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REVIEW PAPER

# Long-term effect of a tidal, hydroelectric propeller turbine on the populations of three anadromous fish species

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Tidal hydroelectric power has been proposed as one potential solution for sustainable energy sources. The first tidal turbine in North America began continuous operation in the Annapolis River estuary (44 °45′N; 65° 29′W) in June, 1985. The machine is an axial-flow, hydraulic-lift propeller turbine, a type known to cause fish mortality. Anadromous populations of American shad *Alosa sapidissima*, striped bass *Morone saxatilis* and Atlantic sturgeon *Acipenser oxyrinchus* utilize the Annapolis River for spawning and other life history phases. After power generation commenced obvious turbine mortalities of these fishes began appearing downstream of the turbine. Assessments of the *A. sapidissima* adult spawning runs during 1981–1982 (pre-operation) and 1989–1996 (operational) indicated significant changes in population characteristics after power generation began. Adult length, mass, age and per cent repeat spawners declined and total instantaneous mortality (*Z*) increased from 0.30 to 0.55. The pre-turbine spawning runs had older fish with numerous adult cohorts whereas by 12 years after operation began runs consisted of younger fish with fewer adult cohorts. During 1972–1987 numerous studies indicated the Annapolis River had an important angling fishery for *M. saxatilis*, but detailed annual records kept by a fishing contest during 1983–1987 and an elite angler family during the period 1976–2008 demonstrated a rapid decline in the number of fish >4.0 kg after turbine operation began. Pre-turbine catch by the angling family of fish >4.0 kg accounted for 84.1% of total catch, but declined significantly to 39.6% of total catch from 1986–1999, and to none from 2000–2008. The existence of an *A. oxyrinchus* stock in the Annapolis River was unknown before turbine operation, but during 1985–2017, 21 mortalities were recovered by chance seaward of the turbine. Mechanical strike and cavitation mortalities consisted of juveniles, mature males and gravid and spent females of ages 10 to 53 years found during June to October, the period when this anadromous species returns to its natal river to spawn. The results of the long-term studies at Annapolis indicate managers should realize substantial risks exist for the fish resources of the world's oceans from deployment of instream propeller turbines.

KEYWORDS
abundance declines, Canada, creel census, fisheries resources, population characteristics, turbine mortalities

## 1 | INTRODUCTION

Tidal power development is underway worldwide as a means to produce hydroelectricity that is sustainable and with low $CO_2$ emissions (Lewis *et al.*, 2015). The Bay of Fundy (BoF) is considered the most economically feasible region for tidal power production in the western hemisphere (Karsten *et al.*, 2008). The embayment, along with its associated estuaries has one of the highest recorded tides in the world of up to 17 m. The potential output from large, tidally driven generation facilities using barrages in the BoF was estimated at 20,000 GWh year$^{-1}$ (Baker, 1984) but this form of tidal power generation has fallen in disfavour because of its potential, wide-ranging environmental effects (Gordon & Dadswell, 1984; Walters *et al.*, 2013). Instead, tidal power developers are now examining the potential for instream hydrokinetic devices in the open ocean, many of which have been installed or are being planned worldwide (Gill, 2005; Lewis *et al.*, 2015; Zangiabadi *et al.*, 2016). This form of tidal, hydroelectric power generation has been estimated to have a maximum potential yield in the Minas Passage region of the BoF for 5.7 GW or approximately 50,000 GWh a year (Walters *et al.*, 2013).

The development of modern, large-scale hydroelectric tidal power generation began in Europe with the La Rance River estuary project in Britanny, France (48 °37′ 04″ N; 02° 01′ 31″ W). Completed in 1966, the La Rance project was a tidal barrage with an installed capacity of 240 MW from six, axial-flow, hydraulic-lift bulb turbines (Andre, 1978). Unfortunately, no pre-operation studies were conducted to determine effects of the power plant on the aquatic environment or the local fisheries (Retiere, 1994).

North America's first, tidal hydroelectric power project was completed in 1985 at Annapolis Royal, Nova Scotia, Canada on the Annapolis River estuary, a tributary of the Bay of Fundy (Dadswell *et al.*, 1986). The plant has a single, 7.6 m diameter axial-flow, hydraulic-lift STRAFLO propeller turbine in a barrage with an installed capacity of 20 MW (Douma & Stewart, 1981). The installation was a pilot project to assess the potential of the STRAFLO turbine for large-scale, barrage tidal power developments in the inner BoF. The station operates in an ebb tide flow regime at head differentials of 5–7 m. In this case, numerous pre-operation studies were conducted on the Annapolis River and its estuary to assess the effect of the power plant on the aquatic environment and the local fish populations (Daborn *et al.*, 1979a,*b*; Melvin *et al.*, 1985; Jessop, 1980).

The propeller turbine installed at Annapolis Royal is a type known to cause fish mortalities (Von Raben, 1957; Dadswell *et al.*, 1986; Gibson & Meyers, 2002a). As they rotate the blades of axial-flow, hydraulic-lift propeller turbines change the physical characteristics in the water (pressure, velocity) flowing over them, and the rapid movement of the blades can strike aquatic organisms that pass through the spinning propeller. During turbine passage aquatic organisms can be affected by mechanical strike, shear, pressure flux and cavitation (Von Raben, 1957; Čada, 1990; Dadswell & Rulifson, 1994; Deng *et al.*, 2005; Stokesbury & Dadswell, 1991). Unfortunately, many of the instream hydrokinetic machines installed or planned worldwide are also large propeller turbines (Gill, 2005; Lewis *et al.*, 2015; FORCE, 2017) and the same physical phenomena will be encountered by organisms that pass through them (Bucklund *et al.*, 2013; Hammer *et al.*, 2015; Zangiabadi *et al.*, 2016).

We present this study from the point of view that the developing, worldwide, instream tidal turbine installations in the ocean will be interacting with many more marine organisms and valuable fisheries than a propeller turbine in a single estuary (Redden *et al.*, 2014; Dadswell *et al.*, 2016). Consequently, it will be even more important to conduct detailed studies on the pre-operational environment and its ecology in the region of installations to determine future consequences of instream propeller turbines for valuable marine resources (Gill, 2005). The open ocean contains large stocks of economically important fishes and invertebrates, and also marine mammals, many of which are endangered or threatened and are now protected. These resources sustain the economic viability of many coastal communities and their loss will affect the livelihoods of their human populations (Dadswell & Rulifson, 1994; Gill, 2005). Because the instream propeller turbines operate without a barrage the chance of fish encounters are considered to be reduced (Shen *et al.*, 2016; Bevelhimer *et al.*, 2017), however, because of their size and the fact most operate on both ebb and flood tide means they will pass huge amounts of water through their draft tube (*c.* 1,200 $m^3$ $s^{-1}$ for a 16 m diameter machine; FORCE, 2017) potentially affecting large numbers of fishes and capable of impacting cetaceans (Tollit *et al.*, 2011; Hammer *et al.*, 2015). Is it wise and justifiable to replace one renewable resource with another when alternate forms of electric generation are possible?

In the case of the Annapolis Royal tidal plant, sufficient studies were done before and after turbine installation to examine the long-term effects of the propeller turbine on the populations of three andromous fish species in the Annapolis River. Here, we present observations made over 43 years on the natal populations of American shad *Alosa sapidissima* (Wilson 1811), striped bass *Morone saxatilis* (Walbaum 1792) and Atlantic sturgeon *Acipenser oxyrinchus* Mitchill 1814. We postulated that the long-term operation of the propeller turbine on the Annapolis would selectively remove larger fish from these populations thereby changing population characteristics and abundance. To our knowledge, this is the only study to date on the long-term effects of a tidal, propeller turbine on fish populations.

