, 2010 Annual Report.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2012a. Occurrence, detection, and habitat use of larval lamprey in Columbia River mainstem environments: Bonneville Tailwater and tributary mouths. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, 2011 Annual Report.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2012b. Occurrence, detection, and habitat use of larval lamprey in the White Salmon River Basin: pre-Condit Dam Removal. U.S. Fish

and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA, 2011 Annual Report.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2012c. Occupancy and detection of larval Pacific lampreys and *Lampetra* spp. in a large river: the Lower Willamette River. Transactions of the American Fisheries Society 141:305-312.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2013a. Occurrence, detection, and habitat use of larval lamprey in Columbia River mainstem environments: The Dalles Pool and Deschutes River mouth. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA, 2012 Annual Report.

Jolley, J.C., G.S. Silver, and T.A. Whitesel. 2013b. Occurrence, detection, and habitat use of larval lamprey in the Lower White Salmon River and mouth: Post-Condit Dam removal U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA, 2012 Annual Report.

Jolley, J.C. G.S. Silver, J.J. Skalicky, and T.A. Whitesel. 2014. Evaluation of larval Pacific lamprey rearing in mainstem areas of the Columbia and Snake rivers impacted by dams. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA, 2013 Annual Report.

Lee, D.S., and J.G. Weise. 1989. Habitat selection of lentic larval lampreys: preliminary analysis based on research with a manned submersible. Journal of Great Lakes Research 15:156-163.

Li, W., M.J. Siefkes, A.P. Scott, and J.H. Teeler. 2003. Sex pheromone communication in the sea lamprey: implications for integrated management. Journal of Great Lakes Research 29, Supplement 1:85-94.

Liedtke, T.L., L.K. Weiland, and M.G. Mesa. 2015. Vulnerability of larval lamprey to Columbia River hydropower system operations - effects of dewatering on larval lamprey movements and survival. U.S. Geological Survey, Cook, Washington. 28 pp.

Luzier, C.W, H.A. Schaller, J.K. Bostrom, C. Cook-Tabor, D.H. Goodman, R.D. Nelle, K. Ostrand, B. Strief. 2011. Pacific lamprey (*Entosphenus tridentatus*) assessment and template for conservation measures. U.S. Fish and Wildlife Service, Portland, OR.

Malmqvist, B. 1980. Habitat selection of larval brook lampreys (*Lampetra planeri*, Bloch) in a South Swedish stream. Oecologia 45:35-38.

McGree, M., T.A. Whitesel, and J. Stone. 2008. Larval metamorphosis of individual Pacific lampreys reared in captivity. Transactions of the American Fisheries Society 137:1866-1878.

Meeuwig, M.H., and J.M. Bayer. 2005. Morphology and aging precision of statoliths from larvae of Columbia River Basin lampreys. North American Journal of Fisheries Management 25:38-48.

Mesa, M.G., and E.S. Copeland. 2009. Critical uncertainties and research needs for the restoration and conservation of native lampreys in North America. Pages 311–321 *in* L. R. Brown, S.D. Chase, M.G. Mesa, R.J. Beamish, and P.B. Moyle, editors. Biology, management, and conservation of lampreys in North America. American Fisheries Society, Symposium 72, Bethesda, Maryland.

Mesa, M.G., L.K. Weiland, and H.E. Christiansen. 2015. Synthesis of juvenile lamprey migration and passage research and monitoring at Columbia and Snake River dams. U.S. Geological Survey, Cook, Washington. Draft report.

Moser, M., A. Jackson, M.C. Lucas, and R.P. Mueller. 2015. Behavior and potential threats to survival of migrating lamprey ammocoetes and macrophthalmia. Reviews in Fish Biology and Fisheries 25:103-116.

Moser, M.L., P.A. Ocker, L.C. Stuehrenberg, and T.C. Bjornn. 2002. Passage efficiency of adult Pacific lampreys at hydropower dams on the Lower Columbia River, USA. Transactions of the American Fisheries Society 131:956-965.

Moser, M.L., and D.A. Close. 2003. Assessing Pacific lamprey status in the Columbia River basin. Northwest Science 77:116-125.

Moursund, R. A., D. D. Dauble, and M. J. Langeslay. 2003. Turbine intake diversion screens: investigating effects on Pacific lamprey. Hydro Review 22:40-46.

Mueller, R.P., C.L. Rakowski, W.A. Perkins, and M.C. Richmond. 2014. Assessment of fluctuating reservoir elevations using hydraulic models and impacts on larval Pacific Lamprey rearing habitat in the Bonneville Pool. PNNL-23876, final report submitted to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon, by Pacific Northwest National Laboratory, Richland, Washington.

Nichols, J.D., J.E. Hines, D.I. Mackenzie, M.E. Seamans, and R.J. Gutiérrez. 2007. Occupancy estimation and modeling with multiple state and state certainty. Ecology 88:1395-1400.

NPPC (Northwest Power and Conservation Council). 2004. Walla Walla Subbasin Plan. Portland, Oregon. 210 pp.

Nursall, J. R., and D. Buchwald. 1972. Life history and distribution of the arctic lamprey (*Lethenteron japonicum* (Martens)) of Great Slave Lake, N.W.T. Fisheries Research Board of Canada Technical Report 304.

Ojutkangas E., K. Aronen, E. Laukkanen. 1995. Distribution and abundance of river lamprey (*Lampetra fluviatilis*) ammocoetes in the regulated river Perhonjoki. Regulated Rivers 10:239–245.

