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MANAGEMENT BRIEF

Observations of American Shad *Alosa sapidissima* Approaching and Using a Vertical Slot Fishway at the Head-of-Tide Brunswick Dam on the Androscoggin River, Maine

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Abstract

American Shad *Alosa sapidissima* have historically supported an important fishery along the Atlantic coastal waters of North America. However, the construction of dams reduced populations and restricted landings. Fishways are intended to mitigate obstacles to anadromous fish migrations, but a thorough evaluation of their efficiency is warranted. We analyzed data collected from video recordings, hydropower turbine operations, and telemetry conducted by the Maine Department of Marine Resources to evaluate American Shad behavior while approaching and using a vertical slot fishway at the head-of-tide Brunswick Dam on the Androscoggin River in Maine. American Shad passage at the dam has been poor, ranging from 0 to 1,100 fish per year, relative to passage at other facilities in the region. Additionally, our observations indicate that there are relatively high numbers of American Shad present downstream in the river (averaging 50,000) compared with the entrance of the fishway or its pools (<8,000). On average, the rates of observed American Shad on the side of the river near the fishway entrance were significantly higher (6.5–8.6 individuals/min) when the turbine closest to the entrance of the fishway was not operating compared with when it was operating (4.1 individuals/min). Most of the radio-tagged American Shad remained in the river below the dam or went undetected. Eleven of 57 tagged fish were detected at the fishway entrance and of those only five were detected in the lower fishway. Individuals that were detected were observed making multiple attempts at entering the fishway, but movements were restricted to the lower pools. Our results suggest that this fishway is not conducive to the passage of American Shad. Examining the relationship between hydropower operations and other environmental variables on the behavior and passage of migrating anadromous fish remain an area for further study.

American Shad *Alosa sapidissima* is an anadromous species requiring connectivity between marine and freshwater habitats to complete their lifecycle. Historically, populations of American Shad supported recreational, subsistence, and commercial fisheries along the Atlantic coastal waters of North America with annual landings ranging in the millions of pounds (Hightower et al. 1996; ASMFC 2007). However, overfishing, pollution, and habitat loss resulting from dams, restricted passage, and human development have reduced populations and subsequently total landings (Limburg et al. 2003; ASMFC 2007; Limburg and Waldman 2009). Many state and federal agencies have prioritized the management of American Shad by supporting research and monitoring programs aimed at conserving and restoring populations (ASMFC 2007).

Dams threaten anadromous fish populations by severing the migration of populations between marine and

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freshwater habitats (Limburg and Waldman 2009). Additionally, dams can impose migration delays and exert negative effects on survival and fitness (Castro-Santos and Letcher 2010). The construction of fishways at dams is one approach used to mitigate obstructions to migrating fish. However, many of the fishways in rivers along the east coast of the United States have not been thoroughly evaluated for passage of American Shad and often adopted designs intended to be suitable for Pacific Salmon (Haro and Castro-Santos 2012). Quantifying fish behavior under the variability of altered environmental conditions (e.g., flows) imposed by dams may inform managers of the efficacy of fish passage structures and identify areas for modification.

Data collected by state and federal agencies are often incorporated into reports as "gray" literature and are used to inform or direct management and research. Additionally, many agencies collect data through monitoring efforts that are not strictly hypothesis-driven. Nevertheless, these data may provide insight to population dynamics, fish ecology, and fisheries management. Here, we synthesize and analyze data collected by the Maine Department of Marine Resources (MDMR) on migrating American Shad behavior approaching the head-of-tide Brunswick Dam and passage through a vertical slot fishway. The synthesis of these data presents a timely opportunity to inform managers of the efficacy of this fishway to pass migrating American Shad in preparation for the Federal Energy Regulatory Commission's (FERC) relicensing of the dam in 2024. Vertical slot fishways are a commonly employed fishway at many dams in the Northeast but their passage efficiencies for nonsalmonids are relatively poor (Noonan et al. 2012). Over the next 5–10 years, many of these dams will be up for FERC relicensing and the synthesis of research and monitoring efforts will be used to characterize and evaluate fish passage (FERC 2019). Broadly, we describe challenges facing American Shad that encounter obstacles to migration and highlight opportunities for synthesizing best available science to inform management.

Our objective was to characterize the behavior of upstream-migrating American Shad that use a vertical slot fishway when approaching the Brunswick Dam on the Androscoggin River, Maine. We hypothesize that this vertical slot fishway creates an environment that is not conducive to the migration of American Shad. Specifically, certain operational configurations of the powerhouse's turbines may alter river flows and influence the behavior of American Shad approaching the fishway. We used four sets of collected data to characterize the behavior and movement of American Shad: passage counts, video recorded counts in the river and fishway, hydropower turbine operations, and movement of tagged fish in a telemetry study.

METHODS

Study site.— This work was conducted at the head-of-tide Brunswick Dam on the Androscoggin River, Maine's third largest river, in the town of Brunswick, Maine (Figure 1). The headwaters of the Androscoggin River are in New Hampshire and the river flows through Maine before emptying into Merrymeeting Bay and eventually the Atlantic Ocean. Historically, prior to dams, diadromous fishes on the main stem of the Androscoggin River would have unrestricted upstream movement until encountering Lewiston Falls, a natural barrier located 35.2 rkm above head-of-tide (Figure 1). It was documented that a few species, notably Atlantic Salmon *Salmo salar* and American Eel *Anguilla rostrata,* could ascend these falls and continue upstream to an impassible natural barrier at Rumford Falls, 128 rkm above tide. Historical accounts describe American Shad spawning in riverine habitats throughout the watershed below Lewiston Falls (Brown et al. 2006).

