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[Management Brief]

Observations of American Eels Using an Upland Passage Facility and Effects of Passage on the Population Structure

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Abstract.—Over two seasons, we observed passage of American eels *Anguilla rostrata* at an eel passage facility (eel ladder) placed adjacent to an upland mill dam on a small tributary to the Hudson River, New York. American eel use of the ladder was significantly correlated with freshets and moon phase, similar to other studies of eel migration. Most of the migrants were young (<20 cm total length). Several large American eels (>35 cm) exhibited local movements, including use of the ladder, as shown by recaptures of individuals marked with coded wire tags. Operation of the eel ladder greatly reduced the density of small American eels below the mill dam. Placing eel ladders on upland obstructions has the potential to enhance the productivity of silver (sexually mature) eels, an important consideration in the Hudson Valley, where hundreds of barriers have been constructed on upland tributaries.

A decrease in landings of American eels *Anguilla rostrata* since the 1980s has raised concerns about the health of the population (Haro et al. 2000). The U.S. Fish and Wildlife Service recently considered listing the American eel as a threatened or endangered species but determined that listing was not warranted at this time. Several factors can affect the American eel population size, including changes in ocean conditions, overfishing, habitat degradation, and habitat loss. In many rivers, habitat loss has been caused by dams, which effectively restrict or eliminate access to critical upstream habitats where eels mature and grow. In addition, obstacles to migration may reduce the number of female American eels because the proportion of females increases in upstream areas (Oliveira and McCleave 2000).

Small dams are common barriers to upstream habitat in the northeastern USA. The tributaries to the Hudson River have almost 800 recorded dams (and many more unrecorded; Swaney et al. 2006) that are spread throughout the watershed, mostly in upland locations rather than at the mouth of the tributaries (Schmidt and Cooper 1996). The annual run of age-0 eels (elvers) for the Saw Kill, a small Hudson River tributary, has been estimated to be as high as 10,000 (Yozzo et al. 2005). This leads to high eel densities (131–169 eels/100 m^2; Schmidt et al. 2006; Machut et al. 2007) at the mouth of the Saw Kill. Upstream of the first dam on Hudson River tributaries including the Saw Kill, eel densities are significantly lower (1.7–5.5 eels/100 m^2; Machut et al. 2007). These upstream densities are lower than those found in other northeastern rivers with eel passages (8–22 eels/100 m^2; Oliveira and McCleave 2000), suggesting that this upstream habitat might be able to support higher densities of American eels.

Improving access to upland habitat for American eels can be done by removing (partially or completely) the barrier or by installing eel passage facilities (eel ladders). Removing or modifying dams is difficult and expensive and although ultimately this may be the best solution for American eels and other species, eel ladders are relatively cheap and can provide passage quickly. Most eel passage facilities have been situated on large dams, often in tidal water, where large numbers of immigrating elvers can be passed (Verdon and Desrochers 2003; Verdon et al. 2003). In this study, we placed a small eel ladder on a small upland dam in the Saw Kill to determine what effects the facility would have on local American eel populations and to associate American eel passage with environmental conditions.

Methods

Study site.—The Saw Kill is a small tributary, about 8 m wide at its mouth, to the fresh-tidal Hudson River estuary, which is located in northern Dutchess County,

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Annandale, New York. The watershed (68.8 km^2) is mostly forested and is undergoing suburban development (Hart and Barten 1998). Water quality is generally good but has elevated chlorides and nitrates, probably related to suburban development (Nieder 1995). A moderately large (16 m high) waterfall is near the tidal mouth of the stream. American eels ascend the waterfall, but it is a partial barrier to upstream movement (Machut et al. 2007). A small mill dam (2 m high) is located about 35 m upstream of this waterfall, about 120 m upstream from the tidal mouth of the Saw Kill. We focused on the population of American eels between the waterfall and the dam, an area of about 281 m^2.

American eel population estimation.—Population size of American eels between the dam and the waterfall was estimated by sequential removal on 16 April 2006 and 10 July 2007. Eels were caught by electrofishing the entire area between the waterfall and the dam, bank to bank, with a Smith-Root backpack shocker. Reduction sampling (Kohler and Hubert 1999) with three passes was done, and all eels shocked and netted were removed at each pass. They were anesthetized in clove oil, counted, and measured for total length (TL). We tagged all eels greater than 16 cm with coded wire tags (Thomassen et al. 2000) inserted in the musculature near the origin of the anal fin. A preliminary study on six tagged eels kept in an aquarium showed no mortality after 2 weeks, similar to other studies (Simon and Dörner 2005). After recovery, all were returned to the Saw Kill. The population estimates were done with a Bayesian approach, the binomial depletion model following the protocol of Machut et al. (2007) that allows calculation of confidence intervals and is especially useful when population densities are low.

