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Passage of downstream migrant American eels through an airlift-assisted deep bypass

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ABSTRACT

Traditional downstream guidance and bypass facilities for anadromous fishes (i.e., surface bypasses, surface guidance structures, and behavioral barriers) have frequently been ineffective for anguillid eels. Because eels typically spend the majority of their time near the bottom in the vicinity of intake structures, deep bypass structures with entrances near the bottom hold promise for increased effectiveness, thereby aiding in the recovery of this important species. A new design of a deep bypass system that uses airlift technology (the Conte Airlift Bypass) to induce flow in a bypass pipe was tested in a simulated intake entrance environment under controlled laboratory conditions. Water velocities of 0.9–1.5 $m\,s^{-1}$ could be generated at the bypass entrance (opening with 0.073 m^2 area), with corresponding flows through the bypass pipe of 0.07–0.11 $m^3\,s^{-1}$. Gas saturation and hydrostatic pressure within the bypass pipe did not vary appreciably from a control (no air) condition under tested airflows. Migratory silver-phase American eels (*Anguilla rostrata*) tested during dark conditions readily located, entered, and passed through the bypass; initial avoidance rates (eels approaching but not entering the bypass entrance) were lower at higher entrance velocities. Eels that investigated the bypass pipe entrance tended to enter headfirst, but those that then exited the pipe upstream did so more frequently at lower entrance velocities. Eels appeared to swim against the flow while being transported downstream through the pipe; median transit times through the bypass for each test velocity ranged from 5.8 to 12.2 s, with transit time decreasing with increasing entrance velocity. Eels did not show strong avoidance of the vertical section of the pipe which contained injected air. No mortality or injury of bypassed eels was observed, and individual eels repeatedly passed through the bypass at rates of up to 40 passes per hour, suggesting that individuals do not avoid repeated entrainment through the bypass. Airlift technology appears to be a viable method for increasing passage effectiveness for American eels through a deep bypass system.

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1. Introduction

Freshwater eels (genus *Anguilla*) are ecologically, commercially, culturally, and recreationally important species of high conservation concern due to recent population declines as a result of threats to recruitment and stock recovery (Dekker and Casselman, 2014). All anguillid eel species migrate downstream to spawn in ocean environments, often having to pass multiple man made barriers. Impoundments created by dams have been shown to delay eel migration, and dams with operating hydroelectric facilities can cause direct mortality via impingement on trashracks or entrainment through the turbines (Environment Agency UK, 2011; Montén, 1985). Anguillid eels are particularly susceptible to turbine mortality, and suffer direct mortality rates as high as 25–100%, largely due to their large size and elongate body shape (Electric Power Research Institute (EPRI), 2001).

Methods to protect downstream migrant eels from hydroelectric turbine mortality are not well developed. Typical remediation measures for smaller-scale hydroelectric projects include reduced intake bar rack spacing or overlay screening, or temporary suspension of generation, which are expensive and affect project performance and energy production (Electric Power Research Institute (EPRI), 2001). Traditional downstream guidance and bypass facilities for anadromous fishes (i.e., surface bypasses, surface guidance structures, lights and sound) are usually ineffective for anguillid eels (Electric Power Research Institute (EPRI), 2001; Richkus and Dixon, 2003; Bruijs and Durif, 2009). However, eels often initially avoid entrainment through relatively large bar rack

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spacing or screen/overlay openings and appear to actively search within hydroelectric project forebays for hydraulic features that may indicate a route of downstream passage (Brown et al., 2009; McGrath et al., 2003; Russon et al., 2010; Russon and Kemp, 2010). Entrance area and total flow of bypass entrances are probably important with respect to bypass efficiency, but if eels use cues such as entrance velocity and flow acceleration to locate and enter bypasses, bypass entrances could be designed to optimize these cues and potentially minimize required bypass flows or the total number of bypass entrances required at a site. Because anguillid eels typically spend the majority of their time in hydroelectric forebay environments near the bottom (Brown et al., 2009; Gosset et al., 2005), bypass systems with deep entrances hold some promise for increased passage effectiveness, thereby aiding in the protection of this important species.

Airlifts, which use air injected into vertical submerged conduits to induce flow through the conduit, have been adapted for transporting live fish in aquaculture (Parker and Suttle, 1987; Summerfelt et al., 2009; Loyless and Malone, 1998) and for offloading fish from commercial fishing vessels (Roach et al., 1964). Airlifts have also been employed to sample migrating juvenile salmonids at the John Day and Bonneville dams on the Columbia River, USA (Brege et al., 1990; Hawkes et al., 1992; Sims et al., 1981). An experimental airlift downstream bypass system for juvenile salmonids on the Black River, Washington, had low efficiency (<11%) with associated delays in passage, assumed to be caused by insufficient bypass flow and attraction (Fender 1979).