The Brunswick Dam hydroelectric station and fishway were constructed in 1982 and became the lower-most dam on the Androscoggin River at head-of-tide (Figure 2). The Brunswick Dam Project consists of a 12-m-high, 184-m-long concrete gravity dam. The powerhouse contains three vertical propeller turbine generators that generate electricity at a capacity of 19,000 kW. The project normally operates as run-of-river, relying on the seasonal flows of the river to generate electricity. The Brunswick fishway has a vertical slot design providing an attraction flow of 2.8 m^3/s. Fish are routed through a 173-m-long elevated concrete raceway consisting of forty-two 2.5 × 3-m pools with 28-cm-wide openings. A switchback, located approximately halfway, requires a 180° turn and divides the "lower fishway" from the "upper fishway." At the end of the fishway, fish are corralled into a hopper with an electric hoist that lifts them into a sorting facility where they can be captured or counted and moved upstream. The tide influences the water level in the first six pools of the lower fishway with a tidal amplitude of up to 1.8 m. The fishway was designed to pass 85,000 American Shad per year (MDMR 2014). However, anywhere from 0 to 1,100 (but usually < 12) American Shad have passed the dam annually since 2003 and monitoring by MDMR suggests that low passage rates were evident even earlier (Figure 3; Brown et al. 2006). Other diadromous fish species observed using the Brunswick fishway include Alewife *Alosa pseudoharengus*, Blueback Herring *Alosa aestivalis*, Atlantic Salmon, American Eel, Rainbow Smelt *Osmerus mordax*, and Sea Lamprey *Petromyzon marinus.*

Video-recorded counts.— Underwater video cameras were used to quantify the relative abundance of American Shad in the river and their approach and use of the vertical slot fishway during their spawning migration. Cameras were deployed from June to July during 2001–2004. One

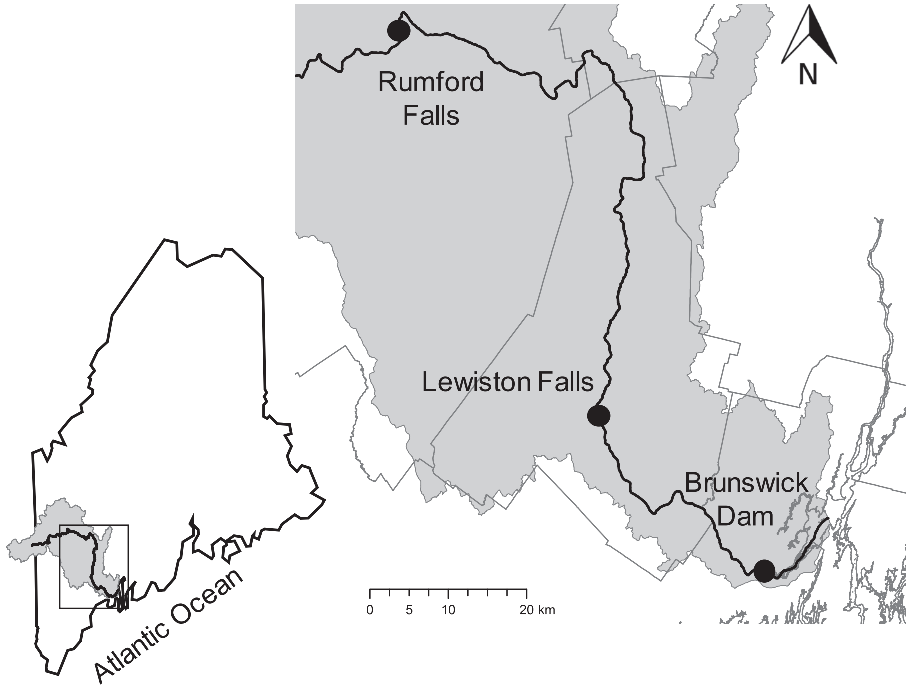

FIGURE 1. The location of the head-of-tide Brunswick Dam on the Androscoggin River, Maine, and Lewiston and Rumford falls, natural features serving as barriers to the upstream movement of American Shad and other anadromous fish. The shaded area delineates the Androscoggin River watershed boundary.

