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Mortality of Juvenile American Shad and Striped Bass Passed through Ossberger Crossflow Turbines at a Small-Scale Hydroelectric Site

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Abstract.—A full-recovery technique was used in mortality experiments conducted with juveniles of American shad *Alosa sapidissima* and striped bass *Morone saxatilis* passed through Ossberger crossflow turbines to obtain antecedent information about their fish passage characteristics. Immediate turbine-induced mortality was 66% for 85-mm-long (total length) American shad. Turbine-induced mortality of striped bass was significantly related to the total length of the fish and ranged from 16% for 67–83-mm-long fish to 39% for 136-mm-long fish immediately after passage; after 24 h, turbine-induced mortalities of these two size-groups were 61 and 72%, respectively. The mortality of striped bass was not affected by power output (320–600 kW) of the turbine or by turbine size (650 versus 850 kW). Because of high mortality of control fish, the full-recovery technique was not fully adequate for obtaining reliable delayed-mortality estimates for these fragile fish species.

Recent concerted efforts to rehabilitate runs of anadromous fishes in rivers of eastern North America have, by chance, coincided with a resurgent interest in small-scale hydropower development in this region (Gloss and Wahl 1983). Fish passage facilities at many hydroelectric sites are allowing movement of anadromous fish migrants to upper-river spawning areas, but few sites have downstream bypass capabilities to protect migrating juveniles, subadults, and postspawn adults from entrainment. Total mortality probable for fish passed through turbines, particularly juvenile migrants, has consequently become an important consideration in regional fisheries management planning and environmental impact assessment.

Populations of American shad *Alosa sapidissima* are being successfully restored with increasing frequency in U.S. east-coast river systems where hydropower obstacles must be negotiated (Howey 1981; Moffitt et al. 1982). Migrations of subadults of striped bass *Morone saxatilis* into both natal and nonnatal rivers (and through fishways) have been frequently documented (Raney et al. 1954; Nicholas and Miller 1967; Kynard and Warner 1987). Whereas reasonable mortality estimates are available for several salmonid species passed through any of various turbine types (Turbak et al. 1981; Gloss and Wahl 1983), such data are scarce for nonsalmonids, as is information on the suitability of associated-mortality testing procedures. Taylor and Kynard (1985) estimated immediate turbine-induced mortality of juvenile American shad passed through a 17-MW Kaplan turbine at three levels of power generation. Stokesbury and Dadswell (1991) estimated the immediate mortality of several clupeid species passing through a STRAFLO turbine at a low-head tidal-power dam. However, in neither case were shad held for determination of delayed mortality; hence, it is likely that these results underestimate total turbine-induced mortality. No published documentation exists for turbine-induced mortality of subadult striped bass.

Estimates of mortality resulting from passage of fish through hydraulic turbines have been based on various recovery techniques. These have included using returns of adult fish that were marked as juveniles before turbine passage and the partial-recovery techniques of Schoeneman et al. (1961), as well as full-recovery methods in which all fish are recovered in nets immediately after they pass through turbines (Cramer and Donaldson 1964). If returns of adult fish are monitored, several years are required to evaluate results, and there are inherent, potentially severe, problems related to sta-

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tistical reliability. Partial-recovery methods, though potentially valid statistically (Paulik 1961), require extremely large sample sizes (dependent on anticipated recovery rates) and the testing of numerous assumptions regarding recovery ratios of live and dead fish in experimental and control groups. Full-recovery methods yield near-unity values for recovery rates and ratios, and require substantially smaller sample sizes than do partial-recovery methods to produce a similar degree of statistical accuracy. Both recovery methods subject test fish to mortality resulting from stress or mechanical injury, which is a major consideration in the testing of fragile fish species. Most recovery methodologies were originally developed for use with emigrating juvenile salmonids. The full-recovery net system appears to have the most desirable properties for estimating salmonid mortality resulting from turbine passage (Turbak et al. 1981), but this system has not been adequately tested with nonsalmonid species.