Parsley, M.J., L.G. Beckman, and G.T. McCabe. 1993. Spawning and rearing habitat use by white sturgeons in the Columbia River downstream from McNary Dam. Transactions of the American Fisheries Society 122:217-227.

Peterson Lewis, R.S. 2009. Yurok and Karuk traditional ecological knowledge: insights into Pacific lamprey populations of the Lower Klamath Basin. Pages 1-39 *in* L.R. Brown, S.D. Chase, M.G. Mesa, R.J. Beamish, and P.B. Moyle, editors. Biology, management, and conservation of lampreys in North America. American Fisheries Society, Symposium 72, Bethesda, Maryland.

Peterson, J.T., and J. Dunham. 2003. Combining inferences from models of capture efficiency, detectability, and suitable habitat to classify landscapes for conservation of threatened bull trout. Conservation Biology 17:1070-1077.

Potter, I.C., R.W. Hilliard, J.S. Bradley, and R.J. McKay. 1986. The influence of environmental variables on the density of larval lampreys in different seasons. Oecologia 70:433-440.

Renaud, C. B. 1997. Conservation status of northern hemisphere lampreys (Petromyzontidae). Journal of Applied Ichthyology 13:143-148.

Royle, J.A. and J.D. Nichols. 2003. Estimating abundance from repeated presence-absence data or point counts. Ecology 84:777-790.

Russell, J. E., F. W. H. Beamish, and R. J. Beamish. 1987. Lentic spawning by the Pacific lamprey, *Lampetra tridentata*. Canadian Journal of Fisheries and Aquatic Sciences 44:476-478.

SAS Institute, Inc. 2002. SAS/STAT user's guide, version 9.1 edition. Cary, NC, USA: SAS Institute, Inc.

Scheidegger, K.J., and M.B. Bain. 1995. Larval fish distribution and microhabitat use in free-flowing and regulated rivers. Copeia 1995:125-135.

Schleen, L.P., G.C. Christie, J.W. Heinrich, R.A. Bergstedt, R.J. Young, T.J. Morse, D.S. Lavis, and T.D. Bills, J.E. Johnson, and M.P. Ebener. 2003. Development and implementation of an integrated program for control of sea lampreys in the St. Marys River. Journal of Great Lakes Research 29(Supplement 1):677-693.

Scott, W.B., and E.J. Crossman. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada, Ottawa.

Smith, D., S. Welsh, and P.J. Turk. 2011. Selection and preference of benthic habitat by small and large ammocoetes of the least brook lamprey (*Lampetra aepyptera*). Environmental Biology of Fishes 91:421-428.

Spice, E.K., T.A. Whitesel, C.T. McFarlane, and M.F. Docker. 2011. Characterization of 12 microsatellite loci for the Pacific lamprey, *Entosphenus tridentatus* (Petromyzontidae), and cross-amplification in five other lamprey species. Genetics and Molecular Research 10:3246–3250.

Stevens, D.L., and A.R. Olsen. 2004. Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99:262-278.

Stone, J. 2006. Observations on nest characteristics, spawning habitat, and spawning behavior of Pacific and western brook lamprey in a Washington stream. Northwestern Naturalist 87:225-232.

Stone, J., and S. Barndt. 2005. Spatial distribution and habitat use of Pacific lamprey (*Lampetra tridentata*) ammocoetes in a western Washington stream. Journal of Freshwater Ecology 20:171-185.

Sutton, T.M., and S.H. Bowen. 1994. Significance of organic detritus in the diet of larval lamprey in the Great Lakes Basin. Canadian Journal of Fisheries and Aquatic Sciences 51:2380-2387.

Torgersen, C.E., and D.A. Close. 2004. Influence of habitat heterogeneity on the distribution of larval Pacific lamprey *Lampetra tridentata* at two spatial scales. Freshwater Biology 49:614-630.

Vinson, M.R. 2001. Long-term dynamics of an invertebrate assemblage downstream from a large dam. Ecological Applications 11:711-730.

Wagner, W.C., and T.M. Stauffer. 1962. Sea lamprey larvae in lentic environments. Transactions of the American Fisheries Society 91:384-387.

Weitkamp, L.A., P.J. Bentley, and M.N. Litz. 2012. Seasonal and interannual variation in juvenile salmonids and the associated fish assemblage in open waters of the lower Columbia River estuary. Fishery Bulletin 110:426-450.

Weitkamp, L.A., S.A. Hinton, and P.J. Bentley. 2015. Seasonal abundance, size, and host selection of western river (*Lampetra ayresii*) and Pacific (*Entosphenus tridentatus*) lampreys in the Columbia River estuary. Fishery Bulletin 113:213-226.

White, J. L., and B. C. Harvey. 2003. Basin-scale patterns in the drift of embryonic and larval fishes and lamprey ammocoetes in two coastal rivers. Environmental Biology of Fishes 67:369-378.

Wydoski, R.S. and R.R. Whitney. 2003. Inland fishes of Washington, 2nd edition. American Fisheries Society and University of Washington Press, Bethesda, Maryland, and Seattle, Washington.

Young, R. J., G.C. Christie, R.B. McDonald, D.W. Cuddy, T.J Morse, and N.R. Payne. 1996. Effects of habitat change in the St. Marys River and northern Lake Huron on sea lamprey (*Petromyzon marinus*) populations. Canadian Journal of Fisheries and Aquatic Sciences 53:99-104.

U.S. Fish and Wildlife Service
Columbia River Fisheries Program Office
1211 SE Cardinal Court, Suite 100
Vancouver, WA 98683

February 2016