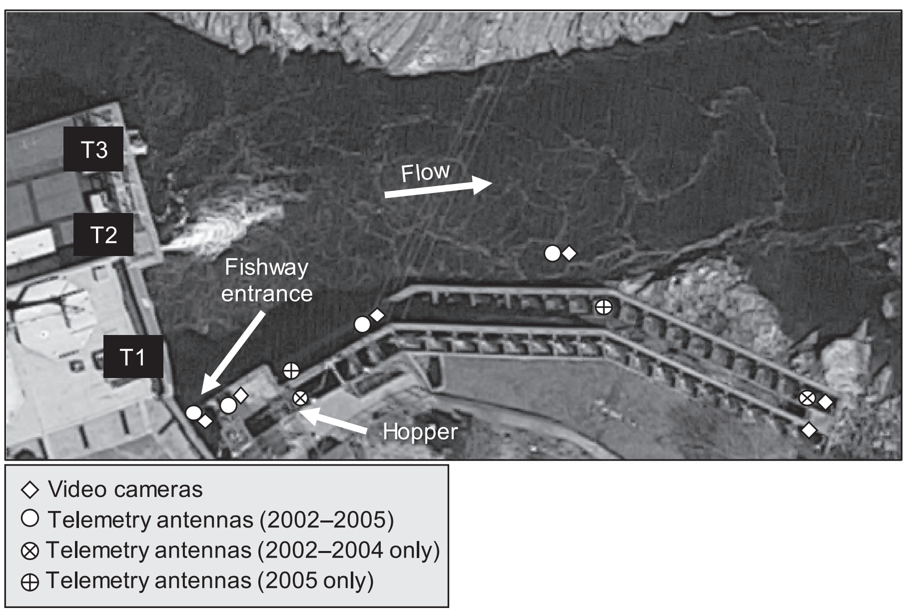

FIGURE 2. An aerial view of the Brunswick Dam (left) and fishway (bottom). T1, T2, and T3 denote the locations of the three hydropower turbine units. Areas where underwater video cameras were deployed are denoted by diamonds, and locations of telemetry receivers are represented by unique circle symbols denoted for specific years. Arrows depict the direction of flow and locations of the fishway entrance and hopper.

camera was placed in the river near the fishway. Five cameras recorded conditions in various locations in the fishway: the entrance, pool 1, pool 6, and the entrance and exit to the switchback pool. Camera depths deployed in the fishway ranged from approximately 1 to 1.8 m; the depths varied since the lower sections were influenced by the tide. Similarly, the camera placed in the river experienced tidal fluctuations and depths up to 1.2 m. Video

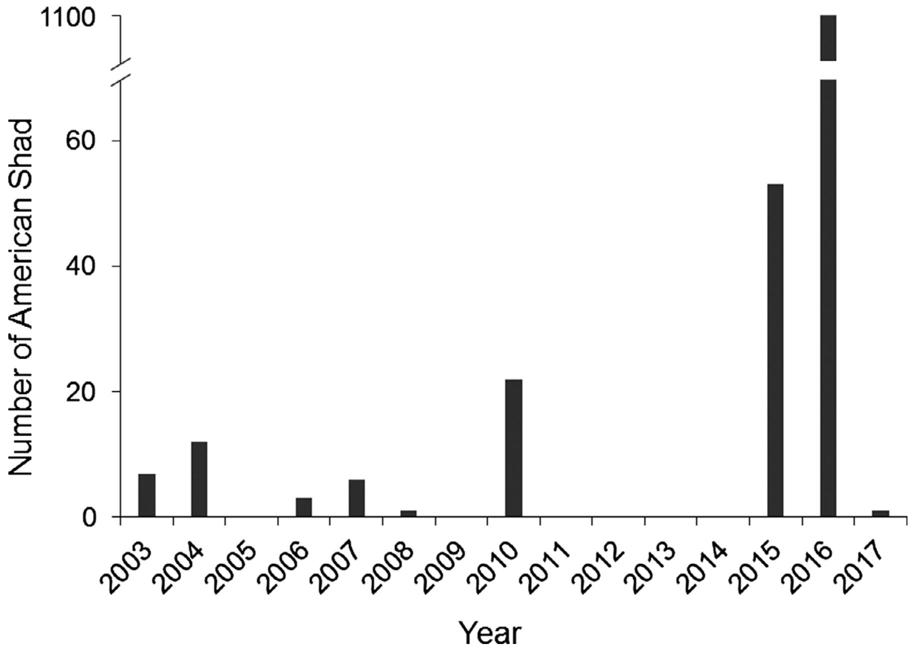

FIGURE 3. The numbers of American Shad that passed through the hopper of the vertical slot fishway at the Brunswick Dam on the Androscoggin River, Maine, from 2003 to 2017.

cameras continuously recorded their environment from 0600 to 1800 h daily. Maine Division of Marine Resources staff subsampled the video recordings by viewing the first 3 min of every 10-min period following methods adopted from Haro and Kynard (1997). Multiple observers viewed the recordings and corroborated the final counts. During these 3-min viewings, all American Shad were counted. Counts of American Shad represented only the observer counts and were not adjusted for subsampling. Fish may have been counted more than once.

Hydropower turbine operations.— We hypothesized that the operational configurations of the three turbines may influence the behavior of American Shad on their approach to the fishway (Figure 2). Utilizing turbine operational flow data and video-recorded counts from the river camera from 2004, we examined under which turbine operation combinations the majority of American Shad were counted. In 2004, cameras operated from June 8 to July 23 for a total of 45 d. We examined all operating combinations of the turbines as a 3-factorial design or 9 total combinations of the turbines either on or off (Table 1). We standardized the counts by calculating the average observation rate of American Shad (number/min) in every 3-min subsampled recording during which each of the four selected turbine configurations were operating. These reported rates were calculated from unadjusted sampled counts (i.e., not adjusted for subsampling). We found that four configurations comprised approximately 90% of all video-recorded river counts (Table 1); therefore, we only focused on those combinations in our analysis. We ran a nonparametric Kruskal–Wallis test to compare the rates of American Shad counts among the four selected turbine operating configurations. Statistical significance was gauged using a critical alpha value of 0.05. We used Dunn's post hoc test to explore pairwise differences among turbine configurations with an adjusted critical alpha value to reduce type I error rates (Benjamini and Hochberg 1995).