## 2 | STUDY REGION

The Annapolis River and estuary (44° 45′ N; 65° 29′ W) is a tributary to the eastern side of the outer Bay of Fundy (Figure 1). The river has a meander length of 97 km and drains a catchment of 1,603 $km^2$ (Melvin *et al.*, 1985). It is a low gradient, warm-water stream and summer water temperature often exceeds 26° C. Annual flow at Annapolis Royal is *c.* 38 $m^3$ $s^{-1}$. The estuary stretches from Bridgetown to its outlet from Annapolis Basin at Digby Gut, a distance of 95 km. Tidal range in the estuary seaward of the causeway is *c.* 7 m.

A tidal dam was constructed on the estuary at Annapolis Royal in 1960 to protect farm land from saltwater intrusion and created a head-pond reservoir of $10.8 \times 10^3$ $km^2$ (Figure 1; Melvin *et al.*, 1985). The dam consists of three units: a rock-fill causeway between Granville Ferry and Hog's Island, Hog's Island itself, and an open concrete structure containing a sluiceway and a permanently open fishway between Hog's Island and Annapolis Royal. The sluiceway has two gates with a 7.3 × 9.1 m opening, and the fishway is 3.0 m wide × 7.3 m deep.

During 1983–1985 a hydroelectric tidal plant was constructed on Hog's Island (Figure 1). The plant has a 15 × 15 m turbine intake and draft tube that contains the 7.6 m diameter, STRAFLO propeller turbine set 12 m below the head-pond level. There is also a 3 × 3 m box culvert fishway, the top of which is at high-tide level. The 20 MW STRAFLO unit is the modern version of an axial-flow turbine with a rim-type generator (Douma & Stewart, 1981). It is a low-head, propeller turbine arranged in a horizontal water passage with the generator field poles attached to a rotor rim mounted around the periphery of the propeller. Operation of single-effect, ebb generation is such that during the flood and high tide period seawater enters the reservoir through the sluice gates and the freewheeling turbine. During ebb and

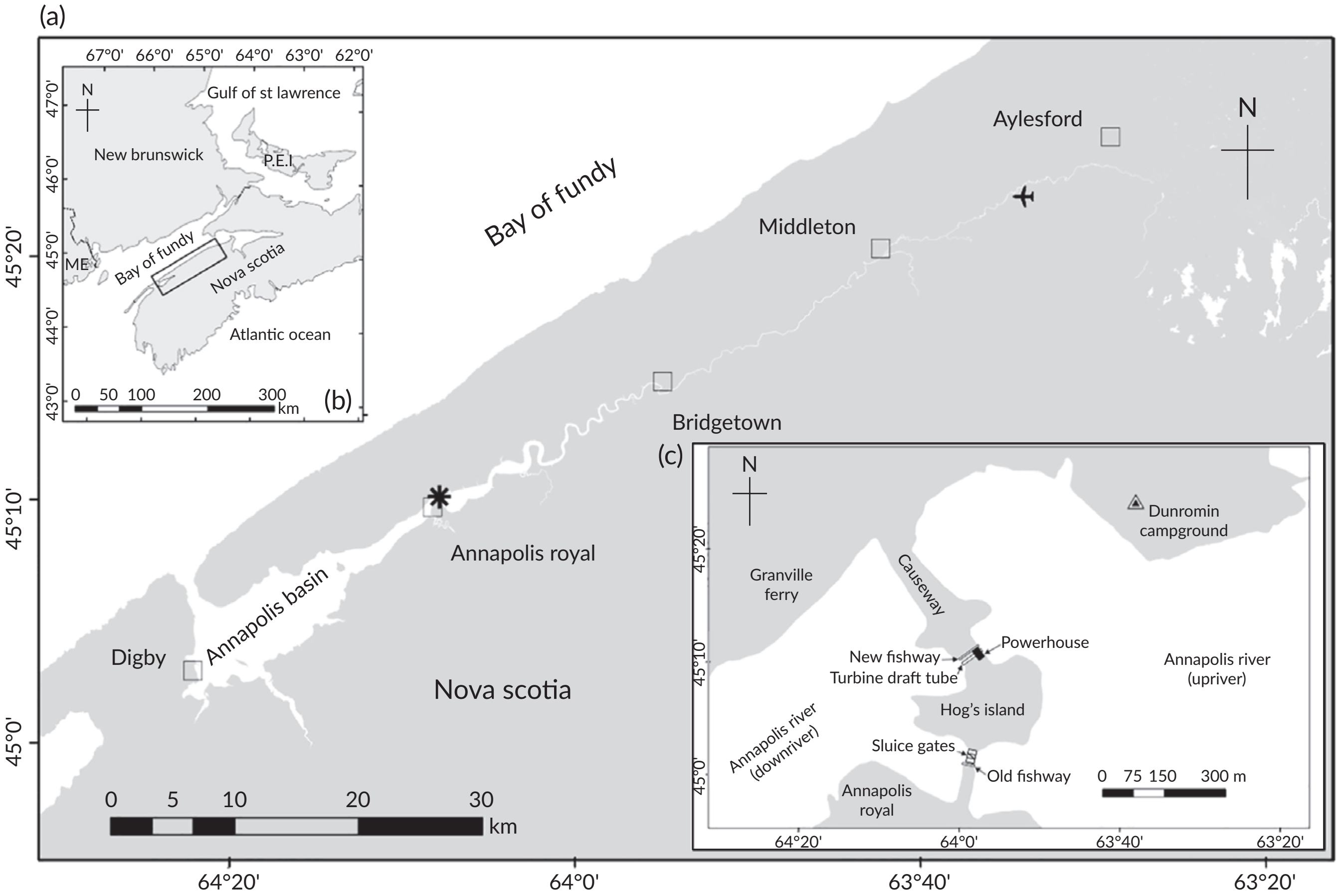


**FIGURE 1** (a) Annapolis River and Annapolis Basin, Nova Scotia with (b) the bay of Fundy region in eastern Canada and (c) the causeway in which the fishways and tidal turbine structures at are situated at Annapolis Royal

low-tide periods the sluice gates are closed, and the turbine operates to generate power when the head differential between reservoir and sea exceeds 1.4 m. During an average tidal cycle the turbine generates power for *c.* 6 h. Since the sluice gates are closed during generation and the fish-passage volumes low, the main, downstream flow of water that migratory fish follow is through the turbine draft tube (Dadswell & Rulifson, 1994; Gibson & Meyers, 2002a).

## 3 | TIDAL TURBINE CHARACTERISTICS

The critical design parameters of the STRAFLO turbine for fish passage are: turbine diameter, hub diameter, number of blades, discharge volume, rotational speed, pressure flux and cavitation potential (Čada, 1990; Von Raben, 1957). Using the mathematical relationships developed by Von Raben (1957) the water length ($L_W$; distance between each successive pass of the runner blades) of the STRAFLO is 3.2 m and the impact velocity (velocity of a blade tip) is 16.9 m s$^{-1}$ (Dadswell & Rulifson, 1994). The probability of fish strike is determined by fish total length ($L_T$) $L_W{}^{-1}$ which for a 50 cm fish is 15.6%, and for a 1 m fish, 31.2%. Since impact velocity exceeds 10 m s$^{-1}$, all strikes within the mutilation range for a fish species would result in strike damage of which 45–60% depending on fish species would be fatal (Von Raben, 1957). The STRAFLO is set at 12 m below head-pond height and operates under a 7 m head, which means the pressure flux along the turbine centre line corresponds to a pressure drop of 70,928 N m$^{-1}$ (0.7 atmos.) and would increase to 121,590 N m$^{-1}$ (1.2 atmos.) at the bottom of the draft tube (Dadswell *et al.*, 1986). These pressure fluxes are imposed on fishes in 0.2 s during transit of the turbine blades (Dadswell & Rulifson, 1994). Pressure flux in this range exceeds the tolerance of many fish species (Tsvetkov *et al.*, 1971; Blaxter & Hoss, 1979; Hoss & Blaxter, 1979). Also, because of the shallow setting and variable head due to changing tide level, the Thoma criterion (cavitation number, $\sigma$) is low (Čada, 1990), which results in considerable cavitation potential around the blades at low tide.