Eel ladder.—The small trap-and-transfer eel ladder was designed by Alden Research Laboratory, Inc. (Holden, Massachusetts). The framework was constructed from aluminum and was attached to rock at the base of the dam (not to the dam itself). An attraction flow (0.5 L/s total) was created by a pair of siphons that delivered water from above the dam to an adjustable spray bar at the top of the ladder and to the base of the ladder. A collection bucket was filled from the spray bar and a standpipe delivered water from the collection bucket to the end of the ramp; when eels were in the bucket, this delivered eel odor as an attractant (Briand et al. 2002). The ramp had two types of plastic substrate glued to the aluminum to provide purchase for different sizes of eels: a set of large pegs (Akwachain) on one side of the ramp and a plastic mesh (Enkamat) on the other side. This ladder is relatively small; the ramp was 42 cm wide and 1.9 m long and was at a 35.7° angle to the river surface.

The collection bucket on the ladder was checked at least twice weekly. All American eels captured were anesthetized with clove oil, checked for tags, and measured for TL (cm). We inserted coded wire tags behind the head of eels greater than 16 cm to distinguish individuals that had used the ladder from those tagged elsewhere. This means that some eels were tagged twice. Once recovered, they were released above the dam. In 2006 the ladder was in place on April 15 and was removed on October 30. In 2007 the ladder was in place by April 30 and was removed on October 30.

Other data and analyses.—Water depth and temperature (among other variables) were recorded in the impoundment at the dam spillway (New York State Department of Environmental Conservation, Hudson River National Estuarine Research Reserve), and we used water depth as a surrogate variable for discharge. Moon illumination was continuously quantified for each date (U.S. Naval Observatory 2007). Counts of American eels in the ladder and their TLs were normalized before statistical analyses, and means were back-calculated from the lognormal distribution. The environmental data from the day before eel collection were used in the analysis. Multiple regression analyses were done in JMP software (SAS Institute, Cary, North Carolina) to examine relationships among temperature, water depth, moon phase, and eel movement patterns. Because one eel in the bucket was needed to create eel odor and eels are more likely to use the ladder when odor is present (Briand et al. 2002), we also did the statistical analyses using only dates when more than one eel was in the bucket. To further elucidate movement patterns, eels were arbitrarily divided into three size (TL) categories: small (<20 cm), medium (20–30 cm), and large (>30 cm).

Results

American Eel Population Estimation

In April 2006, we tagged 46 American eels (>16 cm TL) of the 53 caught between the dam and the waterfall. In July 2007, we tagged 30 more eels (>16 cm) of the 31 caught in the same area (Figure 1). In 2006 we caught 34, 14, and 5 eels in each subsequent round of shocking (13.2–59.5 cm TL), and in 2007 we caught 23, 4, and 4 eels in each subsequent round of shocking (22.2–52.8 cm; Figure 1). Eel density was estimated to be 19.6 eels/100 m^2 in April 2006 and 11.0 eels/100 m^2 in July 2007. This corresponded to a population in the study area of about 55 eels on the sampling dates in 2006 and about 31 eels in 2007.

