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Providing refuges for adult Pacific lamprey *Entosphenus tridentatus* inside fishways

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A B S T R A C T

Fishways at hydroelectric dams are unnatural environments that typically present fish with channels of uniform depth, variable water velocity, and lack of cover. Fish retention and overall passage success may be improved by providing rest and sheltering areas inside fishways. We examined adult Pacific lamprey *Entosphenus tridentatus* use of two specially designed fishway refuges at Bonneville Dam on the Columbia River (northwestern USA). These relatively small boxes (1.1 m × 0.4 m × 0.2 m) provided low-velocity, dark refuge from predation for Pacific lamprey, a largely nocturnal species. Refuge boxes were equipped with antennas to detect entry of lamprey tagged with passive integrated transponder (PIT) tags. We PIT tagged and released 3,247 lamprey, including 599 that were double-tagged with a PIT and a radio transmitter, over three study years (2012–2014). In each year, PIT-tagged lamprey detected at nearby fishway exits had used a refuge: 12% in 2012, 28% in 2013, and 36% in 2014. Median residence time of PIT-tagged lamprey in the refuges for each year was 20.3 h, 16.6 h, and 13.1 h. Lamprey entrance into refuges peaked at 0300–0500 PDT, and they typically exited at around 2000 PDT, suggesting that refuges primarily functioned as shelter from daylight. Probability of refuge use increased with a morphological indicator of sexual maturity (distance between dorsal fins). In the radio-tagged group, refuge users were equally likely to pass Bonneville Dam as non-users. However, refuge users were less likely than non-users to be detected at sites upstream from the dam, perhaps owing to their maturation status or longer mean passage time through our study area (2.0 vs. 0.6 d for non-users). Refuges show promise for improving fish retention in fishways, particularly for nocturnal and/or small-bodied species that seek shelter from light or predation.

1. Introduction

Man-made obstacles to fish movement (dams, weirs, tide gates, culverts, etc.) result in fragmented habitats and population declines (Lucas & Baras, 2008). To mitigate for these effects, fishways are often constructed to offer fish a passage route around the obstacle (Clay, 1995). These fishways are typically constructed of concrete or metal and are designed to accommodate the swimming performance of target species. Fishway engineers also must factor in construction costs, maintenance requirements and space available (Clay, 1995).

The resulting fishways are often unnatural environments that present fish with both behavioral and physical challenges. Fish can be forced into proximity with artificially high densities of conspecifics and other species, including potential predators (Agostinho, Agostinho, Pelicice, & Marques, 2012). In addition, fishways often feature high velocities and turbulence, are subject to man-made noise/vibration, can present fish with thermal barriers, and are often uniform in depth. Shallow fishways have unnatural lighting conditions, with high penetration of both natural light in daytime and artificial light at night. Many fish species are sensitive to these conditions, and after fishway entry, may avoid them by retreating downstream and abandoning migration (Castro-Santos, Cotel, & Webb, 2009; Haro & Kynard, 1997; Keefer, Caudill, Clabough, et al., 2013).

Early in the history of fishway design, the need to provide fish with refuge from high water velocity was recognized (Clay, 1995). Technical solutions included incorporation of baffles, resting areas, or turn pools into many fishway designs. More recently, efforts to provide velocity heterogeneity and reduce turbulence within fishways have been a design focus (Muraoka, Nakanishi, & Kayaba, 2017; Silva, Katapodis, Ferreira, & Pinheiro, 2012). Nature-like fishway designs further address the need for more familiar and less extreme hydraulic elements to promote passage for a wider variety of species.

While the need for hydraulic refuges is well established, providing cover where fish can shelter during technical fishway passage has not, to our knowledge, been tested. Refuge from light and/or predation in fishways may be particularly important for small-bodied species that are susceptible to predation/mutilation or the mere presence of potential predators. Agostinho et al. (2012) documented the

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