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RESEARCH PAPER | OPEN ACCESS

American eel resilience to simulated fluid shear associated with passage through hydroelectric turbines

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Abstract – American eel (*Anguilla rostrata*) populations have declined within their native range along the eastern coast of North America due to factors such as commercial fishing, habitat alteration, and dams. American eel are catadromous fish species, and high mortality rates (>40%) have been observed for freshwater life-stage adult eel passing downstream through hydropower turbines. Lacerations and sectioning of fish have been observed downstream of turbines and these injuries are commonly associated with direct contact with the turbine runner, whether through blade strike or pinching and grinding. Exposure to fluid shear may also be a source of injury, however, little is known about American eel susceptibility to this physical stressor. Eels are considerably flexible when compared to other fish species and lack other morphological characteristics that would make them susceptible to fluid shear, such as protruding eyes, large scales, and large operculum. European eel, which have previously been tested for susceptibility to fluid shear, were found to be resilient. To determine if American eel are also resilient to fluid shear, forty American eel were exposed to a water jet, simulating severe fluid shear (strain rate > 800 s^{-1}) that fish may experience when passing downstream through turbines. No immediate or delayed (48 h) signs of injury were observed after exposure to severe fluid shear. Based on this study, and a previous study conducted on American eel susceptibility to barotrauma, the source of injury and mortality of American eel passing through turbines is likely attributed to blade strike or pinching and grinding.

Keywords: Fish passage / hydropower / water jet / stressor / morphology

Résumé – **Résilience de l'anguille américaine au cisaillement simulé du fluide associé au passage dans les turbines hydroélectriques.** Les populations d'anguilles d'Amérique (*Anguilla rostrata*) ont diminué dans leur aire de répartition d'origine le long de la côte est de l'Amérique du Nord en raison de facteurs tels que la pêche commerciale, la modification de l'habitat et les barrages. L'anguille d'Amérique est une espèce de poisson catadrome, et des taux de mortalité élevés (>40%) ont été observés chez les anguilles adultes au stade de la vie en eau douce qui passent en aval des turbines hydroélectriques. Des lacérations et des sections de poissons ont été observées en aval des turbines et ces blessures sont généralement associées à un contact direct avec la roue de la turbine, que ce soit par le choc des pales ou par le pincement et le broyage. L'exposition au cisaillement du fluide peut également être une source de blessures, mais on sait peu de choses sur la sensibilité de l'anguille d'Amérique à ce facteur de stress physique. Les anguilles sont considérablement flexibles par rapport aux autres espèces de poissons et ne possèdent pas d'autres caractéristiques morphologiques qui les rendraient sensibles au cisaillement des fluides, comme des yeux saillants, de grandes écailles et un grand opercule. Les anguilles européennes, dont la sensibilité au cisaillement des fluides a déjà été testée, se sont révélées résistantes. Pour déterminer si les anguilles américaines sont également résistantes au cisaillement des fluides, quarante anguilles américaines ont été exposées à un jet d'eau, simulant un cisaillement sévère des fluides (taux de déformation > 800 s^{-1}) que les poissons peuvent subir en passant en aval des turbines. Aucun signe de blessure immédiate ou différée (48 heures) n'a été observé après l'exposition à un cisaillement important du fluide. Sur la base de cette étude, et d'une étude précédente menée sur la sensibilité de l'anguille d'Amérique au barotraumatisme, la source de blessure et de mortalité de l'anguille d'Amérique passant à travers les turbines est probablement attribuée au choc ou au pincement et au broyage des pales.

Mots clés : Passage des poissons / hydroélectricité / jet d'eau / facteur de stress / morphologie

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1 Introduction

Many freshwater eel populations around the word have declined, including American Eel (*Anguilla rostrata*; Dekker, 2003). American eel support a viable fisheries and are a culturally significant food source to many Native American tribes of the US and First Nations peoples of Canada (MacGregor *et al.*, 2008). The Committee on the Status of Endangered Wildlife in Canada listed American eel as a threatened species and American eel were listed as an endangered species under Ontario's (Canada) Endangered Species Act in 2008 (Tremblay, 2012). Additionally, American eel are listed as endangered on the Red List of Threatened Species by the International Union of Conservation of Nature (IUCN) and the populations trend is currently assessed by the IUCN as decreasing (Jacoby *et al.*, 2017). Several factors are have led to the decline of American eel populations, including commercial fishing, habitat alteration, and dams (Jacoby *et al.*, 2017). Dams cause migrationalbarriers and can directly expose fish to stressors, particularly when fish pass downstream through hydropower turbines (Čada, 1997).