Telemetry study.— During May–June in 2002–2005, a telemetry study was conducted to track the movement and behavior of American Shad approaching and using the fishway. During 2002–2004, five antennas were deployed in the following locations: the river, the lower fishway consisting of the fishway entrance, the pool receiving the attraction flow, pool 6, and the upper fishway consisting of the switchback pool and the entrance to the hopper (Figure 2). In 2005, the configuration of deployed antennas was modified. The antennas located in the upper fishway were moved to pools in the lower fishway to include pool 3 and pool 14 (Figure 2). A Yagi aerial antenna was used at the fishway entrance, while dropper antennas, made from stripped coaxial cable, were used in the other locations.

American Shad were collected by angling a section of river below the dam. Fish were tagged with 11- × 42-mm microprocessor-coded internal gastric radio tags with a 29.4-cm external antenna (Lotek Wireless, Newmarket, Ontario, Canada; model MCFT-3BM). The tags had a pulse rate of 1 s and an approximate 67-d battery life. The duration of fish handling was minimized as much as possible to limit potential stress on the fish. Tagged fish were released at the same location where they were caught and

TABLE 1. Mean and SD of the number of American Shad/min observed from river camera counts and the percentage of the total counts among all turbine combinations operated during 2004 at the head-of-tide Brunswick Dam, Androscoggin River, Maine. Among turbine configurations, a "0" indicates that the turbine is off, while a "1" indicates that the turbine was on. Bolded values represent the four turbine configurations that comprised 91% of all American Shad observations used for statistical comparison (see Figure 5).

			Turbine configuration		
Mean (±SD)	Number of video segments	Percentage of total observations	Turbine 1	Turbine 2	Turbine 3
9.0 (11.1)	9	2	0	0	0
6.5 (5.6)	**105**	**21**	**0**	**0**	**1**
8.6 (6.2)	**88**	**18**	**0**	**1**	**0**
7.4 (6.7)	**182**	**37**	**0**	**1**	**1**
4.1 (3.3)	**79**	**16**	**1**	**0**	**0**
5.2 (4.5)	4	1	1	0	1
4.4 (3.2)	17	3	1	1	0
3.0 (1.9)	14	3	1	1	1

tagged below the dam. A total of 57 American Shad were tagged from 2002 to 2005 (10 in 2002 and 2003, 22 in 2004, and 15 in 2005). Each year, the angling and tagging of American Shad began in June and fish were tracked through July. In 2005, mobile tracking of radio-tagged fish was conducted on several occasions several km downstream from the study site. We used river discharge data from the U.S. Geological Survey gauging station on the Androscoggin River in Auburn, Maine, (approximately 35 rkm above the Brunswick Dam), to visually assess American Shad movement in relation to river discharge.

Radio receivers were calibrated and adjusted prior to fish tagging to define the coverage areas of the receivers to their respective pools or specific locations. However, after data collection, we observed multiple antennas picking up a single tagged fish simultaneously. This was observed during all years and we corrected for it in two ways. First, we established a minimum threshold of power output for every detection by eliminating all detections with power levels lower than the 25% quantile. Second, we eliminated any detections with < 10 events.

RESULTS

Video-Recorded Counts

Video-recorded counts served as an index of the abundance of American Shad in the river and fishway. From

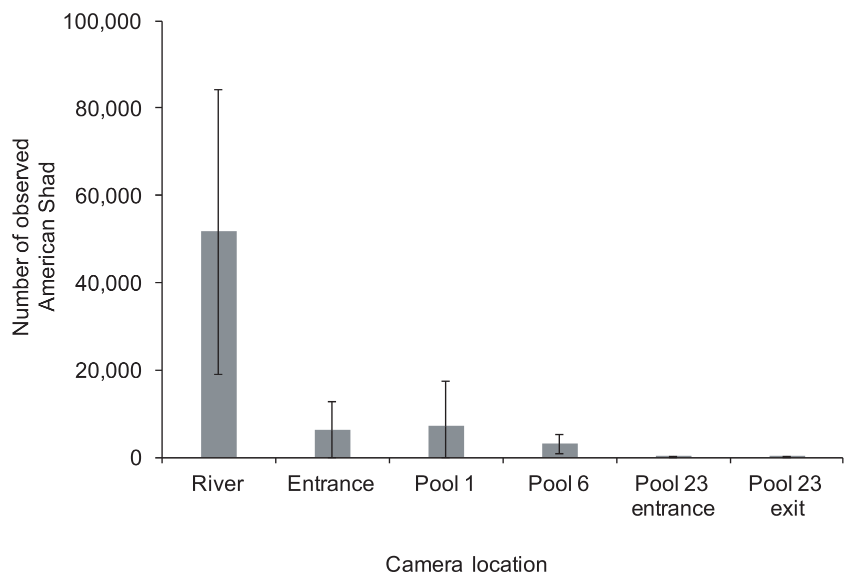

FIGURE 4. The means and SDs of counted American Shad serving as an index of abundance. Individuals were counted with the use of underwater cameras deployed during 2001–2004 at six locations in the river, fishway entrance, and select pools in the fishway. Fish may have been counted more than once. Refer to Figure 2 for locations of the cameras.