We used a full-recovery system originally designed to estimate mortality incurred by juvenile salmonids passed through Ossberger crossflow turbines to estimate turbine-induced mortality for juvenile American shad and striped bass. Mortality estimates were derived with a relative recovery rate estimator, as described by Ricker (1975) and Burnham et al. (1987), to separate mortality caused by turbine passage from that attributable to other sources (e.g., damage caused by recovery nets). Mortality differences attributable to fish size, turbine size, and power output were examined. Our objectives addressed two issues of urgent concern to workers assessing the impacts of hydropower development on anadromous fish species: (1) what mortality can be expected among juvenile out-migrant American shad and striped bass, and (2) what procedures can be used to estimate mortality for fragile fish species.

Study Site and Turbine

The Colliersville Dam (9.75-m head) on the north branch of the Susquehanna River in south-central New York impounds the 150-hectare Goodyear Lake. The power plant, which was operated commercially from 1907 to 1969, was refurbished during the late 1970s and retrofitted with two Ossberger crossflow turbines of 650 and 850 kW. The entire flow available, up to 20 m^3/s (the maximum discharge capacity of the two turbines), is diverted through the powerhouse. These Ossberger turbines were the first installed in the USA, and they provided the opportunity to obtain antecedent information about their fish passage characteristics. (No anadromous fish populations were extant in this reach of the Susquehanna drainage.)

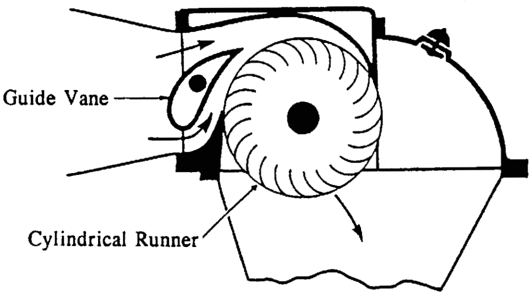

FIGURE 1.—A horizontal-admission Ossberger turbine in cross section. Arrows indicate direction of water flow.

Ossberger turbines are of the radial, impulse type and operate at relatively low speed. The two guide vanes, which regulate water intake, and the cylindrical runner (Figure 1) are the only moving parts. Control of intake flow by partial or complete opening of one or both guide vanes allows these turbines to develop optimum efficiency over water flows of 16–100% of each unit's capacity. The rapidly ascending asymptotic efficiency curve typical of Ossberger crossflow turbines is in contrast to the more parabolic curves of reaction-type turbines. The relation between water discharge and generator output is nearly linear over the plateau of operating efficiency, and revolutions of the runner are constant in this range (Table 1). Spacing between the runner blades is approximately 30 mm on the 650-kW unit and 40 mm on the 850-kW unit. The clearance between the runner and the housing of each is about 3 mm. More complete descriptions of the study site and turbine were given in Gloss and Wahl (1983).

Methods

Two general size-groups (mean total lengths, 67–83 mm and 136 mm) of striped bass were obtained from the Harrison Lake National Fish Hatchery, Charles City, Virginia. (Hereafter, all fish lengths are given as total length.) Handling procedures for

TABLE 1.—Operating characteristics of Ossberger turbines at Goodyear Lake.

Rated output (kW)	Diameter of runner (m)	Revolutions per minute	Maximum discharge (m^3/s)	Design head (m)
650	1.00	135	8.5	10
850	1.25	104	11.5	10

