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Research Paper

Climbing above the competition: Innovative approaches and recommendations for improving Pacific Lamprey passage at fishways

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A R T I C L E I N F O

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A B S T R A C T

We evaluated the behavior and capabilities of upstream migrating adult Pacific Lamprey using a series of experimental trials in relation to existing and novel fishway designs using Passive Integrated Transponder (PIT) telemetry. Five treatments were evaluated with PIT telemetry of 164 upstream migrating Pacific Lamprey. Experimental treatments included an existing pool and weir fishway, two in-situ modifications of the existing fishway and two treatments designed to provide lamprey-specific routes. The probability of passage success through trials (10 m distance and 1 m elevation gain over 1 night) was related to treatment. The existing pool and weir fishway provided the lowest predicted passage efficiency at 0.44 (95% CI 0.29–0.59), while tube and culvert treatments had perfect efficiencies. For individuals that successfully ascended trials, passage time was also related to treatment. Lampreys ascending the pool and weir structure had the longest predicted passage time at 5.2 h (95% CI 3.96–6.46) while individuals in the tube were the fastest, with a 20-fold reduction in migration time at 0.26 h (95% CI 0.21–0.30). Lamprey ranged from 52 to 66 cm TL, however length did not influence passage success or migration time. Over 200 h of night-time observations were used to improve our understanding of how lampreys pass barriers and where they encounter particular challenges. Our results and observations of lamprey migration behavior confirm that pool and weir fishways and design features common to other fishways types can pose a substantial obstacle to Pacific Lamprey migration. We provide a set of recommendations for behavioral considerations and design features, both beneficial and those that should be avoided at fishways. This study identifies a variety of solutions applicable to a range of obstacles that, if implemented, should significantly improve the opportunity for Pacific Lamprey to pass existing and future man-made structures.

1. Introduction

Anadromy allows fishes to exploit a wide range of resources, often over broad geographic ranges, but is coupled with a unique set of challenges. Along much of the western coast of North America the Pacific plates collide with the North American Plate, creating a rugged interface that drains steep coastal mountain ranges forming gateways between marine and freshwater habitats. Waterfalls, steep cascades and rapids are frequently encountered and provide a riverine architecture that has shaped the evolution of native anadromous fishes (Montgomery, 2000). Anadromous fishes that evolved within this environment have developed adaptive strategies for navigating obstacles to maximize access to upstream freshwater resources (Montgomery, 2000). Anadromous Pacific salmonids (*Oncorhynchus* spp.) are well known for their ability to ascend riverine obstacles by jumping, which facilitates passage beyond impediments and extends their distribution within drainages (Stuart, 2014; Yoshiyama et al., 2001). The proficiency of salmonids to jump has been a crucial component in engineering solutions that facilitate fish passage over man-made obstacles (Clay, 1994). However, the ability to jump is not universal among anadromous fishes.

Pacific Lamprey (*Entosphenus tridentatus*) are the most widely distributed anadromous fish in the Pacific Basin (Ruiz-Campos and Pister, 1995; Ruiz-Campos and Gonzalez-Guzman, 1996; Mecklenburg et al., 2002; Augerot, 2005; Orlov et al., 2008, 2009; Reid and Goodman, 2016a; Renaud, 2008, 2011; Abadía-Cardoso et al., 2016). They span the North Pacific Rim, with marine feeding grounds extending from as far north as the Bering Sea (63.5°N) to as far south as the Revillagigedo Archipelago off México (18.3°N) and the Naka River, Honshu, Japan (36.3°N). Freshwater spawning occurs in most rivers along the Eastern Pacific from the Aleutian Islands as far south as the Río Santo Domingo, Baja California (30.7°N) as well as down to Japan in the western Pacific.

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Although Pacific Lamprey lack the ability to jump, they are observed in rivers upstream of natural waterfalls that limit the distribution of even the most athletic of salmonids (Moser and Mesa, 2009; Goodman and Reid, 2012).

While the anadromous Pacific Lamprey is widely distributed and generally sympatric with anadromous salmonids, it takes a different, and arguably more successful, approach to navigating impediments to upstream migration. Pacific Lamprey have evolved the ability to climb, using their suctorial mouths, a rare capability among fishes, and documented in perhaps only one other species of lamprey, *Geotria australis* (Kemp et al., 2009; Reinhardt et al., 2008; Tweed, 1987; Zhu et al., 2011). They typically ascend subaerial, inclined and vertical wetted surfaces with an energetically efficient dyno-climbing behavior (derived from moutaineering terminology), attaching with their suctorial mouth, flexing their body in a waveform, then extending upward and reattaching by means of their mouth (Zhu et al., 2011). During climbing ascents, lampreys typically seek subaerial routes where lower velocities exist outside of primary flow, such as shallow flow or even splash zones, where they are partially or completely out of the water (Miller, 2012; Petersen-Lewis, 2009; Goodman and Reid, this paper). In natural settings, Pacific Lamprey are able to ascend even large obstacles like waterfalls (10 m vertical or greater), a skill which provides access to a range of habitats not accessible by jumping. However, their approach to passing obstacles requires smooth attachment points and rounded surfaces without acute angles, common in natural features, but not typically considered when designing artificial fishways (Keefer et al., 2010).