## 4 | FISH MORTALITIES

Construction on the turbine and causeway began in 1983 and the plant was officially opened in September 1984, but operation was immediately shut down because of mechanical difficulties. The turbine was repaired and reopened in June 1985 and has been operating without shutdowns except for annual maintenance (1 week), and for 1 week in August, 2004 when a humpback whale *Megaptera novaeangliae* entered the head pond (Tethys, 2016). Although the turbine was operating in 1985 anglers were unable to fish at the causeway because reconstruction of the tidal sluice gates continued until autumn of that year.

Immediately after generation commenced in June 1985 fish mortalities began to appear downstream of the turbine (Dadswell *et al.*, 1986). Larger fishes were being maimed or killed by mechanical strike, shear and cavitation (Figure 2; Dadswell & Rulifson, 1994; Dadswell, 2006) and smaller fishes mainly by pressure flux and shear (Stokesbury & Dadswell, 1991). Diversion techniques were only partially successful (Gibson & Meyers, 2002b) and almost every species of fish known to occur in the Annapolis Estuary has been affected to a greater or lesser degree (Dadswell & Rulifson, 1994; Gibson & Meyers, 2002a).

## 5 | THE FISHERIES

The Annapolis River is a unique case for eastern Canada when examining the history of its fisheries. Unlike other eastern Canadian rivers the *A. sapidissima* and *M. saxatilis* spawning runs have been closed to commercial fishing with selective gear (gill nets) in the river and estuary since the 1880s (Dadswell *et al.*, 1984; Melvin *et al.*, 1985). The only fisheries permitted were angling for *A. sapidissima* and *M. saxatilis* and a small, commercial dip-net fishery for *A. sapidissima* which operates on Mondays and Tuesdays from May 1–31. Landings in the dip-net fishery between 1895–1912 and 1947–1982 were *c.* 6,200 kg $y^{-1}$ or about 0.01% of the adult stock size and angling catches, based on tag returns, varied annually from 0.5–4.0% (Melvin *et al.*, 1985). Lack of a selective gill-net fishery in the Annapolis was probably one reason that the mean age estimated for the 1981 and 1982 spawning runs of *A. sapidissima* (Melvin *et al.*, 1985) was greater than any other studied river population in eastern North America, where commercial shad populations sustain up to 15% fishing mortality without changes in population characteristics (Leggett & Carscadden, 1978). Also, the instantaneous mortality rate was lower than in any other river previously investigated (Leggett, 1976; Melvin *et al.*, 1985). There was never a directed fishery for *A. oxyrinchus*.

The angling fishery for *M. saxatilis* in the Annapolis River was popular, attracting anglers from Nova Scotia (95%), and other Canadian provinces and the United States (5%; Harris, 1988). There was no minimum size limit for retention of fish until 1994 when a limit of 46 cm fork length ($L_F$) was imposed. The limit was raised to 58.5 cm $L_F$ in 1995 and finally to 68.5 cm $L_F$ in 1997 (DFO, 2014). A 68.5 cm $L_F$ *M. saxatilis* has a mass of *c.* 4.0 kg (Rulifson & Dadswell, 1995).

## 6 | STUDIES ON *A. SAPIDISSIMA*

Pre-operation studies on the *A. sapidissima* adult, spawning run were conducted during April–June in 1981 and 1982 (Melvin *et al.*, 1985). Adults were captured with a 10.1 cm stretched-mesh spearhead trap net in the estuary seaward of the causeway and 12.4, 13.6 and 15.2 cm stretched-mesh gill nets in the river. Since body depth varies among pre and post-spawn *A. sapidissima* (a factor that affects gill-net selectivity) only fish that had not spawned were selected for

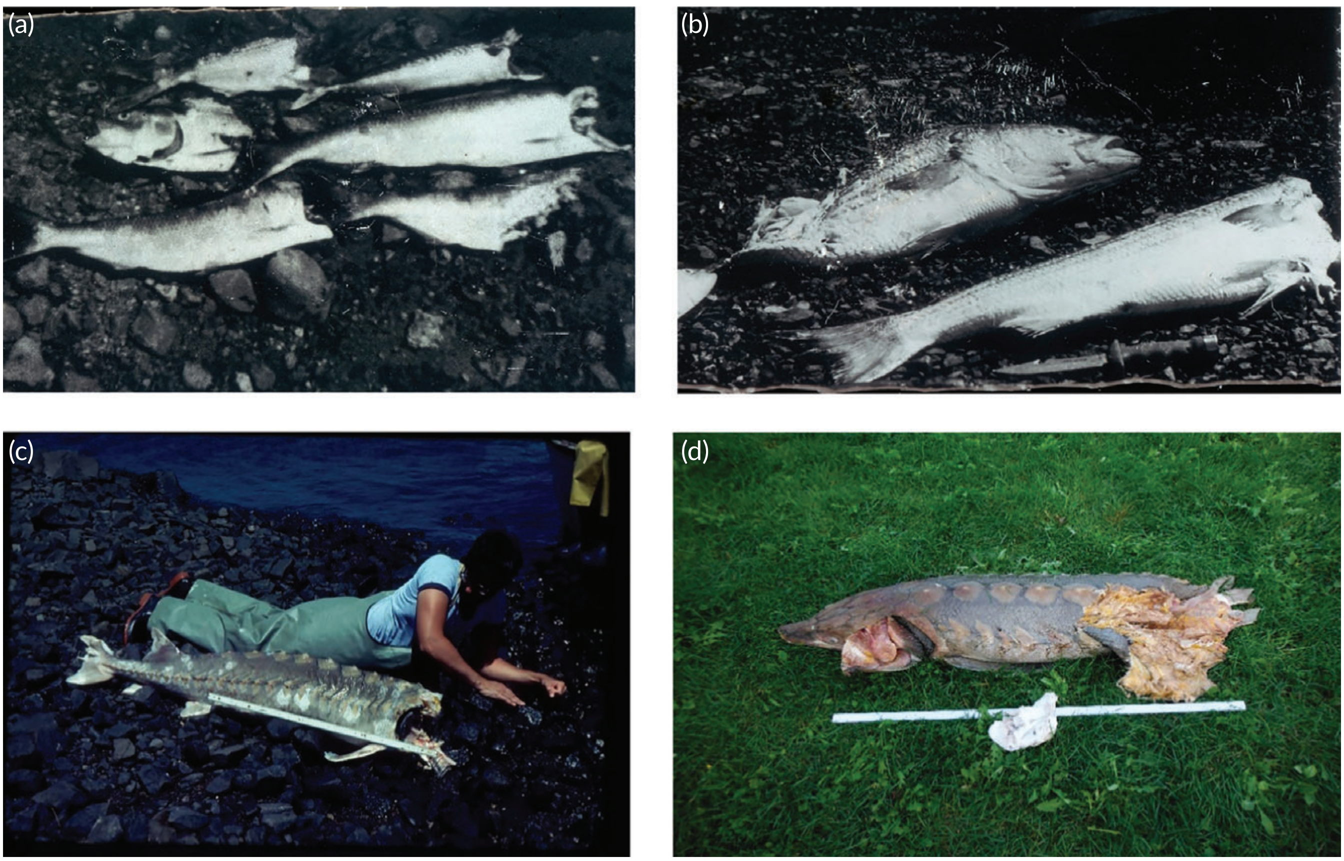


**FIGURE 2** Turbine mortalities of anadromous fishes found seaward of the Annapolis Royal tidal turbine: (a) mechanical strike and shear victims of *Alosa sapidissima*, July 1985; (b) mechanical strike victims of *Morone saxatilis*, June 1985; (c) decapitated, mechanical strike of *Acipenser oxyrinchus*, July, 1985; (d) pre-dorsal, mechanical strike victim of *Acipenser. oxyrinchus.* September 2014

analysis. Fish were sacrificed at selected intervals, and supplemented with net mortalities when available, and frozen for laboratory analysis. Prior to freezing fork length *L* was measured to the nearest mm and mass measured with a Mettler balance (www.mt.com) accurate to 0.1 g (Melvin *et al*., 1985). Fish were then bagged, labelled and frozen. In the laboratory fish were thawed and remeasured and weighed using the same techniques as in the field. Gonads were examined for sex, and scales and otoliths taken for aging. Scales were cleaned in water, mounted between glass slides and read with a dissecting microscope. Age and spawning history were determined using criteria of Cating (1953) and Judy (1961) for identifying annuli and spawning marks. Otoliths were cleaned, mounted in black plastic trays with 1,2-diethyl chloride and cleared with 90% ethanol for aging, using a dissecting microscope. Annuli were determined as one set of clear and opaque bands. Final assigned age for individual fish was a reconciliation of independent readings by two experienced researchers. Statistical analysis was conducted on an HP 3000 computer (www.hp.com) using SPSS and Fortran programs (Melvin *et al*., 1985).