Turbine Operation	Turbine 1	Turbine 2	Turbine 3
A	0	0	1
B	0	1	0
C	0	1	1
D	1	0	0

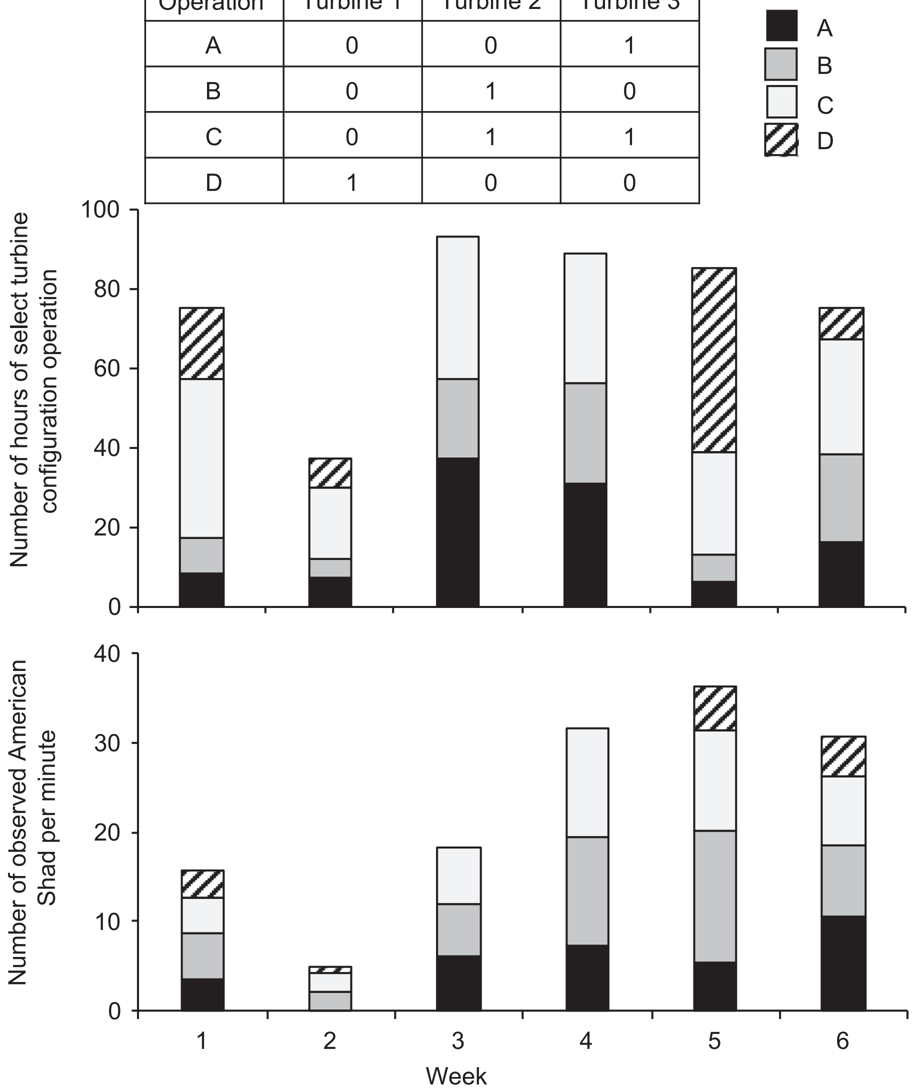

FIGURE 5. The total number of hours of turbine operation (upper graph) and observed American Shad per minute (lower graph) among select turbine operation configurations **(A–D)** for each week during the period of American Shad migration. Rates of American Shad passage were estimated from video recordings from underwater cameras placed in the Androscoggin River, Maine. See Figure 2 for camera placement.

2001 to 2004, the unadjusted counts of American Shad in the study area were relatively high in the river, averaging approximately 51,000 and ranging from 25,000 to nearly 100,000 per year (Figure 4). This was in comparison with the number of observations in either the entrance of the fishway or the lower fishway (i.e., pools 1 and 6), which averaged <8,000. Very few fish (≤130 fish on average) were observed entering or exiting the switchback pool.

Hydropower Turbine Operations

The amount of time that each of the four selected turbine configurations operated was relatively consistent over the daily time period (0600–1800 hours) that video recordings were viewed. However, there were generally higher numbers of fish in the morning hours (0600 hours) and a decline in counts toward the evening (1800 hours; Supplementary Figure 1 available in the online version of this article). In contrast, the amount of time that each of the four turbine configurations operated over the 6-week period of American Shad migration was not equivalent and some turbine configurations operated more frequently than others (Figure 5). Furthermore, during the course of the season, we observed higher numbers of American Shad during weeks 4 and 5.