Globally, lampreys are a growing conservation concern, with over half of the species in the Northern Hemisphere classified as extinct, endangered or vulnerable in at least part of their range (Renaud, 1997). Pacific Lamprey are no exception, with populations declining and their distribution contracting, particularly in the southern extent of their range (Reid and Goodman, 2016a). Habitat loss due to the lack of access to historic habitats, caused by dams and other man-made barriers, has been identified as one of the greatest threats to Pacific Lamprey during their time in freshwater and has substantially curtailed their distribution (Goodman and Reid, 2012). Low passage success has been observed at dams and other man-made obstacles even where fishways exist, highlighting the need to consider lamprey-specific needs (Moser et al., 2002a; Jackson and Moser, 2012). Appropriate strategies and designs for lamprey passage, incorporating the unique climbing abilities of Pacific Lamprey, have only recently been considered (Moser et al., 2015).

Herein, we investigate behavior and performance of upstream migrating Pacific Lamprey at a series of experimental modifications to an existing fishway. We use Passive Integrated Transponder (PIT) telemetry to track the performance of individuals, coupled with observational studies to evaluate how lampreys approach passage within fishways. The scope of this assessment is limited to behavior of upstream migrating lampreys within fishways and does not evaluate other aspects of fishways that almost certainly affect lamprey migration (i.e. attraction efficiency, downstream migration, etc.). Results are discussed in the context of applying modifications to existing fishways and considerations for incorporating the needs of Pacific Lamprey into new designs.

2. Materials and methods

2.1. Study site

The Eel River in northern California was named after its historically abundant Pacific Lamprey run by European settlers who mistook the abundant lamprey for eels due to their anguilliform bodies. It flows from south to north, entering the Pacific Ocean 150 km south of the Oregon-California border and is the third largest drainage in the state, covering 9540 km^2. The river is known for its unstable geology and highly variable discharge (0.3–21,300 m^3/s; USGS gauge 11477000).

This study was conducted at Cape Horn Dam, located on the Eel River 240 km upstream of the estuary, near the town of Ukiah, California (lat. 39.3861°, long. −123.1164°,WGS84, 463 m). Cape Horn Dam was constructed in 1907 and facilitates one of California's first inter-basin water diversions. The dam is 19 m in height (measured from bedrock base) and is used to divert water from the Eel River into the Russian River through a 3 km long wooden tunnel. The primary uses of the diverted water are agriculture and power generation. Cape Horn Dam is 20 km downstream of the artificial limit to anadromy at Scott Dam, a 42 m high storage facility, which is used to regulate streamflow for the inter-basin diversion and blocks approximately 90 km of anadromous habitat (Venture Tech Network Oregon Inc., 1982).

All passage experiments and observations were conducted at a pool and weir fishway designed to aid salmon in passing Cape Horn Dam. The fishway was constructed in 1922 and was designed to provide upstream passage for Chinook Salmon (*O. tshawytscha*) and steelhead Rainbow Trout (*O. mykiss*). The primary passage features in the ladder are a series of 50 step pools, with each step approximately 25 cm tall and separated by pools of about 2 m in length and 1 m in depth within a mixed cement, bedrock and cobble channel. Steps are formed by wooden board weirs, held in place by vertical u-channels in concrete bulkhead walls.

2.2. Experimental trials

Passive Integrated Transponder (PIT) telemetry was used to evaluate Pacific Lamprey passage in relation to fishway design features. Custom PIT-tag interrogation antennas (hereafter, antenna) were constructed for the study using 3.8 cm diameter polyvinyl chloride (PVC) pipes, as described in Reid and Goodman (2016b) and Steinke et al. (2011). The antennas were 130 × 61 cm and sized to fit within channels separating fishway pools. Available lamprey passage routes in the study reaches all passed through antenna loops and were within 25 cm of antenna housing. Antennas were connected to a centralized multiplex radio-frequency identification transceiver that was run continuously during experimental trials (Biomark FS1001M-Mux).

Migrating Pacific Lampreys were netted while ascending the fishway entrance between April 5 and 7, 2016. Collections were made during a period when numerous lamprey were attempting to ascend the fishway and likely coincided with the peak of migration during that year. Glass encapsulated 12.5 mm PIT tags (Biomark FDX-B HPT12) were implanted to provide a unique identifier when individuals were detected by antennas. Tags were implanted in upstream migrating lampreys on the ventral mid-line below the first dorsal fin and anterior to the anus following Reid and Goodman (2016b). Lampreys that were sexually ripe were not tagged or included in the study due to potential impacts on their reproductive success. After tagging and before experimental trials, lampreys were held for at least 24 h. in perforated plastic barrels (120 l) immersed in the fishway's shaded raceway and transferred to the release site in the afternoon prior to the nocturnal test period where they were kept submerged in the same barrels prior to release. For release, the submerged lid was removed to allow volitional exit from the barrel." We evaluated tag effects on lamprey survival and tag retention in 50 individuals held for a 3-week period and found no mortality or tag loss. Individuals used in the tag retention study were not used in experimental trials discussed below.

We evaluated lamprey performance in five treatments including the existing fishway and four modifications intended to improve lamprey passage (Fig. 1).

1. Pool and weir (Control) – Each board weir raised the water surface elevation approximately 25 cm. Boards were standard dimensional wood (6.5 wide by 130 cm long) with square edges and were held in place by steel u-channels (5 cm deep by 7.6 cm wide). This