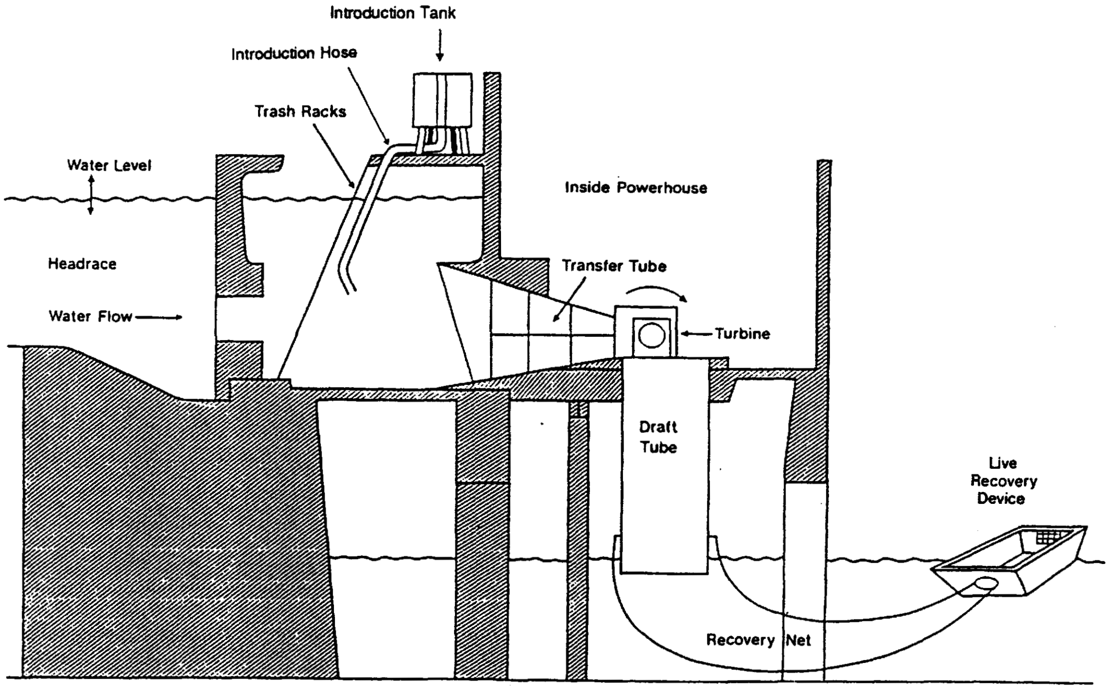

FIGURE 2.—Cross section of powerhouse and tailrace at Colliersville Dam, showing apparatus for introduction and recovery of fish.

striped bass were identical to those described for Atlantic salmon (Gloss and Wahl 1983). American shad (mean length, 85 mm) used for turbine passage experiments were obtained from the lower Delaware River near Byram, New Jersey, during the 1981 emigration. A single group of 40–45-mm-long hatchery-reared American shad (Lamar Fisheries Research and Development Center, U.S. Fish and Wildlife Service, Lamar, Pennsylvania) was used for control experiments because of difficulty in obtaining adequate numbers of wild American shad when needed. Wild American shad were collected by seining without beaching the bag of the seine. Rather, American shad were crowded into the bag of the seine with a live-cage designed for holding fish (Buynak and Mohr 1980), which was held on its side in shallow water. The seine was worked close to the sides of the cage until most fish were crowded into the live-cage; the cage was then turned upright in the water. American shad were dipped out of the live-cage with plastic buckets and dishpans and transferred directly into the transport tank; thus, they were never taken from the water or dip-netted (Chittenden 1971). All subsequent transfers of American shad were made by slowly dipping of individual fish or small groups with buckets or dishpans; no dip nets were used. All equipment and procedures recommended by Chittenden (1971) to minimize excitement-related stress were adhered to, including transport in aerated tanks containing a 0.5% NaCl solution.

Fish Passage

The procedures and gear described by Gloss and Wahl (1983) for estimating turbine-induced mortality of juvenile salmonids were adapted for similar experiments with juvenile American shad and striped bass. Known numbers of test fish (35–100, varying with fish size and species) were acclimated in an introduction tank on the deck of the powerhouse, then released through the bottom of the tank by way of an introduction hose that emptied underwater behind the trash racks and just upstream from the turbine intake (Figure 2). Water velocity near the end of the delivery tube was 0.3–0.6 m/s (measured with a Marsh–McBirney direct-reading current meter) and theoretically increased toward the turbine. Fish were recovered in a floating recovery box similar to that described by Craddock (1961), after they passed through a trawl-shaped recovery net that encompassed the outlet of the turbine draft tube (mouth of net was entirely above water during discharge). The recovery net was constructed of treated knotless nylon with a mouth opening of 4.6 × 3 m and length of 13.5 m. Mesh sizes (stretched measure) were 19 mm in the mouth section (8 m long), 12 mm in the throat section (2.5 m long), and 6.3 mm in the cod end (3 m long). The maximum turbine discharge rate at which we introduced experimental or control fish was about 8.5 m^3/s. Current velocity near the mouth of the recovery net was modest and only reached 0.3 m/s under peak discharge. After passage, recovered fish were classified as dead, injured, or uninjured (no apparent physical damage or loss of orientation). Living fish were transferred from the recovery box to covered, floating livecages (Buynak and Mohr 1980) that were anchored in quiet water adjacent to the tailrace for observations of delayed mortality. Fish were examined twice at 24-h intervals.