Mean rates of observed American Shad from 2004 video recordings ranged from 4.1 to 8.6 individuals/min among the four combinations (Table 1; Figure 6). We

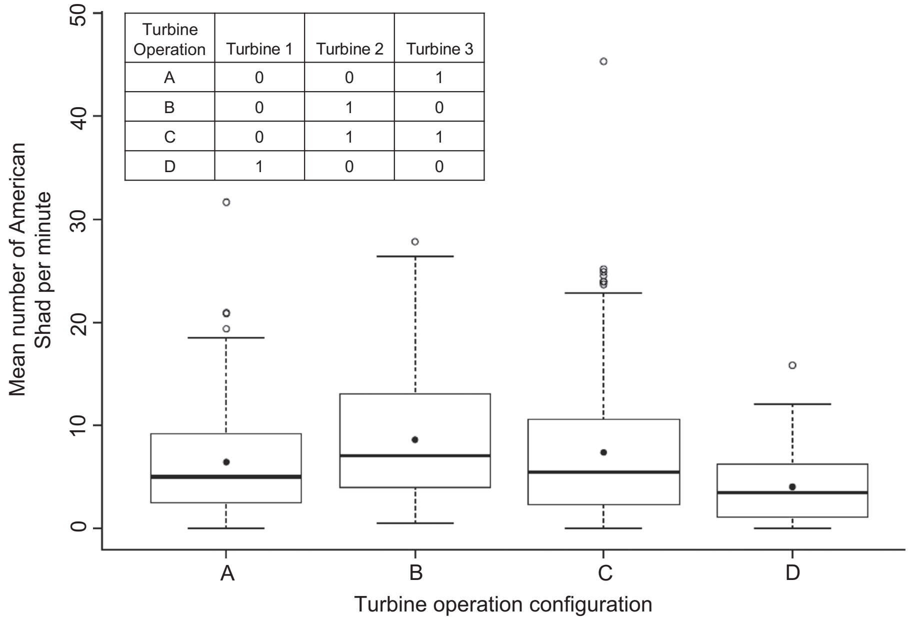

FIGURE 6. Box and whisker plots of numbers of American Shad per minute across four select hydropower turbine configurations **(A–D)**. Black lines across each box represent the median and black dots represent the mean rate for each turbine configuration. The box represents the values of the middle 50% of the calculated rates and the ends of the whiskers indicate the lowest and highest rates. The table inset indicates the operation of each turbine. A "0" indicates that the turbine was not operating while a "1" indicates that the turbine was operating. Results from a Kruskal–Wallis test found significant differences in rates of observed American Shad passage among the four combinations.

TABLE 2. The total number of radio-tagged American Shad (*N*) per year and the numbers associated with the location(s) of their detections. Undetected fish were never detected after tagging. Mobile tracking of fish downstream of the study site was only conducted in 2005. Individual fish could be detected at multiple locations; therefore, the sum of these locations is generally not equal to *N*.

		Location(s) of detections				
Year	*N*	Undetected	River adjacent to fishway	Fishway entrance	Lower fishway	River downstream
2002	10	10	0	0	0	N/A
2003	10	6	4	3	2	N/A
2004	22	14	8	4	2	N/A
2005	15	4	10	4	1	9
Total	57	34	22	11	5	9

found significant differences among the number of American Shad observed across the four hydropower turbine combinations ($H = 28.82$; $P < 0.05$). Mean numbers of observed American Shad were higher, ranging from 6.5 to 8.6 individuals/min when turbine 1 (the one closest to the fishway) was not operating, compared with 4.1/min when it was operating.

Telemetry Study

Among years, the time period over which tagged American Shad were detected ranged from 1 d to approximately 16 d. This detection variation was observed among all tagged fish regardless of whether they were detected in the river, fishway entrance, or fishway. The majority of tagged American Shad (34 of 57; 59%) were not detected after tagging and release. Eleven (19%) were detected approaching the entrance to the fishway and of those, 5 (8%) were detected in the lower fishway (Table 2). Of those fish that approached and used the fishway, several were generally detected making multiple attempts at entering and ascending the fishway. Periods of movement appeared to be aligned with increases in stream flow (Figure 7). In 2005, 9 individuals (15%) were detected from mobile tracking efforts downstream of the study site. None of the tagged fish were detected in the upper fishway or passed above the dam.

DISCUSSION

We synthesized a series of studies that suggest that American Shad exhibit poor passage through the