When passing downstream through hydropower turbines, fish can be exposed to several stressors, including blade strike, pinching or grinding within moving parts of the structure, rapid decompression, and fluid shear (Čada, 1997; Neitzel *et al.*, 2004; Brown *et al.*, 2012b; Bevelhimer *et al.*, 2019). Mortality rates vary greatly between different turbines, but rates greater that 40% have been observed for American eel passing through turbines (Eyler *et al.*, 2016). American eel susceptibility to blade strike has been observed in laboratory testing, where mortality occurred in 35% of American eel when exposed to simulated turbine blade strike over various combinations of blade thicknesses, blade velocities, strike locations, and fish orientations (Saylor *et al.*, 2019). Studies have linked turbine induced injuries and mortality in American eel to strike or pinching and grinding because the observed injuries included lacerations or complete sectioning of the fish (Heisey *et al.*, 2019; Saylor *et al.*, 2019). However, there is potential that injuries can also be caused by exposure to rapid decompression (*e.g.* swim bladder rupture, internal hemorrhaging, and gas emboli) or fluid shear (*e.g.* spinal fracture), which can result in injures that may not be visually observed during an external examination.

Though rapid decompression has been observed to be a potentially significant source of injury or mortality for several fish species (Brown *et al.*, 2012a; Pflugrath *et al.*, 2018, 2020), American eel have a very low susceptibility (Pflugrath *et al.*, 2019). This is primarily because American eel are a demersal fish and don't fill their swim bladder to achieve neutral buoyancy like pelagic fish (Pflugrath *et al.*, 2019). The expansion of the swim bladder, which responds according to Boyle's law during decompression, is the major driving force of barotrauma in fish (Brown *et al.*, 2012b; Pflugrath *et al.*, 2012). Additionally, American eel have a physostomous swim bladder, possessing a duct connecting the swim bladder to the gastrointestinal tract that allows them to quickly inflate or deflate the swim bladder. And, American eel are particularly adept at quickly evacuating gas from the swim bladder when decompressed (Pflugrath *et al.*, 2019). These traits, reduce the capacity of the swim bladder to expand and overinflate during decompression, consequently reducing the likelihood that American eel will suffer swim bladder rupture and barotrauma (Brown *et al.*, 2012b; Pflugrath *et al.*, 2012).

Though the susceptibility of American eel to fluid shear has not been examined, it has been examined in European eel (*A. anguilla*) which were found to be very resilient (Turnpenny *et al.*, 1992). No injuries were observed when fish were exposed to a submerged water jet with a jet velocity of $20.7\,\mathrm{m\,s^{-1}}$ creating an exposure strain rate of $1153\ \mathrm{s^{-1}}$ (Turnpenny *et al.*, 1992; Neitzel *et al.*, 2000). European eel are very similar to American eel, with minimal genetic variation between the two species, only differing slightly on genes that contribute to growth and metabolism (Jacobsen *et al.*, 2014a, 2014b). These slight genetic differences result in the American eel maturing quicker than European eel. Because of the quicker maturation, American eel are larvae for a shorter period and leave the Gulf Stream in search of fresh water sooner, which happens to place them near the Atlantic coast of North America (Pujolar *et al.*, 2014). European eel remain in the Gulf Stream longer and exit near Europe (Pujolar *et al.*, 2014). The two species have been observed to hybridize, and the offspring tend to mature at a rate between the two species and end up leaving the Gulf Stream near Iceland (Pujolar *et al.*, 2014). Morphologically the two species are nearly indistinguishable except that European eel have more vertebrae, potential due to the longer maturation process (Avise *et al.*, 1990). Therefore, due to their similarities, we hypothesize that American eel would have similar resilience to fluid shear as European eel.

To determine if American eel have a similar resistance to fluid shear as European eel, this study exposed American eel to a submerged water jet and assessed each fish for injuries and mortality. By determining the susceptibility of American eel to fluid shear, we can better understand the stressors that are causing injuries and mortality in eel passing through hydropower turbines, and implement measures, such as design and operational changes, to reduce these effects and help to restore native eel populations.