Total instantaneous mortality rates (*Z*) for both 1981 and 1982 was calculated from otolith-determined ages and age size classes from trap net samples (Melvin *et al*., 1985). Size of male age 4 and 5 year classes were adjusted using per cent maturity from scale spawning histories to account for immature males unrepresented in the spawning run. The 4 and 5 year age classes were not used to determine female *Z*. The von Bertalanffy growth parameters were calculated for both sexes using $L_t = L_\infty (1 - e^{-K[t-to]})$, where: $L_t = L_F$ at age *t* (years), $L_\infty$ = asymptotic $L_F$, *K* is the Brody growth coefficient and $t_0$ is age at length zero if the fish had always grown according to the von Bertalanffy model.

Studies after turbine generation began were planned around the 5 year maturity cycle of *A. sapissima* such that collections were obtained from the first and second generations after 1984. Sampling of the spawning run took place during May and June, 1989–1990, and 1995–1996 (Gibson, 1996). Adults were captured with 10.1, 11.4, 12.7, 13.6 and 15.2 cm stretched mesh gill nets. All sampling was conducted at sites upriver of the causeway. Only fish that had not spawned were selected for analysis. Fish were returned to the laboratory and sampled fresh or bagged, labelled and frozen. Fork length was measured to the nearest mm. Mass was determined with a Mettler balance accurate to 0.1 g. Gonads were examined for sex and scales and otoliths taken for aging. Scales and otoliths were treated in the same manner as in 1981 and 1982.

Total instantaneous mortalities for 1989, 1990, 1995 and 1996 were calculated from otolith-determined ages and age size classes adjusted for ages 4, 5 and 6 based on per cent maturity in each age class (Gibson, 1996). Separate mortality estimates were determined for males and females. The von Bertalanffy growth parameters were calculated as in 1981 and 1982.

Biological and population characteristics were calculated using raw data and after data had been corrected for gillnet selectivity and relative fishing effort with the different mesh sizes (Gibson, 1996). Gillnet selectivity was determined using the indirect method of Hamley (1975) for the 1989 and 1990 surveys or the indirect method of Regier & Robson (1966) for the 1995 and 1996 surveys. Separate selectivity curves were developed for males and females since pre-spawning females have a wider and deeper body than pre-spawning males (Gibson, 1996). All statistical analyses were done using SPSS for a Microsoft PC (1989/90) or SYSTAT 7.02 (Gibson, 1996).

In both studies, Melvin *et al*. (1985) and Gibson (1996), $L_F$ of frozen specimens were adjusted to fresh length by the factor 1.021 because there was a significant difference (*t*-test, $p < 0.001$) between $L_F$ of fresh and frozen specimens. No significant difference (*t*-tests, $p > 0.05$) was found between ages determined with scales and otoliths in both studies. For comparison of population characteristics of *A. sapidissima* among years in our review, however, we used only their raw data since the difference between raw data and those adjusted for gill-net selectivity seldom differed by more than 1% (Gibson, 1996). Means for the individual years (1981 *v.* 1996) were compared with pooled *t*-tests.

### 6.1 | Pre-operation spawning run characteristics of *A. sapidissima*

A total of 166 males and 143 females were examined during 1981 and 68 males and 127 females during 1982 (Table 1). Males ranged from 4–12 years for both the 1981 and 1982 spawning runs; females, 4–12 years in 1981 and 5–13 years in 1982 (Table 1). Male mean age ± S.D. = 6.68 ± 1.04 years in 1981 and 6.98 ± 1.21 years in 1982 (Figure 3). Female mean age ± S.D. = 7.34 ± 1.14 years in 1981 and 8.28 ± 1.34 years in 1982, which was a significant difference (*t*-test, $p < 0.05$; Melvin *et al*., 1985).

Maximum $L_F$ of males in 1981 was 577 and 530 mm in 1982. For females it was 602 mm in 1981 and 605 mm in 1982 (Table 1). The mean $L_F$ ± S.D. of males in 1981 was 459 ± 38.0 mm and 463 ± 40.5 mm in 1982 (Figure 3). The mean $L_F$ of females in 1981 was 506 ± 42.8 mm and 527 ± 37.6 mm in 1982. The mean $L_F$ of males was not significantly different between 1981 and 1982 (*t*-test, $p > 0.05$; Melvin *et al*., 1985) but female $L_F$ in 1982 was significantly greater than in 1981 (*t*-test, $p < 0.01$; Melvin *et al*., 1985).

The mass of fish did not differ significantly (*t*-test; $p > 0.05$; Melvin *et al*., 1985) between fresh and frozen specimens. Mean mass ± S.D. of males in 1981 was 1,558 ± 400.6 g and 1,473 ± 382.2 g in 1982 (Figure 3). Mean mass ± S.D. of females in 1981 was 2,232 ± 529.7 g and 2,252 ± 499.5 g in 1982. There was no significant difference between years for either sex (*t*-test, $p > 0.05$; Melvin *et al*., 1985).

Previous spawning history determined from scales of sampled fish indicated that 76.5% of males and 72.2% of females in the 1981 spawning run were repeat spawners (Table 1). In 1982, 80.0% of males and 93.6% of females were repeat spawners.

Estimated total instantaneous mortality of males was *Z* = 0.36 in both 1981 and 1982 and for females *Z* = 0.25 in 1981 and 0.22 in 1982 (Table 1). The von Bertalanffy parameters for $L_\infty$ and *K* differed little between years for either sex. Male $L_\infty$ was estimated to be 570 mm in 1981 and 565 mm in 1982; *K* was 0.22 and 0.20. Female $L_\infty$ was estimated as 645 mm in 1981, 640 mm in 1982 and *K* was 0.16 for both years (Table 1).

**TABLE 1** Changes in some important population characteristics for the annual spawning runs of adult *Alosa sapidissima* from the Annapolis River, Nova Scotia, 1981–1996

| Year | Sex | 1981 | 1982 | 1989 | 1990 | 1995 | 1996 | Changes 1981–1996 (%) |
|---|---|---|---|---|---|---|---|---|
| Sample size | M | 166 | 68 | 165 | 241 | 134 | 208 | |
| | F | 143 | 127 | 251 | 379 | 400 | 226 | |
| Maximum age (years) | M | 11 | 11 | 10 | 9 | 9 | 8 | −37.5 |
| | F | 12 | 13 | 11 | 9 | 10 | 10 | −17.7 |
| Maximum $L_F$ (mm) | M | 577 | 530 | 544 | 544 | 490 | 510 | −11.6 |
| | F | 602 | 605 | 587 | 554 | 525 | 540 | −10.3 |
| Repeat Spawners (%) | M | 76.5 | 80.0 | 87.9 | 82.5 | 53.0 | 55.0 | −28.1 |
| | F | 72.2 | 93.6 | 87.4 | 59.8 | 53.7 | 53.0 | −26.6 |
| Total instantaneous mortality ($Z$) | M | 0.36 | 0.36 | 0.81 | 0.89 | 0.47 | 0.61 | +40.9 |
| | F | 0.25 | 0.22 | 0.85 | 0.93 | 0.57 | 0.49 | +49.0 |
| von Bertalanffy $L_\infty$ | M | 570 | 565 | 560 | 494 | 452 | 455 | −20.2 |
| | F | 645 | 640 | 640 | 552 | 508 | 531 | −17.7 |
| von Bertalanffy $K$ | M | 0.22 | 0.20 | 0.19 | 0.38 | 0.45 | 0.48 | +58.3 |
| | F | 0.16 | 0.16 | 0.17 | 0.30 | 0.32 | 0.29 | +44.8 |

## 6.2 | Operational spawning run characteristics of *A. sapidissima*

Sample sizes ($n$) from the spawning runs during 1989–1990 and 1995–1996 were as large as or larger than those taken in 1981–1982 and ranged from 134 to 241 males and 226 to 400 females (Table 1). The maximum age of captured males declined from 10 years in 1989 to 8 years in 1996. Similarly the maximum age of females decreased from 11 years in 1989 to 10 years in 1996. Overall there was a decrease of 37.5% in the maximum age of males and 17.7% in the maximum age of females between 1981 and 1996 (Table 1).