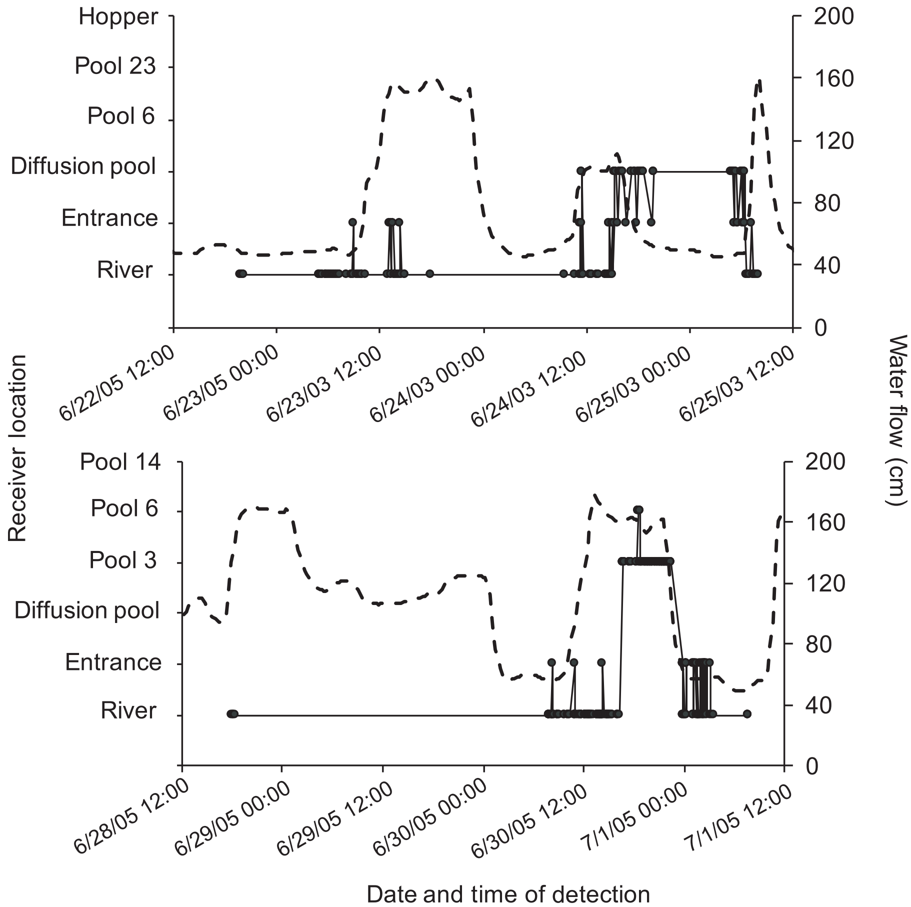

FIGURE 7. Movement of two radio-tagged American Shad from 2003 (top) and 2005 (bottom) during spawning migration in the Androscoggin River, Maine, and the Brunswick fishway. The solid line refers to locations where individuals were detected (left *y*-axis). The dashed line refers to water discharge from an upstream U.S. Geological Survey gauging station (right *y*-axis). Refer to Figure 2 for the locations of telemetry antennas.

Brunswick Dam vertical slot fishway on the Androscoggin River, Maine. American Shad were present in the river below the dam, but the operation of the turbines (particularly the one closest to the fishway) may alter flows and deter their approach to the fishway. Passage conditions at the fishway and management operations at the hydropower facility have remained largely unchanged since these studies were completed in 2005; therefore, it is likely that American Shad continue to face challenges to upstream migration. This work represents a timely step toward understanding American Shad behavior and passage that may be used to direct future research efforts, and demonstrates a case study in which the best available science, in the form of several small studies, may be used to inform management decisions.

The evaluation of fish passage through fishways typically focuses on two aspects: the attraction of the fish to the fishway entrance and the passage of the fish through the structure. Other studies examining American Shad passage align with our findings. Aunins et al. (2013) observed no radio-tagged American Shad passing through a vertical slot fishway at Bosher's Dam on the James River, Virginia, and suggested that American Shad may have difficulty locating the attraction waters of the fishway. Barry and Kynard (1986) found that the turbulence generated by the flow of water from a hydroelectric turbine may disorient American Shad, thereby imposing delays on migration. The vertical slot fishway at the Brunswick Dam was adopted from designs targeting salmonids and deployed in relatively large rivers; however, when scaled down to suit smaller Atlantic coast rivers, it may disproportionately alter hydraulics and create unsuitable passage conditions with higher turbulence and velocity (ASMFC 2010). Salmonids are generally considered relatively stronger swimmers than American Shad (Gowans et al. 1999), so certain fishway designs may create unintended physiological limitations to movement that vary by species. Thus, like previous studies, our work suggests that American Shad face obstacles including finding the attraction waters of the fishway and scaling the elevated pools of the fishway.

The Brunswick fishway was initially designed to pass 85,000 American Shad (MDMR 2014). However, the FERC did not issue a license contingent on the evaluation of efficiency studies for upstream and downstream passage of fish. The evaluation of altered flows and fishway hydraulics and the consideration of the swimming behavior of the fish intended for passage are critical components that are best identified during the fishway designing process (Weaver 1965; Castro-Santos 2005; Bunt et al. 2012; Williams et al. 2012). Furthermore, the flows encountered by migratory fish approaching the Brunswick Dam are influenced by turbine operation, river discharge, and tidal stage, creating a challenging environment to manage fish passage. The data that we synthesized suggest that significant structural changes could improve American Shad passage and could be considered by managers as this dam's FERC license expires in 2024.

Among years, 25–100% of our radio-tagged fish were not detected after release and may have succumbed to mortality or exhibited fallback behavior. Other tagging studies have reported substantial fallback behavior (i.e., downstream movement) of American Shad after tagging and release back into the river (Beasley and Hightower 2000; Aunins and Olney 2009; Grote et al. 2014). Fallback can only be identified from detections by additional downstream radio receivers, which were not present during our studies. Limited mobile tracking that took place several km downstream of the dam during 2005 detected nine fish on one or two occasions suggesting fallback behavior, but this tracking effort was not integrated as a primary component of the study and therefore any conclusions regarding this behavior are speculative.

The management of American Shad and the pattern of poor passage in the Androscoggin River has remained consistent over the last 20 years, including the years when the monitoring projects described here occurred. Relatively high passage was reported in 2016, but that was a year of historically high passage rates regionally. For example, 7,800 American Shad were passed at the Milford Dam on the Penobscot River, Maine, in 2016 (NOAA Northeast Fisheries Science Center 2016). These patterns suggest that American Shad are still present below the dam but continue to face challenges associated with passage.