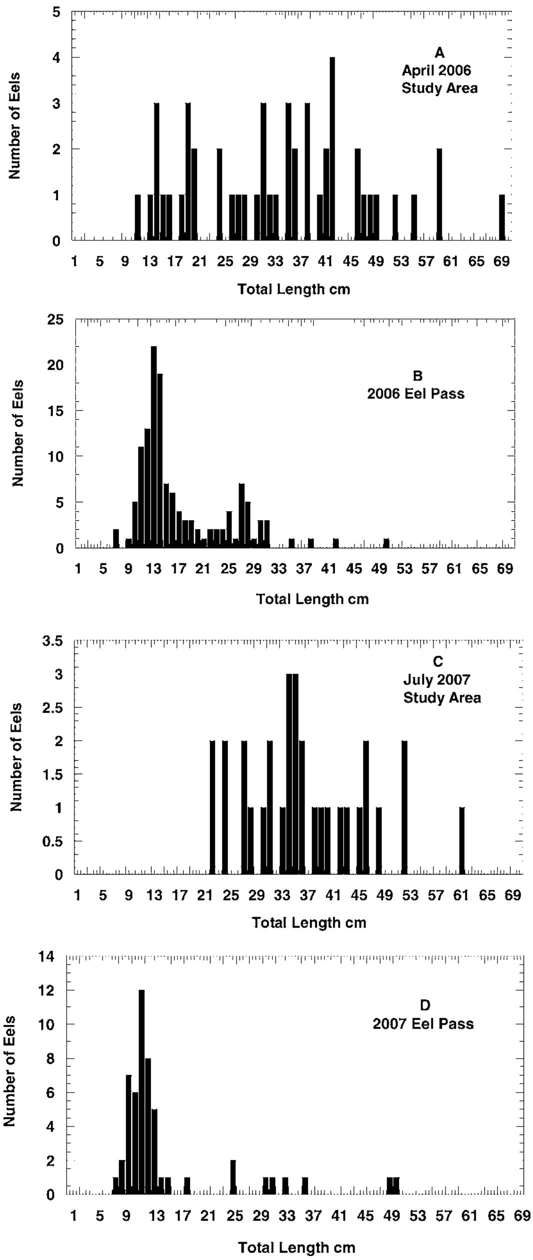

FIGURE 1.—Length frequency distributions (total length) of American eels in the Saw Kill (Hudson River drainage), New York: **(A)** individuals collected between the dam and the waterfall in spring 2006 before eel ladder installation, **(B)** individuals that passed through the eel ladder (postinstallation) in 2006, **(C)** individuals collected between the dam and the waterfall in 2007 after the eel ladder was functioning for a season, and **(D)** individuals that passed through the eel ladder in 2007.

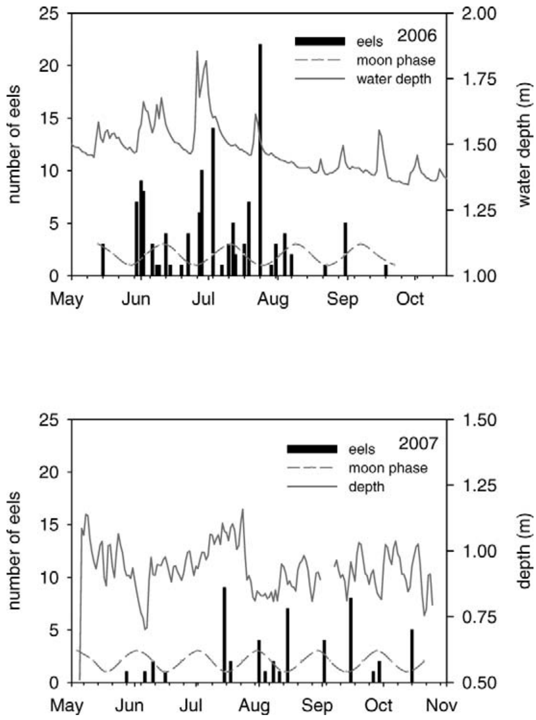

FIGURE 2.—Distribution of American eels using the eel ladder in the Saw Kill, New York, as related to water depth and moon phase (cycle peaks = full moon, cycle troughs = new moon) in 2006 and 2007.

Eel Ladder

Overall, 183 American eels used the ladder. In 2006, 132 eels migrated up the ladder between May 15 and September 18; in 2007, 51 eels migrated up the ladder between May 26 and October 13. Most eels ascending the ladder were small. Small eels made up 73% of the eels using the ladder in 2006 and 86% in 2007. The distribution of sizes that used the ladder was similar in 2006 (range = 7.4–51.0 cm TL, mean = 16.4 cm, median = 13.4 cm) and 2007 (range = 8.8–51.0 cm, mean = 14.1 cm, median = 12.7 cm; Figure 1). Medium eels only used the ladder in 2006 with the exception of one eel in 2007. Larger eels used the ladder throughout the season in 2006, but in 2007 were only found in the ladder before mid-June and after late September.

American eels in the ladder occurred when water temperatures were greater than 12°C, and peak eel abundance occurred at water temperatures of around 20°C. However, water temperature was not a significant variable in our model. Eels in the ladder were significantly related (Figure 2) to water depth ($P < 0.03$) and moon illumination ($P < 0.03$; multiple regression, $P < 0.01$, $R^2 = 0.23$), and this relationship was much stronger when only dates with more than one eel captured were used, both for depth ($P < 0.05$) and illumination ($P < 0.01$; multiple regression, $P < 0.001$, $R^2 = 0.4$).

A small number of previously tagged American eels used the ladder, and some eels used the ladder more than once. We do not know how eels pass over the dam; however, the drop is only 2 m, and they could simply swim over the top. Nine eels (19.6%) tagged below the dam ascended the ladder in 2006 and five did in 2007. One eel captured during the 2007 tagging had been tagged in April 2006 and had ascended the ladder in 2006. This eel (34.7 cm) had morphological signs of maturing sexually (silvering) on July 10, 2007. In 2007, two of the eels captured in the ladder had ascended the ladder previously. A 37.6-cm eel captured in June 2007 had been tagged in the ladder in 2006. Two of the other June 2007 recaptures in the ladder had been tagged below the dam in April 2006. The other recaptures were in September, and they could have been tagged in either 2006 or 2007.