Control Experiments

Each phase of the test procedure for both species was examined for sources of mortality other than passage through the turbine. In tests simulating introduction, fish were discharged through a delivery tube (about the same length and angle as the test introduction hose) into a 1,900-L circular tank, from which they were recovered and monitored. Mortality attributable to the recovery apparatus was examined by placing fish into the mouth of the recovery net while the turbine was operating (at the same level of turbine output as in passage trials). These fish were subsequently recovered from the live-box and treated as during turbine passage trials (they spent the same amount of time in the recovery box). Although a seemingly better experimental design would have been to have simultaneously released treatment and control fish, such an approach would have required marking fish, which would have contributed an additional source of stress. Hence, control trials were run at a separate time. Estimates of mortality attributable to handling and holding procedures were made by acclimating fish in the introduction tank, then recovering and monitoring these fish.

Analysis

Most test and control trials were conducted in triplicate, though several trials were replicated four or five times. Occasionally, only one or two trials were done because of limited numbers of fish or failure of equipment. We assumed that virtually all fish that were released for turbine passage but were not recovered had escaped upstream before entering the turbine. However, if a few fish did pass through a turbine and were not subsequently recovered, we assumed that dead, injured, and uninjured fish in this category had equal chances of not being recovered. For each trial we calculated escapement (1 − [number recovered/number introduced]), immediate mortality, and cumulative mortality after 24 h. Because control mortality occurred for both species (particularly from the recovery process), we used a relative recovery rate estimator as described by Ricker (1975) and Burnham et al. (1987). The basic structural model for calculating turbine mortality (M) was

$$M = 1 - [(A/R)/(a/r)];$$

A = number of fish alive at recovery after a turbine passage trial,
R = number of fish recovered after a turbine passage trial,
a = number of fish alive at recovery after a recovery-net trial, and
r = number of fish recovered after a recovery-net trial.

Because there was no immediate mortality of striped bass during any of the control experiments, no recovery-net adjustment was necessary for calculating their immediate turbine-induced mortality. Estimates of delayed (24-h) turbine-induced mortality of striped bass and estimates of immediate turbine-induced mortality of American shad were corrected for recovery-net mortality as in the above equation. We did not attempt to estimate turbine-induced mortality of striped bass beyond 24 h or delayed turbine-induced mortality of American shad, because when control mortality is high, as it was for these groups, the relative-recovery-rate method is not useful. We ignored holding and handling mortality because there was none initially, nor was there any for striped bass after 24 h. We analyzed percent mortality and recovery rate data with the nonparametric Mann–Whitney U-test, Kruskal–Wallis test, and Wilcoxon rank-sum test, and we used linear regression to examine the relationship between mortality and power output.

Results

American Shad

Four batches of wild American shad were subjected to an 8–10-h process involving collection, transportation, and handling. The first batch consisted of 3,000 fish, and although initial mortality (i.e., mortality at the time of transfer to holding tanks at the site) was only 0.5% in a 700-L tank, 99% of the fish died within 24 h. During subse-

TABLE 2.—Mean mortality of American shad and striped bass passed through Ossberger turbines (data from 650-kW and 850-kW units combined).

Species	Size-group (total length, mm)	Number of trials	Mean number of fish per trial	Mean turbine-induced mortality (%)	
				Immediate	24-h cumulative
American shad	85	12	42	66	[a]
Striped bass	136	6	96	39[b]	72
Striped bass	67–83	27	50	16	61

[a] This mortality value could not be estimated because of high mortality related to the recovery net.