Mean age ± S.D. of males in the spawning runs declined from 6.61 ± 1.06 years in 1989 to 5.56 ± 1.03 years in 1996 (Figure 3) and the overall decline between 1981 and 1996 was 16.7%, which was significant ($t$-test, $p < 0.001$). Mean age ± S.D. of females in the spawning runs declined from 6.87 ± 1.02 years in 1989 to 6.32 ± 1.22 years in 1996 and the overall decline between 1981 and 1996 was 13.8%, which was a significant difference ($t$-test, $p < 0.001$). The maximum $L_F$ of males in the spawning runs declined from 544 mm in 1989 to 510 mm in 1996 and for females declined from 587 mm in 1989 to 540 mm in 1996 (Table 1). Overall the observed decline in maximum length between 1981 and 1996 was 11.6% for males and 10.3% for females. Mean $L_F$ ± S.D. of males in the spawning run declined from 450 ± 25.8 to 414 ± 28.7 mm between 1989 and 1996 (Figure 3) and the overall decline between 1981 and 1996 was 9.8%, which was a significant difference ($t$-test, $p < 0.001$). Similarly the mean $L_F$ ± S.D. of females declined from 484 ± 26.9 to 462 ± 34.8 mm between 1989 and 1996 and the overall decline between 1981 and 1996 was 8.7%, which was significantly different ($t$-test, $p < 0.001$). Mean mass ± S.D. of spawning males was 1,376 ± 206.3 g in 1989 but declined to 953 ± 264 g by 1995 (Figure 3; mass unmeasured in 1996; Gibson, 1996). Similarly the mean mass ± S.D. of females in 1989 was 1,711 ± 288.8 g but declined to 1,439 ± 387.0 g in the 1995 spawning run. Overall between 1981 and 1995 the mass of males and females in the spawning runs declined by 38.8% and 35.5%, respectively and both declines were significant ($t$-test, $p < 0.001$).

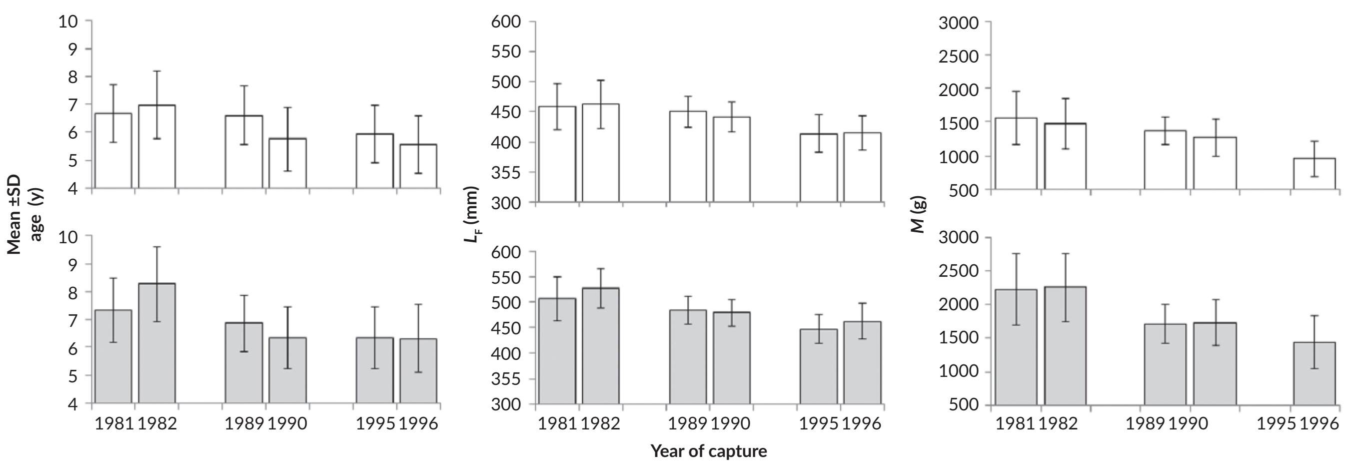


**FIGURE 3** Mean ± S.D. of age (years), fork length ($L_F$) and mass ($M$) of male (□) and female (▒) *Alosa sapidissima* captured from spawning runs during turbine pre-operational (1981–1982) and operational (1989–1990 and 1995–1996) periods on the Annapolis River. All comparisons between 1981 and 1996 (1995 for mass) were significant ($t$-test, $p < 0.001$)

Total Instantaneous mortality estimates for males varied among years from 0.89 in 1990 to 0.52 in 1995 (Table 1). Similarly female $Z$ was estimated to be as high as 0.93 in 1990 and as low as 0.49 in 1996, but all of the $Z$ estimates for spawning runs during operational assessments were greater than those obtained in 1981–1982. Estimated $Z$ for males increased by 40.9% between 1981 and 1996 and for the larger females the increase was 49.0%.

Von Bertalanffy growth parameters in 1989 were a $L_\infty$ of 560 mm for males and 640 mm for females, with a $K$ of 0.19 for males and 0.17 for females (Table 1). In 1990, however, there was a shift in growth parameters to a smaller $L_\infty$ and a higher $K$ which continued until 1996. By 1996 the estimated $L_\infty$ for males declined to 455 mm and to 531 mm for females and $K$ increased to 0.48 for males and 0.29 for females. Overall the estimated $L_\infty$ for the population declined by 20.2% between 1981 and 1996, while the estimated $K$ parameter increased by 58.3% for males and 44.8% for females (Table 1).

## 7 | STUDIES ON *M. SAXATILIS*

Pre-operation studies on *M. saxatilis* included angler creel surveys with questionnaire returns from angling licences (Jessop & Doubleday, 1996), fishing contests (Harris, 1988) and private angler records. During 1978 a total of 2,430 anglers returned license questionnaires (Jessop, 1980). Fish were recorded by mass (kg) using each fisher's spring balance. Annual fishing contests were conducted during 1982 and 1983 at the Dunromin camping ground (www.dunromincampground.ca/) next to the Annapolis Causeway (Harris, 1988). Fish were recorded by mass using a merchant's meat packing scale accurate to 1 g. The Kennedys, an elite, Annapolis Valley angling family, maintained detailed annual records from 1976–1982 of dates fished, total catch and mass of each captured *M. saxitilis*. Fish mass was recorded with a spring balance accurate to 57 g. A minimum size limit of 68.5 cm $L_F$ (*c.* 4.0 kg) was not placed on the angling fishery until 1996 but we analyzed the available data in terms of a > 4.0 kg legal fish. All means ± s.d. are given as simple arithmetic values without arcsine transformation.

Studies after generation began included records from the Dunromin camping ground annual fishing contests for 1986 and 1987, angler interviews and assessment of their catches and private angling records. During June to October 1987, 898 anglers fishing at the causeway were interviewed over a period of 937 h (Harris, 1988). The Kennedy family continued their detailed annual angling records from 1986 to 2008, including dates fished, total catch and mass of each *M. saxitilis*. Mass was recorded with a spring balance accurate to 57 g.