2 Materials and methods

2.1 Fish acquisitions and handling

Yellow-phase American eel were purchased from South Shore Trading Co. Ltd (Port Elgin, NB, Canada) and shipped to the Pacific Northwest National Laboratory (PNNL) Aquatic Research Laboratory (ARL) in September of 2019. Yellow-phase eel may exhibit multiple life history patterns, including freshwater resident, saline resident, and interhabitat shifter. Because these fish were captured in fresh water, they are likely freshwater residents or interhabitat shifters and may encounter hydropower facilities while conducting both upstream and downstream migrations including the outmigration as they begin to convert to the silver-phase in preparation for spawning. Fish had a median length of 34.0 cm (range = 26.5–45.3 cm) and weight of 53.0 g (range = 24.0–112.0 g). Prior to testing, fish were held for 7 weeks in a circular tank (2 m diameter and 1 m depth) with a water depth of 0.3 m. Ambient filtered Columbia river water was continuously flowed through the tank, with temperatures slowly cooling from 17.6 to 12.4 °C over the holding period. Testing was conducted at 12.6 °C.

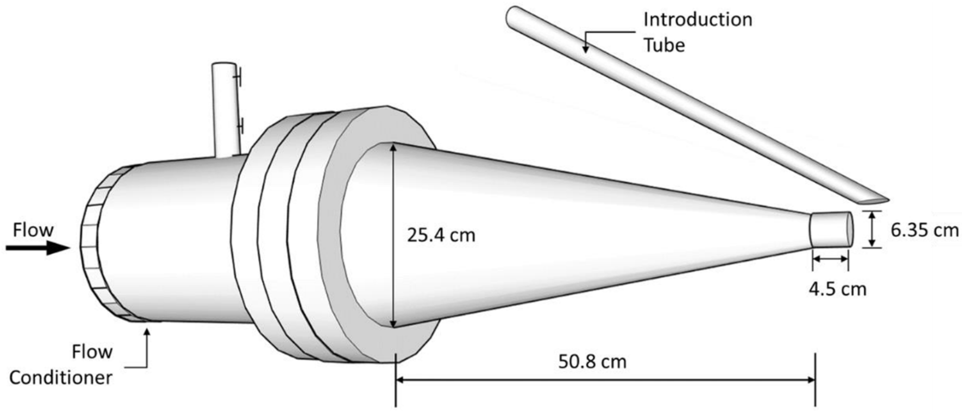

Fig. 1. Diagram of the Jet nozzle used to create an elevated fluid shear environment simulating fluid shear fish may encounter during turbine passage.

2.2 Exposure to fluid shear

All test fish were transferred to a shallow raceway to facilitate capture and transport to the test tank. Individual fish were collected from the holding tank and placed in a transparent acrylic tube with a diameter of 3.8 cm and a length of 60 cm, hereafter referred to as the cartridge. The cartridge was paced in the trough and eel were allowed to volitionally swim into the cartridge, after which both ends of the cartridge were temporarily sealed—on one end with a rubber stopper, and the other end with a flexible polyurethane foam plug. Each fish was then visually examined within the cartridge for preexisting injuries or deformities.

Fish were then exposed to elevated levels of fluid shear, simulating values expected to be encountered during passage through a hydropower turbine (Neitzel *et al.*, 2004), using a submerged water jet in a rectangular flume (9 m long, 1.2 m wide, and 1.2 m deep), hereafter referred to as the shear flume (Neitzel *et al.*, 2004). The jet nozzle (Fig. 1), which constricted flow from a 25.4 cm pipe to 6.35 cm over a span of 50.8 cm and had a 4.5 cm tip with a diameter of 6.35 cm, was powered by an electronic-speed-controlled centrifugal pump with a capacity of 158 L s^{-1} (Neitzel *et al.*, 2004). The pump was set to the desired speed and corresponding jet exit velocity. To introduce the fish to the fluid shear created by the jet, the foam plug was removed from the cartridge and the cartridge was placed on the end of an induction tube which was mounted to the top side of the nozzle at a 30° angle from the direction of flow. Eel swam down the induction tube, headfirst and were exposed to fluid shear upon exit. This orientation of induction has been determined to be the worst-case scenario for fluid shear exposure (as opposed to tail-first) and is why this method was selected for testing (Neitzel *et al.*, 2004). Fluid shear exposures were captured on two high-speed video cameras (Photron-Fastcam Mini UX50, Photron USA, Inc., San Diego, CA, USA) to provide observation of exposure and identify the occurrence of any injuries. Cameras recorded at 1000 fps and were positionedto record the nozzle exit through acrylic ports located on the side and bottom of the shear tank.