The operation and effectiveness of a prototype deep-entrance airlift bypass (Conte Airlift Bypass) was evaluated for attraction and transport of adult downstream migrating American eels (*Anguilla rostrata*) in a large-scale laboratory flume environment. Primary objectives were to: (1) assess hydraulics and physical (pressure, gas saturation) characteristics of the bypass; (2) determine rates of avoidance/attraction to, entry into, and passage through the airlift system under varying bypass flows; (3) characterize repeated passes of individual eels through bypass over time; and (4) assess whether eels were injured or killed by passage through the bypass.

2. Material and methods

2.1. Airlift design

A small diameter airlift was designed to accommodate passage of large (approximately 100 cm total length) adult silver-phase eels. The airlift was designed to operate in the bubbly-slug flow regime which is characterized by a liquid–gas two-phase flow in which the gas phase exists as large bubbles approaching the diameter of the riser tube, separated by liquid "slugs" containing smaller bubbles (Reinemann et al., 1990). Slug-flow airlifts favor increased pumping action, resulting in water velocities high enough at the airlift entrance to enhance attractiveness of the entrance to downstream migrant eels (>1 m s^{-1}). The airlift was constructed from steel and PVC pipe and fittings, and had a 30.5 cm diameter circular entrance (Fig. 1), with the entrance invert located 11.4 cm above the floor of the flume. The entrance tapered to a 20.3 cm diameter horizontal section that transitioned to the vertical 25.4 cm diameter airlift riser section via two 45° angle fittings. The vertical section extended 33.5 cm above the water surface with a total water depth of 3.84 m. Air was injected into the bottom of the vertical riser section to create a total vertical lift from the invert of the bypass entrance of approximately 4.5 m. Air was supplied to the bottom of the vertical riser section of the airlift from a portable rotary screw compressor powered by an internal combustion engine. A valve was used to regulate the airflow from the compressor through the 2.5 cm diameter flexible airlines that terminated in a manifold consisting of four 2.5 cm diameter injection pipes. The pipes were used to introduce air horizontally into an expansion fitting.

2.2. Physical measurements

Airflow rates were measured using a digital flowmeter (EXAIR Model 9095) located in the main compressed air line supplying the manifold. Water velocities were measured at the plane of the entrance with a 1-dimensional water velocity probe (Marsh-McBirney Model 2000) positioned in the center of the airlift entrance, at airflows ranging from 0.42 to 7.31 m^3 min^{-1}. Dissolved oxygen and temperature were measured with a portable oxygen meter (Hach HQ40D). A portable total gas pressure meter (Point 4 Systems Inc. PT4 Tracker) was used to measure ΔP as well as local barometric pressure. Oxygen, temperature, and pressure data were measured at the airlift entrance and exit at airflows of 1.4 and 4.0 m^3 min^{-1}. Pressure (stagnation pressure) distribution throughout the length of the airlift pipe was measured from five taps located at the airlift entrance, 90° bend, above the air injection manifold, midpoint of the riser, and exit, using differential pressure cells (Rosemount Model 1151DP) and a computer data acquisition system at airflow rates of 0, 1.68, and 3.64 m^3 min^{-1}. All test probes were removed from the airlift during biological testing.

Theoretical transit times for a passive particle traveling through the centerline of the pipe between pairs of PIT detection antennas were calculated using in-pipe velocities (based on entrance velocity and pipe cross-sectional area) and between-antenna distances. Transit times were also measured directly for a passive drifter using PIT tags attached to 75 cm diameter neutrally buoyant spheres (drifters) released into the bypass entrance.

2.3. Biological test conditions

An eel containment area was created in the 6.1 m wide hydraulic flume by constructing two 3.9 m high retention screens (1 cm plastic mesh) oriented perpendicular to the flume flow (Fig. 1). The bypass pipe system was installed 0.5 m away from one wall, with the entrance penetrating but flush with the screen. A box made of wood at the exit of the airlift system was used to direct all flow and eels back into the containment area; thus individual eels could pass through the airlift system more than once.

Passage of eels was monitored with four separate passive integrated transponder (PIT) coil antennas located at the entrance to the airlift and at three locations within the airlift pipe. PIT receivers (Texas Instruments TIRIFD model S-2000) were interfaced to a computer that logged detections of individually tagged eels within 0.25 m of each antenna to the nearest 0.1 s. The airlift entrance was also continuously monitored with a downward-looking underwater video camera, with the viewing area illuminated by two 500 W underwater lights fitted with infrared filters (740 nm cutoff wavelength, creating infrared illumination not visible to eels; Andjus et al., 1998) and a 1 m by 1 m retroreflective background (3 M Diamond Grade 3990) placed on the flume floor. Ambient nighttime light levels inside the flume from outside sky illumination through skylights were approximately 0.0015 μW cm^{-1} or less, far below locomotor synchronization thresholds for eels of 20 μW cm^{-1} (van Veen and Andersson, 1982). Although these low ambient light levels may still have permitted eels to see structures within the test apparatus, the infrared illumination was considered to have no effect on attraction/repulsion to the bypass entrance, and behaviors were assumed to be representative of typical nocturnal behaviors of eels.

Transit times of a passive particle moving through pairs of adjacent PIT antennas were calculated by dividing the nominal velocity through the pipe section between antennas (accounting for changes in pipe diameter) by the flow-path distance between

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