Management Implications

In closing, we suggest that the vertical slot fishway at the Brunswick Dam on the Androscoggin River, Maine, provides poor passage for upstream migrating American Shad. Our work highlights the sensitivity of passage conditions to hydropower generation and the importance of characterizing the permutations of turbine operations. Experiments that systematically explore the relationship between turbine operations, river discharge, and resulting fish movement and behavior may provide additional data to characterize fishway approach and passage. Exploring the effects of river discharge, hydropower operations, and other environmental variables (e.g., tidal stage) on the behavior and passage of migrating anadromous fishes remain an important area for further study. Therefore, we demonstrate that small-scale studies, when synthesized, provide opportunities to inform the design of future studies for regulatory mandates (i.e., FERC relicensing) and for the conservation and management of fisheries.

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REFERENCES

ASMFC (Atlantic States Marine Fisheries Commission). 2007. American Shad stock assessment. ASMFC, Stock Assessment Report 07-01, Washington, D.C.

ASMFC (Atlantic States Marine Fisheries Commission). 2010. Upstream fish passage technologies for managed species. Fish Passage Working Group, Washington, D.C.

Aunins, A. W., B. L. Brown, M. Balazik, and G. C. Garman. 2013. Migratory movements of American Shad in the James River fall zone, Virginia. North American Journal of Fisheries Management 33:569–575.

Aunins, A. W., and J. E. Olney. 2009. Migration and spawning of American Shad in the James River, Virginia. Transactions of the American Fisheries Society 138:1392–1404.

Barry, T., and B. Kynard. 1986. Attraction of adult American Shad to fish lifts at Holyoke Dam, Connecticut River. North American Journal of Fisheries Management 6:233–241.

Beasley, C. A., and J. E. Hightower. 2000. Effects of a low-head dam on the distribution and characteristics of spawning habitat used by Striped Bass and American Shad. Transactions of the American Fisheries Society 129:1316–1330.

Benjamini, Y., and Y. Hochberg. 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society B 57:289–300.

Brown, M. E., J. Maclaine, and L. Flagg. 2006. Anadromous alosid restoration in the Androscoggin River watershed. Maine Department of Marine Resources, Project AFC-37, Augusta.

Bunt, C. M., T. Castro-Santos, and A. Haro. 2012. Performance of fish passage structures at upstream barriers to migration. River Research and Applications 28:457–478.

Castro-Santos, T. 2005. Optimal swim speeds for traversing velocity barriers: an analysis of volitional high-speed swimming behavior of migratory fishes. Journal of Experimental Biology 208:421–432.

Castro-Santos, T., and B. H. Letcher. 2010. Modeling migratory energetics of Connecticut River American Shad (*Alosa sapidissima*):

implications for the conservation of an iteroparous anadromous fish. Canadian Journal of Fisheries and Aquatic Sciences 67:806–830.

FERC (Federal Energy Regulatory Commission). 2019. Pending licenses, relicenses and exemptions. Available: www.ferc.gov/industries/hydropower/gen-info/licensing.asp. (July 2019).

Gowans, A. R. D., J. D. Armstrong, and I. G. Priede. 1999. Movements of adult Atlantic Salmon in relation to a hydroelectric dam and fish ladder. Journal of Fish Biology 54:713–726.

Grote, A. B., M. M. Bailey, and J. D. Zydlewski. 2014. Movements and demography of spawning American Shad in the Penobscot River, Maine, prior to dam removal. Transactions of the American Fisheries Society 143:552–563.

Haro, A., and T. Castro-Santos. 2012. Passage of American Shad: paradigms and realities. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science [online serial] 4:252–261.

Haro, A., and B. Kynard. 1997. Video evaluation of passage efficiency of American Shad and Sea Lamprey in a modified Ice Harbor fishway. North American Journal of Fisheries Management 17:981–987.

Hightower, J. E., A. M. Wicker, and K. M. Endres. 1996. Historical trends in abundance of American Shad and river herring in Albemarle Sound, North Carolina. North American Journal of Fisheries Management 16:257–271.

Limburg, K. E., K. A. Hattala, and A. Kahnle. 2003. American Shad in its native range. Pages 125–140 *in* K. E. Limburg and J. R. Waldman, editors. Biodiversity, status, and conservation of the world's shads. American Fisheries Society, Symposium 35, Bethesda, Maryland.

Limburg, K. E., and J. R. Waldman. 2009. Dramatic declines in North Atlantic diadromous fishes. BioScience 59:955–965.

MDMR (Maine Department of Marine Resources). 2014. American Shad habitat plan. Atlantic States Marine Fisheries Commission, Arlington, Virginia. Available: www.asmfc.org/files/ShadHabitatPlans/AmShadHabitatPlan_ME.pdf. (July 2019).

NOAA (National Oceanic and Atmospheric Administration) Northeast Fisheries Science Center. 2016. The return of American Shad: successful spawning in Maine river a positive sign. NOAA, Northeast Fisheries Science Center, Silver Spring, Maryland. Available: www.nefsc.noaa.gov/press_release/pr2016/scispot/ss1614/. (July 2019).

Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A quantitative assessment of fish passage efficiency. Fish and Fisheries 13:450–464.

Weaver, C. R. 1965. Observations on the swimming ability of adult American Shad (*Alosa sapidissima*). Transactions of the American Fisheries Society 94:382–385.

Williams, J. G., G. Armstrong, C. Katopodis, M. Larinier, and F. Travade. 2012. Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. River Research and Applications 28:407–417.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.