A total of 45 fish were exposed to fluid shear (Fig. 2) — 20 at a jet velocity of 15 m s^{-1} (strain rate equivalent = 833 s^{-1}), 20 at 18 m s^{-1} (strain rate equivalent = 1000 s^{-1}) and 5 controls at 0 m s^{-1} (strain rate equivalent = 0 s^{-1}). Strain rate was calculated following the methods described by Neitzel *et al.* (2004), where the shear flume was calibrated by taking detailed measurements of the flow field and strain rate (e) was estimated using the equation:

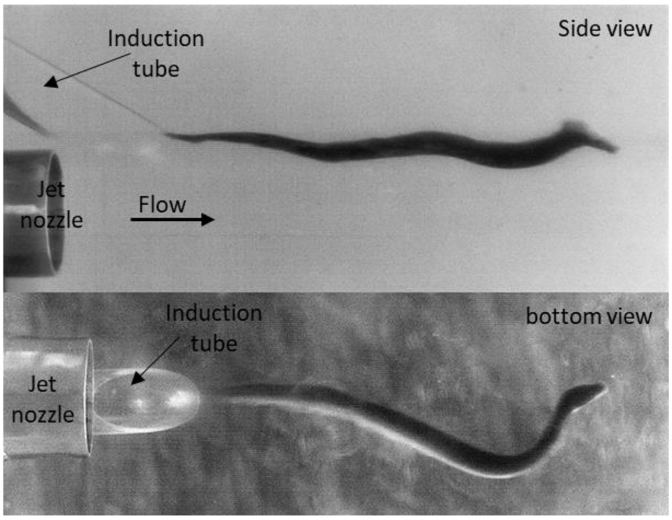

Fig. 2. Frame captures from high speed video (1000 fps) of American eel exposed to a jet of water simulating exposure to fluid shear during turbine passage.

$$e = \frac{\Delta \bar{u}}{\Delta y} \quad (1)$$

where $\bar{u}$ is the mean water velocity (cm/s) and y is the distance (cm) perpendicular to the force (Neitzel *et al.*, 2004). Neitzel *et al.* (2004) originally selected a change in distance (Δy) of 18 mm, which was based on the width of the fish that were examined. This Δy value (18 mm) has been continually used, independent of the width of the fish that were examined, to determine strain rate for similarly conducted fluid shear studies (Neitzel *et al.*, 2004; Colotelo *et al.*, 2018; Pflugrath *et al.*, 2020). In order to make the results from this study comparable to these previous studies, a value of 18mm was used for Δy to calculate strain rate.

Once an eel was exposed, the pump was turned off and the eel was observed by an experienced researcher for any behavioral changes (*e.g.* erratic swimming), incapacities (*e.g.* loss of equilibrium), or deformities (*e.g.* spinal fracture) prior to being dip netted. Once recaptured, eel were placed back into the cartridge, and examined for external injuries including bruising and appendage injury. Eel were then returned to a separate holding trough, where partitions were used to separate fish from each treatment (jet velocity 15, 18, and 0 m s^{-1}). Fish were held for 48 h after exposure to observe any delayed mortality and after the 48 h period eel were euthanized and externally examined a second time for the presence of any injuries.

3 Results

When exposed to fluid shear at strain rates of 833 and 1000 s^{-1}, no injuries or behavioral changes were observed in American eel immediately after exposure to fluid shear nor after 48 h post exposure. When fish were initially placed into the cartridge prior to exposure, a majority of eel immediately began to produce and sluff off mucus. While eel were producing excessmucus, slightly darkened, vertically-oblong spots running along the flank of the fish became evident. These marks dissipated during the post exposure holding period.

