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Pacific Lamprey drag force modeling to optimize fishway design

Hattie Zobott[a], Ralph Budwig[b], Christopher C. Caudill[c], Matthew L. Keefer[c] and William Basham[b]

[a]J-U-B Engineers, Inc, Twin Falls, Idaho, USA; [b]Center for Ecohydraulics Research, University of Idaho, Boise, Idaho, USA; [c]Department of Fish and Wildlife Sciences, College of Natural Resources, University of Idaho, Moscow, Idaho, USA

ABSTRACT

Typically, fish passage design is informed by a critical velocity model whereby fish are assumed to fail passage if the water velocity is higher than the critical swim speed, an assumption that may not be met when locomoting fish are partially submerged. We applied a drag force model (DFM) approach for use in design of Pacific Lamprey (*Entosphenus tridentatus*) Passage Structures (LPS) where lamprey may be partially or fully submerged. Our investigation assessed the dead-drag forces at four levels of static submergence: fully submerged (120 mm), equally submerged (40 mm), partially submerged (15 mm), and skin-flow (5 mm) for a Pacific Lamprey physical model by varying simulated LPS slope and discharge conditions. We then used the results to establish drag force thresholds corresponding to the known critical velocity thresholds of Pacific Lamprey to predict passage success under partial and full submergence conditions. Consideration of drag force in fish passage could be used to improve or create species-specific design recommendations for fishways, or to inform the design of barriers to prevent invasive species passage. The results suggest consideration of drag force in addition to velocity is beneficial to predict Pacific Lamprey passage success under partial submergence conditions.

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Introduction

Fishway designs have often been based on swimming performance for a narrow number of species, primarily salmonid (Salmonidae) fishes (Clay, 1995; Williams et al., 2012). Mismatch between species-specific swimming behaviours and the structural and hydraulic conditions encountered during fishway passage can result in low passage rates of non-target fishes. For example, dams on the lower Columbia River, USA, pass less than 50% of upstream-migrating adult Pacific Lamprey (*Entosphenus tridentatus*) (Moser et al., 2002; Keefer et al., 2013), while adult salmonids (*Oncorhynchus spp.*) typically have greater than 90% passage success (e.g., Caudill et al., 2007).

Prespawn adult Pacific Lamprey typically enter freshwater between April and June and complete migration to their spawning grounds by September before overwintering and spawning the following year (Beamish, 1980; Clemens et al., 2010; Clemens et al., 2013). Man-made dams often impede migration (Beamish, 1980; Moser et al., 2002; Jackson and Moser 2012; and Keefer et al., 2013) as do complex hydraulic features found in traditional fishways used to bypass those dams (Keefer et al., 2011; Kirk et al., 2015; Kirk et al., 2017).

Adult Pacific Lamprey have two primary modes of locomotion: anguilliform swimming, when submerged and at lower water velocities, and saltatory movement at higher water velocities. The saltatory movement is observed when the fish are fully submerged as well as when they are partially submerged and climbing steeper surfaces (Quintella et al., 2004; Keefer et al., 2011). The behavioural transition between modes depends on a number of factors including water velocity, turbulence level, and the presence of predatory fish (Kirk et al., 2015; 2016). Water velocities associated with the transitions between swimming mode and passage failure averaged over a range of Pacific Lamprey age and size are often used as thresholds in fish passage evaluations and have been estimated in laboratory experiments. The maximum sustained anguilliform swimming velocity for adult Pacific Lamprey determined experimentally is approximately 0.85 m/s (Mesa et al., 2003). Pacific Lamprey may initiate saltatory swimming above this velocity (hereafter referred to as the critical velocity) whereby they use their oral disk to attach to smooth surfaces and periodically burst forward (e.g., Reinhardt et al., 2008; Keefer et al., 2010). Once the water velocity reaches between 2.5–3.0 m/s, fully submerged Pacific Lamprey have difficulty achieving forward

CONTACT Ralph Budwig rbudwig@uidaho.edu Center for Ecohydraulics Research, University of Idaho, Boise, Idaho, USA