[b] Mean based on only four of the six trials.

quent collections we transported smaller batches (500–1,000 fish) with greater success. Initial post-transport mortality was characteristically low, ranging from 1 to 3%. However, losses through 48 h consistently exceeded 60%. Mortality after the first 48 h averaged 2–4% daily—an addition of less than 1% per day to the cumulative mortality. Because mortality leveled off after 48 h, American shad were held at least that long before survivors were used for turbine mortality and recovery-net trials. American shad are widely recognized for their sensitivity to stresses imposed by virtually any type of collection or handling procedures and are therefore not readily available for experimental purposes. Other control mortality experiments (handling, holding cages, simulated introduction) were conducted with groups of smaller (40–45-mm-long) hatchery-reared American shad. These fish were too small to be used for recovery-net trials (because they would pass through the recovery net's mesh).

Control experiments with wild American shad produced substantial mortality only during recovery-net trials. In duplicate or triplicate experiments (50–100 fish/replicate) where hatchery-reared American shad were placed in either live-cages, introduction tanks, or the recovery live-box under discharge conditions for 48 h, mortality from each source of stress was low (mean, 7%; range, 0–16%; seven trials; 50–100 fish/trial). Simulated introduction caused an average loss of 3% through 48 h (range, 0–6%; four trials; 100 fish/trial). Neither the simulated introduction technique nor the handling and holding procedures alone produced large immediate or delayed mortality.

Immediate mortality was also low in recovery-net experiments (mean, 6%; range, 0–16%; seven trials; 30 fish/trial), but mortality after 24 h was high (mean, 86%), precluding our ability to estimate delayed mortality of American shad resulting from turbine passage. The immediate turbine-induced mortality of American shad through the 850-kW unit was 66% (Table 2), and power output (range, 320–600 kW) did not have a significant effect ($P > 0.82$). Recovery of American shad after turbine passage averaged 83%, and recovery-net recovery averaged 75% (see Discussion for the effect of leaf fall on recovery).

Striped Bass

We had little difficulty in transporting or handling the two size-groups of striped bass. Control experiments indicated that only the recovery net caused substantial mortality and that this mortality did not occur initially (92% of striped bass used in recovery-net trials were recovered). Mean 24-h recovery-net mortality was 21% (16 trials) and was not influenced by fish size. Although recovery-net losses of striped bass were lower than those for American shad, they still represented a confounding factor that complicated our efforts to estimate delayed mortality due to turbine passage.

Striped bass mortality data for various discharge rates of the turbines were combined because significant differences ($P < 0.05$) were not detected among them or between the two turbines of different capacities. The immediate turbine-induced mortality for both size-groups combined was 19% (31 trials; mean recovery rate, 63%). The delayed (24-h) mortality caused by turbine passage of striped bass was 63% (33 trials). The only turbine-induced mortality comparisons that were significantly different ($P < 0.05$) occurred between the 136-mm and 67–83-mm length-groups. Immediate turbine-induced mortality was significantly greater ($P < 0.01$) for the larger size-group (mean, 39%; range, 17–48%) than for the smaller size-group (mean, 16%; range, 0–40%; Table 2). The delayed (24-h) turbine-induced mortality for the larger group (72%) was not significantly different ($P > 0.09$) from that for the smaller group (61%; Table 2).

Discussion

Our results describing turbine-induced mortality of juvenile American shad and striped bass paralleled results of a similar study with salmonids by Gloss and Wahl (1983) in showing (1) no change in mortality due to power output of Ossberger turbines, and (2) a significant positive relationship between fish size and mortality. The lack of change in mortality relative to power output is probably due to the flat efficiency curve typical of these turbines over a wide range of power outputs. This efficiency characteristic provides little opportunity to mitigate periods of high mortality potential (outmigrations) by changing operating conditions. The immediate turbine-induced mortality we estimated for American shad (66%) is similar to that reported by Taylor and Kynard (1985) for juvenile alosids (62%) passed through Kaplan turbines at their power output of greatest efficiency. The immediate and delayed turbine-induced mortality estimates for striped bass we provide are the first for this species passed through any type of turbine.