### 7.1 | Pre-operation angler catch characteristics of *M. saxatilis*

Before turbine operation began in 1985 there was no minimum size limit on angling catches of *M. saxitalis* but anglers caught mainly fish > 4.0 kg. In 1971–1972, fish > 4.0 kg constituted 64% of the total reported catches from licence surveys (Jessop & Doubleday, 1976). In 1978, 89% of reported licensed catches were fish > 4.0 kg (Jessop, 1980). Similarly angling catches entered in the annual Dunromin Campground contest were dominated by large fish (Figure 4(a)). Of fish entered in the contest during 1982, 71% were > 4.0 kg and in 1983, 69%. Fish 10–18 kg mass were common.

Pre-turbine operation records of *M. saxatilis* angling maintained by the Kennedy family during 1976–1982 indicate they fished for a mean ± s.d. of 17.4 ± 6.3 days over approximately the same period each year (May–October) and captured legal fish (> 4.0 kg) on 88.4 ± 13.4% of days (Table 2). Annual catches were dominated by fish > 4.0 kg (Figure 4(b)) and fish of 10–18 kg were common. Catch day$^{-1}$ for the total catch varied from 1.55–3.50 fish (Figure 5). During each fishing season they captured a mean ± s.d. of 24.3 ± 9.5 legal fish and 84.1 ± 14.3% of the total number of *M. saxatilis* captured were > 4.0 kg (Table 2). The mean mass ± s.d. of fish > 4.0 kg angled each year was 9.2 ± 2.1 kg and the annual maximum mass of captured fish ranged from 15.9–20.4 kg (mean ± s.d. = 17.9 ± 1.7 kg).

### 7.2 | Operational angler catch characteristics of *M. saxatilis*

Catches of *M. saxatilis* of > 4.0 kg recorded in the Dunromin camping ground angling contest were only 51% of the total fish entered in the contest in 1986 and declined to 37% in 1987 (Figure 4(a)). We lack records of the Dunromin catches after 1987 and the contest closed after 2008 because few *M. saxatilis* were being caught and angler interest had declined. Angling catches of *M. saxatilis* by the Kennedy family after the turbine was operational (1986–1999) demonstrated an overall decline in large fish albeit with the occasional better year (Table 2). Although their period of angling during 1986 to 1999 remained similar to pre-operational angling and annual effort in days fished did not differ significantly from pre-operational angling (*t*-test, $p > 0.5$), the catch and percentage of fish > 4.0 kg decreased by 69% and 57%, respectively. After 1985 legal fish were only 39.6 ± 33.2% of the total catch year$^{-1}$ (Figure 4(b)) and while the operational catch day$^{-1}$ for all fish did not decline until after 1994 (Figure 5) legal fish were only captured on 42.6 ± 35.1% of days fished. During 1986–1999 the total annual catch of fish > 4.0 kg declined significantly to 7.6 ± 7.7 (Table 2; *t*-test, $p < 0.001$). The annual mean mass of legal fish also declined significantly to 7.7 ± 2.4 kg (*t*-test, $p < 0.001$). The maximum mass for a fish taken each year during this period ranged from a high of 18.6 kg to a low of 4.6 kg but the mean of largest fish taken each year declined significantly to 13.3 ± 3.5 kg (*t*-test, $p < 0.001$). During the period 1996 to 1999 the Kennedys only captured six fish > 4.0 kg and although the family continued fishing annually until 2008 they never caught a legal fish after 1999.

## 8 | STUDIES ON *A. OXYRINCHUS*

During experimental studies on tidal turbine fish passage mortalities rates from 1985–1987 (Stokesbury & Dadswell, 1991; Dadswell & Rulifson, 1994) records were kept of *A. oxyrinchus* mortalities found seaward of the turbine. From 2007–2017 volunteer river watchers (L. Cliché, Clean Annapolis River Project) recorded if dead *A. oxyrinchus* were found and, when possible, secured the fish until an autopsy could be performed. The autopsies recorded the type of

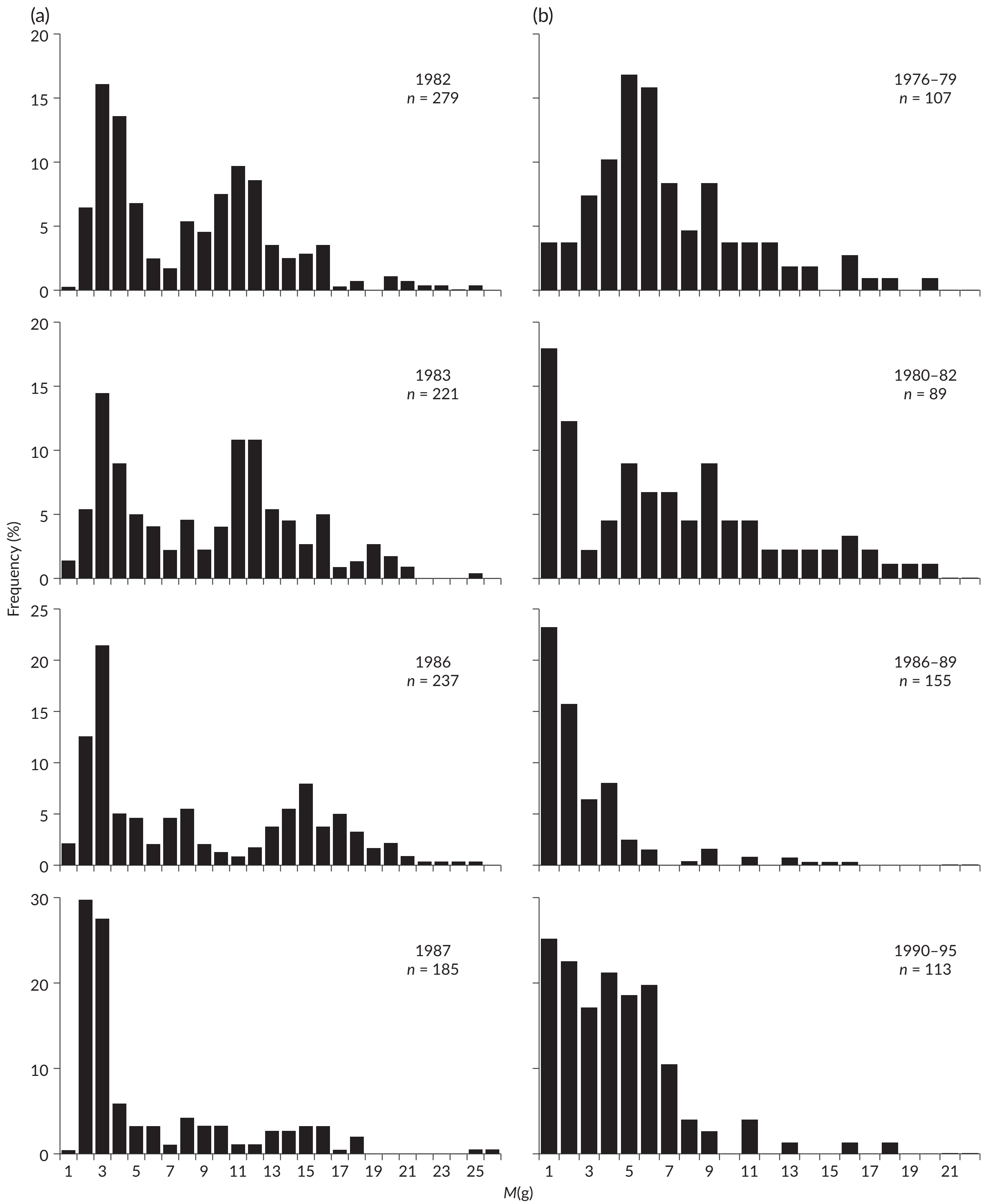


**FIGURE 4** Mass (*M*)–frequency (percentage of total catch) distributions of *Morone saxatilis* caught from the Annapolis River by angling and (a) entered in the annual Dunromin camping ground contest (1982–1987) and (b) recorded by the Kennedy family during pre-operation (1976–1982) and operation (1986–1995) of the Annapolis Royal tidal turbine. *n*, total fish captured

turbine mortality, measured or estimated $L_F$, sex and maturity stage, and a pectoral-fin spine was removed for aging. Estimated $L_F$ was determined using morphometric proportions from Magnin (1962), depending on where each fish was severed. Sex and maturity stage were determined by examining the gonads using the criteria of Cuerrier (1966) and Dadswell (1979) where stage 4 was a ripening fish,