Discussion

American eel use of the ladder was related to dark nights (new moon) and high flows (freshets). We found that upstream migration occurred only when water temperatures were above 12°C (early summer to late fall) and peaked in midsummer when temperatures were around 20°C, which is similar to the overall seasonal patterns of American eel movement reported by Sorensen and Bianchini (1986), Verdon and Desrochers (2003), and Verdon et al. (2003). Other studies have found that sudden changes in water temperature and streamflow stimulate eel movements upstream (Durif et al. 2003; Verdon et al. 2003). Eel activity in general is crepuscular (Bohun and Winn 1966) and is known to increase during periods of reduced moon illumination, often beginning with the third quarter (Lowe 1952; Winn et al. 1975; Lamothe et al. 2000, Cairns and Hooley 2003). Illumination from the moon was particularly significant in our study, but movement during brighter moon phases could have been affected by cloudiness.

The ladder was used predominantly by smaller American eels, probably because of competition with or aggression of larger eels in the habitat below the dam. The mean TL of the eels in our study was smaller than those recorded for larger river systems with ladders at hydroelectric dams: about 30 cm (Hildebrand 2005), 36.8 cm (Verdon et al. 2003), and about 40 cm (McGrath et al. 2003). In the second year, large eels only used the ladder in the early and later part of the season, whereas smaller eels used the ladder throughout the summer, a pattern found in other systems (McGrath et al. 2003).

Some of the American eels using the ladder were probably age-0 pigmented eels. The smallest two individuals were 7.4 and 7.5 cm (captured July 17 and 19, 2006). Over 1.5–3.0 months in spring 2006, these individuals and several other slightly larger ones had probably immigrated into the Saw Kill as glass eels, traveled the 120 m upstream from the tidal mouth to the waterfall, and ascended the 16-m waterfall. This is well within the documented movement rate for eel elvers: 180 m in a month (Haro and Krueger 1988).

Migratory movements of American eels less than 35 cm TL were difficult for us to document, although Oliveira (1997) showed that most migratory movements in a Rhode Island stream were by eels less than 20 cm TL. We did not recapture any 16–35-cm tagged eels after they passed through the ladder, and we were unable to mark those less than 16 cm. However, the almost absolute disappearance of small eels between the dam and waterfall during our study is probably due to upstream migration of the small individuals through the ladder. We interpret these observations to mean that before ladder installation, small migratory eels had been mostly prevented from passing the dam.

The decrease in number of American eels using the ladder in the second year was primarily due to the lack of movement by medium sized eels (20–30 cm TL), which only used the ladder in the first year after installation but not in the subsequent year. Although we only measured the population size twice, we think the initial use of the ladder by medium eels is a response to preexisting high population density below the dam. At the lower population density in the second year, there would be less pressure on remaining eels. Similar patterns at other ladders have been found after installation, specifically, reduced numbers of eels overall (McGrath et al. 2003; Verdon et al. 2003) and fewer large eels using the ladder in subsequent years (Verdon et al. 2003).

In general, few large American eels used the ladder. Large eels have previously been categorized as sedentary, with home ranges of 65 m (Gunning and Shoop 1962) and movements of less than 100 m (Ford and Mercer 1986). In our study area, moving a similar distance could include ascending the dam, descending the dam, or both. The eel ladder would probably increase a large eel's ability to move locally, and we saw evidence for this with the eels that used the ladder more than once. The use of electronic tags, like passive integrated transponder tags, on larger eels would document these local movements and identify home range variables more thoroughly.

Besides the obvious result of allowing passage of smaller American eels and creating access to upstream habitat, the ladder had other positive effects on the eel population that should increase export of mature females from the Saw Kill. Density-dependent mortality on the small eels may be reduced by reducing exposure to predation by large eels (Jessop 1999). Incidence of infestation by the exotic swim bladder nematode *Anguillicola crassus* may be lowered because infestation rates are lower for inland American eels (Machut and Limburg 2008), probably because transmission from secondary hosts is reduced. Growth rates may be increased (Machut et al. 2007) and polychlorinated biphenyls contaminant levels should be lower (Limburg et al. 2008). Finally, more mature (silver) females may be produced because females are more common in upland areas and in areas of lower eel density (Krueger and Oliveira 1999; Oliveira and McCleave 2000).

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