A substantial body of evidence has now accrued (Smith 1960, 1961; Taylor and Kynard 1985; Stokesbury and Dadswell 1991; this article) documenting highly variable immediate mortality, ranging from 14 to 82%, for juvenile alosines passed through any of various turbine types. It is not known why these estimates have been so variable. Taylor and Kynard (1985) suggest that such differences may be species- or age-specific, may be due to experimental design differences, or may be attributable to turbine design, setting, loading, or cavitation characteristics. In general, this evidence indicates that alosines are subject to higher levels of mortality after turbine passage than are salmonids. However, the lack of reliable estimates of delayed turbine-induced mortality for alosines raises serious questions about the use of present estimates for estimation of total turbine-induced mortality. Although it is generally recognized that available estimates may underestimate turbine-induced mortality because they ignored the factor of eventual death from shock, stress, or injuries that did not leave visible signs of damage (Stokesbury and Dadswell 1991), little information is available about how much delayed mortality may occur after fish passage through different types of turbines. Smith (1960, 1961) is the only worker to report estimates of delayed turbine-induced mortality for alosines (calculated by subtracting immediate mortality from mean total mortality after 1 week—an improper calculational approach), but his results were not subjected to peer review and must be cautiously interpreted. His results do, however, suggest that mortality of alosines immediately surviving passage through Smith–Kaplan turbines may have exceeded 30% over the first week. If delayed mortality of alosines after passage through other types of turbines is similarly substantial, total turbine-induced losses could easily exceed 80% in some cases. We mention this point to highlight the need to develop methodologies for estimating the delayed component of turbine-induced mortality in addition to the immediate component, not to advocate use of Smith's estimate of delayed mortality as a standard.

TABLE 3.—Mean recovery of American shad and a size-group of striped bass (total length, 67–83 mm) after turbine passage at low, moderate, and high levels of power output. Paired comparisons of 320-kW and 520–600-kW output tests (P value; Mann–Whitney U-test) showed higher recovery of both species at high output. Numbers of trials (35–50 fish/trial) are in parentheses.

Species	Turbine capacity (kW)	Percent recovery at power output of: 320 kW	440 kW	520–600 kW	P
American shad	850	77 (2)	77 (6)	95 (4)	0.07
Striped bass	850	48 (3)	77 (5)	71 (7)	0.03
Striped bass	650	17 (4)	34 (5)	52 (3)	0.03

Based on our results, the full-recovery technique has serious limitations for use in estimating total turbine-induced mortality of fragile fish species because of considerable mortality attributable to the recovery apparatus. Many hydropower sites have higher tailrace current velocities than those experienced in our study. Our failure to obtain reliable estimates of delayed turbine-induced mortality of American shad under relatively benign conditions at a small-scale site suggests that full-recovery techniques are not suitable for this species.

Not all fish introduced in turbine passage trials in this study were subsequently recovered, which raises the possibility that uninjured survivors of turbine passage may have had a higher probability of escaping recovery than injured or dead fish had. This possibility is important to consider, because if it had occurred, an overestimation of turbine-induced mortality would have resulted. Two lines of evidence support our assumption that we recovered virtually all fish that entered the turbines. First, recovery was higher at high power outputs than at low outputs for both striped bass and American shad (Table 3), suggesting that fish were sometimes able to swim against the current and escape into the headrace, particularly at lower power outputs. Second, recovery rates of 99–100% in five trials with striped bass, and recovery rates exceeding 95% in 25% of the trials with American shad suggest that when fish entered a turbine, recovery was high. A period of heavy leaf fall from late September to early October represented the only opportunity for fish entering a turbine to not be recovered (some fish may have been missed while we sorted through large volumes of leaves in both the recovery box and net). Recovery-net trials, which should have provided a test of our recovery assumption, were conducted mostly during this period of leaf fall (16 of 19 trials), and recovery was poorer during these trials than during the turbine passage trials. Only 12% of the turbine passage trials were conducted during heavy leaf fall.

The relatively close spacing of the runner blades in Ossberger turbines may, in part, explain the greater mortality to larger fish (increased risk of mechanical injury); however, our study design did not specifically address the causes of turbine mortality. Cavitation is considered to be the most important source of mortality to young fish passed through turbines (Muir 1959; Ruggles et al. 1981). Pressure change appeared to be responsible for 65% of the injuries that a STRAFLO turbine caused to clupeids (Stokesbury and Dadswell 1991). In general, clupeids have shown more evidence of pressure damage after turbine passage than have salmonids (Stokesbury and Dadswell 1991), which may result from their having an enclosed swim bladder that extends into the back of the head and is in contact with the brain (Blaxter and Hoss 1979).

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