**TABLE 2** Yearly angling catch and effort of the Kennedy family for *Morone saxatilis* at the Annapolis River causeway, Nova Scotia before (1976–1982) and after (1986–1999) turbine operation

| Year | Effort (days) | Catch days (%) | Catch (>4.0 kg) | Legal catch (% > 4.0 kg) | Maximum size (kg) |
|---|---|---|---|---|---|
| 1976 | 20 | 90.0 | 27 | 93.1 | 17.3 |
| 1977 | 16 | 100. | 23 | 89.6 | 16.2 |
| 1978 | 20 | 95.0 | 24 | 79.3 | 18.2 |
| 1979 | 21 | 85.7 | 36 | 82.9 | 20.0 |
| 1980 | 23 | 86.9 | 32 | 82.8 | 20.4 |
| 1981 | 18 | 61.1 | 22 | 60.6 | 16.4 |
| 1982 | 4 | 100.0 | 6 | 100.0 | 17.1 |
| 1976–1982 (mean ± S.D.) | 17.4 ± 6.3 | 88.4 ± 13.4 | 24.3 ± 9.5 | 84.1 ± 14.3 | 17.9 ± 1.7 |
| 1986 | 30 | 20.0 | 7 | 15.2 | 11.8 |
| 1987 | 29 | 20.6 | 6 | 12.5 | 13.6 |
| 1988 | 16 | 43.7 | 8 | 25.0 | 16.8 |
| 1989 | 19 | 78.9 | 20 | 54.0 | 15.4 |
| 1990 | 16 | 100.0 | 26 | 78.7 | 15.0 |
| 1991 | 9 | 22.2 | 2 | 13.3 | 9.1 |
| 1992 | 8 | 50.0 | 5 | 50.0 | 6.4 |
| 1993 | 11 | 54.5 | 10 | 41.6 | 11.4 |
| 1994 | 16 | 75.0 | 14 | 63.6 | 18.6 |
| 1995 | 3 | 100.0 | 3 | 100.0 | 16.4 |
| 1996 | 20 | 20.0 | 4 | 57.1 | 11.4 |
| 1997 | 16 | 6.0 | 1 | 33.3 | 13.6 |
| 1998 | 12 | 0.0 | 0 | – | – |
| 1999 | 15 | 6.6 | 1 | 10.0 | 4.6 |
| 1986–1999 (mean ± S.D.) | 15.7 ± 7.4 | 42.2 ± 35.1 | 7.6 ± 7.7 | 39.6 ± 33.2 | 13.3 ± 3.5 |

Construction of the power plant at the causeway prevented angling between 1983 and 1985. All means of operational catches (1986–1999) were significantly different than pre-operational catches (1976–1982); *t*-test, $p < 0.001$. Catch days is percentage of angling days that legal fish were caught annually. Catch (> 4.0 kg) is number of legal fish caught annually and legal catch (> 4.0 kg) is the percentage of legal fish caught annually. Maximum size gives the mass of the largest fish caught annually.

stage 5 was a ripe fish and stage 6 was a spent. Pectoral rays were extracted, air dried for 1 month, sectioned (0.5 mm) with a jewellers saw, cleared with 95% ethanol and read under a dissecting microscope. Annuli were determined based on the method of Cuerrier (1951).

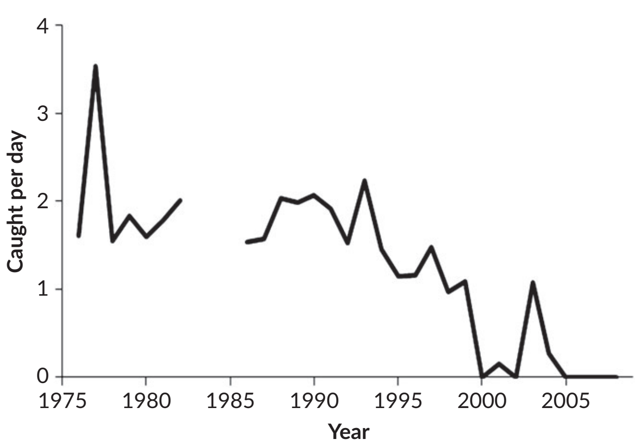


**FIGURE 5** Number of *Morone saxatilis* (< 4.0 kg and legal) caught per day (CPUE) at the Annapolis River causeway, Nova Scotia (data from the Kennedy family's angling records). The break during 1983–1985 was because construction of the tidal turbine hydroelectric plant and sluiceways restricted access to the causeway

### 8.1 | Recovery of *A. oxyrinchus* turbine mortalities

Although *A. oxyrinchus* was unreported from the Annapolis River before 1985, once continuous turbine operation began in June, 1985 obvious turbine mortalities began appearing seaward of the causeway (Figure 2). These mortalities were found on the estuary bottom (recovered by scuba diving; Dadswell & Rulifson, 1994) or in the intertidal zone. During a turbine mortality study at the Annapolis power plant (1985–1986; Dadswell & Rulifson, 1994; Dadswell, 2006) researchers found four turbine-related *A. oxyrinchus* mortalities (Table 3). All of these mortalities were victims of mechanical strike having been severed just posterior to the head or somewhere in the region of the dorsal fin. Estimated $L_F$ was 182 and 185 cm for two autopsied females that were at reproductive maturity stage 5. Two other recovered females were determined to be stage 5 from photographs.

No further observations were made until 2007 when Rierden (2007) recovered three *A. oxyrinchus* turbine mortalities seaward of the turbine (Table 3). One was a 100 cm $L_F$ juvenile. Unfortunately the carcasses were too decayed to determine sex. At this time an *ad hoc* organization of river guardians volunteered to maintain a watch for fish mortalities and information began to be accumulate either in the form of photographs or as recovered fish that could be autopsied after the carcasses were collected. Between 2009 and 2017 a further 17 mortalities were found and reported of which eight were autopsied. Turbine mortalities were predominately mechanical strike (Figure 2) but three fish were intact and had internal wounds indicative of cavitation mortality (Čada, 1990; Dadswell & Rulifson, 1994). Of the autopsied fish, four were adult females and three were adult males. Females were 180–203 cm $L_F$ and 26–53 years old; males were 146–168 cm $L_F$ and 22–27 years old (Table 3). Fish autopsied during June–August were ripe or ripening; those during, September and October, spent. In most years the river guardians found or heard of additional mortalities but we were unable to confirm them because the carcasses were carried away by the tide before they could be examined.

## 9 | DISCUSSION

Operation of an axial-flow, hydraulic lift propeller tidal turbine in the Annapolis River estuary has resulted in extensive fish mortalities to numerous species (Dadswell *et al*., 1986; Dadswell & Rulifson, 1994; Gibson & Meyers, 2002a). Two anadromous species, *A. sapidissima* and *M. saxatilis*, have significant population effects from turbine mortality during the period since 1985 when power generation began. Not enough is known about the population of *A. oxyrinchus* in the Annapolis River, however, to determine if this species is being affected at the population level.