4 Discussion

American eel were found to have a similar resilience to fluid shear exposure as European eel. Certain morphological traits of freshwater eel are likely to lead to this resilience, including small embedded scales; flexibility due to many small vertebrae; conjoined anal, dorsal and caudal fins; small pectoral fins, and non-protruding eyes and operculum. These traits enable eel to avoid common injuries observed in other species, including descaling, vertebral fractures, and damage to fins, eyes, operculum and gills (Turnpenny *et al.*, 1992; Neitzel *et al.*, 2004; Deng *et al.*, 2005; Colotelo *et al.*, 2018; Pflugrath *et al.*, 2020). A similar resilience to fluid shear was also observed in Pacific lamprey (*Entosphenus tridentatus*), which share many of these morphological traits (Moursund *et al.*, 2003). Other species which do not possess many of these traits have been examine and were found to be much more susceptible to fluid shear, including American shad and Chinook salmon. Injury rates were greater than 99% for American shad exposed to shear values that exceeded 500 s^{-1} and 100% mortality was observed at a strain rate of 1000 s^{-1} (Pflugrath *et al.*, 2020). Neitzel *et al.* (2004) similarly examined several life stages of Chinook salmon and found that the strain rate that affects 10% of the population ranged from 495 to 607 s^{-1}.

In addition to finding no injuries when exposed to fluid shear up to a strain rate of 1153 s^{-1}, European eel were also observed to have mucus sluff off during the exposures (Turnpenny *et al.*, 1992). This production of excess mucus appears to be a stress reaction to handling and may not necessarily occur due to exposure to fluid shear. However, exposure to fluid shear did appear to remove excess mucus from the eel and may cause the eel to be more susceptible to diseases, as the mucus layer is an eel's first defense against pathogens (Dalmo *et al.*, 1997; Nielsen and Esteve-Gassent, 2006).

The results from this study and previous studies conducted on American eel exposure to rapid decompression and strike indicate that the likely sources of injury and mortality for American eel, and likely other freshwater eels, passing downstream through hydropower turbines is blade strike and/or pinching and grinding (Pflugrath *et al.*, 2019; Saylor *et al.*, 2019). Though American eel are more resilient to strike than other fish species (Saylor *et al.*, 2019), their elongate morphology increases the likelihood of blade strike occurrences during passage through turbines (Ferguson *et al.*, 2008; Deng *et al.*, 2011). Therefore, when designing turbines to promote safe fish passage for eels, designs to reduce the occurrence and severity of blade strike should be considered, such as lower rotational velocity, fewer blades, and thicker blades. Additionally, different edge geometry designs may reduce the occurrence and severity of blade strike.

For this study, fish were exposed to a maximum strain rate of 1000 s^{-1} which is greater than most fish will likely experience during passage through turbines. For example, sensor fish deployments through a Kaplan turbine at Wanapum Dam recorded severe shear events in only 1% of deployments (Deng *et al.*, 2014). A severe shear event was designated for any Sensor fish recording acceleration values in excess of 932 m s^{-2}. Previous studies have correlated Sensor Fish acceleration to strain rates achieved at various jet velocities within the shear flume (Pflugrath *et al.*, 2020), and an acceleration event of 932 m s^{-2} would likely result in a strain rate exposure of approximately 1000 s^{-1}. However, there is potential that fish may be exposed to strain rates in excess of 1000 s^{-1}, and some turbines, such as Francis type, may be more likely to produce excessive fluid shear (Fu *et al.*, 2016). In these cases, injuries and mortality may be observed due to fluid shear and it may be warranted to study greater strain rates than those examined in this study if fluid shear is expected to commonly exceed 1000 s^{-1} through a relevant turbine. The shear flume used in this study has a maximum jet exit velocity capacity of 18 m s^{-1} through the 6.35 cm diameter nozzle, which corresponded to a strain rate of 1000 s^{-1}, therefore modifications would be necessary to exceed this capacity. Additionally, past studies have indicated that flow rates or fish orientation as they enter the turbines may be a factor in injury and mortality rates (Turnpenny *et al.*, 1992; Haro *et al.*, 2000; Amaral *et al.*, 2011). Therefore, if fish are prone to entering an area of fluid shear in an orientation that differs from what was achieved in this study, injury rates may differ and further examination is needed.

5 Conclusion

Similar to European eel, yellow-phase American eel have a high resilience to fluid shear (Turnpenny *et al.*, 1992). Additionally, American eel are resilient to rapid decompression (Pflugrath *et al.*, 2019). Therefore, injuries and mortality of American eel passing through hydropower facilities are likely caused by blade strike or pinching and grinding. Measures to improve turbine passage survival for American eel should focus on design and operational aspects that are likely to reduce the occurrence and magnitude of these mechanical stressors.

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