### 9.1 | *Alosa sapidissima*

There are anadromous, river spawning populations of *A. sapidissima* from Florida, U.S.A. to Labrador, Canada (Dadswell *et al*., 1987) and all populations display a high degree of fidelity to their natal stream (Melvin *et al*., 1986; Nichols, 1960). These stocks demonstrate a wide scope of population-specific life-history strategies depending on the latitudinal location of the natal spawning river (Leggett & Carscadden, 1978). Southern stocks typically have spawning runs with few repeat spawners and a small number of adult cohorts while northern stocks have a higher proportion of repeat spawners and numerous adult cohorts. This difference between southern and northern stocks is largely related to post-spawning die-off of adults in southern rivers (Leggett & Carscadden, 1978). Before operation of the tidal turbine on the Annapolis the *A. sapidissima* population displayed characteristics of a classic northern population with 70–90% repeat spawners, adults as old as age 13 and up to eight adult cohorts. By 1996, after 12 years of turbine operation, repeat spawners in the population declined to 55% of males and 53% of females, maximum age of males declined to 8 years and females to 10 years, the number of adult cohorts to five for males and six for females, mean age of the population declined 21% and $Z$ increased by 45% (Gibson, 1996). We believe that these significant changes were largely due to tidal-turbine mortality of adult *A. sapidissima* during post-spawning out-migration. The tidal turbine is apparently removing larger and older adults from the population because they have a higher probability of strike and have passed through the turbine repeatedly during successive, annual spawning runs.

Turbine passage experiments in 1985 and 1986 using acoustically tagged adults determined that mortality rates of post-spawn fish were $46.3 \pm 34.7\%$ in 1985 and $21.3 \pm 15.2\%$ in 1986 resulting from mechanical strike, pressure flux and shear (Dadswell & Rulifson, 1994). Most mortalities, however, were from mechanical strike; the rate of which is proportional to the size of the fish (Von Raben, 1957). Annapolis River adult *A. sapissima* ranged from 400–600 mm $L_F$ and would have probable strike rates between 12.5 and 18.7% from the STRAFLO turbine and these rates would apply each year as adults departed the river after spawning. Since the older fish are the ones that contribute to the number of repeat spawning fish, that population parameter would decline as more old fish were removed from the population in successive years. An increase in the estimated $Z$ of the

**TABLE 3** Month and year of dead *Acipenser oxyrinchus* recovered by chance seaward of the Annapolis tidal turbine during 1985–2017, number, cause of turbine mortality, estimated (using morphological proportions from Magnin, 1962) or measured fork length ($L_F$), age, sex and maturity stage

| Date | Number | Nature of turbine damage | $L_F$ (cm) | Sex | Age (years) | Maturity[a] | Reference |
|---|---|---|---|---|---|---|---|
| June 1985 | 1[b] | Strike, decapitated | 182 | F | 28 | Ripe, stage 5 | |
| June 1986 | 2[c] | Strike, severed at anus | – | F | – | Ripe, 5 | |
| July 1986 | 1[a] | Strike, decapitated | 185 | F | 35 | Ripe, 5 | |
| October 2007 | 1[c] | Unknown | 100[d] | J | – | | Rierden, 2007 |
| October 2007 | 2[c] | Unknown | – | – | – | | Rierden, 2007 |
| September 2009 | 1[c] | Strike, severed anus | – | – | – | Unknown | |
| September 2009 | 2[c] | Strike, decapitated | – | – | – | Unknown | |
| September 2012 | 1[b] | Strike, severed pre-dorsal | 180 | F | 26 | Spent, stage 6 | |
| June 2013 | 1[c] | Unknown | – | – | – | Unknown | |
| September 2015 | 1[b] | Cavitation damage | 203[d] | F | 53 | Spent, stage 6 | |
| July 2016 | 1[b] | Strike, decapitated | 152 | M | 27 | Ripening, stage 4 | |
| September 2016 | 1[b] | Strike, severed pre-dorsal | 146 | M | 22 | Spent, stage 6 | |
| October 2016 | 2[c] | Strike, severed pre-dorsal | – | – | – | – | |
| August2017 | 1[b] | Strike, non–severed | 96[d] | J | 10 | Immature | |

[a] maturity stages after Cuerrier (1966) and Dadswell (1979)
[b] Autopsy performed by M.J.D.
[c] Photograph only
[d] Actual $L_F$ measured when autopsied.

population would also occur because of the selective loss of older fish. If older and larger fish were removed from the population a decline in the von Bertalanffy parameter $L_\infty$ and an increase in $K$ should be expected (Ricker, 1975). Because Annapolis River *A. sapidissima* display strong fidelity to their natal stream (Melvin *et al.*, 1986) turbine mortality effects would become more pronounced over time. Although the spawning run in 1989 displayed some similar characteristics to the 1981 and 1982 runs, all examined population characteristics had changed by 1990, with further changes by the 1995 and 1996 runs. Because there has been no size-selective commercial gill-net fishery for *A. sapidissima* in this river since the 1880s and the dip-net and sports fisheries take only an estimated 0.1% and 0.5–0.7% of the population annually (Melvin *et al.*, 1985), we suggest that the notable change in the Annapolis River spawning-run population characteristics is due to size selective mortality by the turbine propeller.

One of the major population effects of turbine mortality on larger *A. sapidissima* Annapolis females would be a decline of total annual egg deposition in the river. Like most fishes larger *A. sapidissima* have up to 250% more eggs than virgin females. The fecundity of Annapolis females related to $L_F$ was determined to be $150 \times 10^3$ eggs for a 450 mm fish and $225 \times 10^3$ eggs for a 525 mm fish (Melvin *et al.*, 1985). Since female $L_F$ in annual spawning runs declined from *c.* 525 mm during 1981–1982 to *c.* 450 mm in 1995–1996, annual egg deposition in the river would have declined by *c.* 33%. Although this decline has apparently not threatened the population a decline in the total number of returning adult fish could be expected.

Since turbine mortality might be expected to decrease the *A. sapidissima* adult population size over time because of both juvenile (Stokesbury & Dadswell, 1991) and adult mortality (Dadswell & Rulifson, 1994), the data to demonstrate such an occurrence were unfortunately lacking. Multiple-census, mark–recapture population estimates in 1981 and 1982 resulted in valid population size estimates ranging from 78,200 to 114,500 spawning adults (Melvin *et al.*, 1985). A single-census, mark–recapture experiment in 1995 resulted in an invalid (not enough tag recaptures) estimate of 57,899 adults and an estimate attempted in 1996 failed to recapture any marks (Gibson, 1996). These data cannot be used to suggest that there has been an adult population decline due to turbine mortality and although the Annapolis River *A. sapidissima* population has altered in biological characteristics, it is apparently surviving the long-term effects of turbine mortalities. The change in population characteristics, however, has resulted in a population of predominately younger adults and fewer adult age cohorts more similar to rivers in the southern portion of the species range (Leggett & Carscadden, 1978). Melvin *et al.* (1985) predicted that if annual turbine mortality was between 10–50% there would be a decline in the mean age and number of repeat spawners in the population. This appears to be what has happened.

## 9.2 | *Morone saxatilis*

Before tidal-turbine operation began in the Annapolis Estuary, the reported angling catch of *M. saxatilis* was predominately composed of large fish up to a maximum of 26 kg. Biological and creel surveys (Harris, 1988; Jessop & Doubleday, 1976), catches from angling contests (Harris, 1988) and the Kennedy family angling records prior to 1983 all demonstrated this characteristic of the population with annual catches composed of 60–90% of fish > 4.0 kg. Since Annapolis River *M. saxatilis* > 4.0 kg measure from 68.5–120.0 cm $L_F$ (Rulifson & Dadswell, 1995), these adults would have had a potential strike rate during a turbine passage of 20–40% (Von Raben, 1957). The mortality from strike in the Annapolis population, however, was probably exacerbated since adults used to aggregate around the causeway because of the concentration of potential prey (Harris, 1988) and the availability of damaged and dead prey in the turbine out-flow (M. Dadswell, pers. obs.). Consequently feeding adults probably made multiple passages through the turbine each year while they were following prey thereby increasing their overall potential turbine mortality.

After tidal turbine operation began, the annual angling record of *M. saxatilis* exhibited a significant rapid decline in catches of larger fish, probably caused by size selective mortality during turbine passage. Fish > 4.0 kg caught in the Dunromin angling contest declined from *c.* 70% before turbine operation to 51% in 1986 and 37% in 1987 (Harris, 1988). The Kennedy family angling records demonstrated a similar decline. Catches of fish > 4.0 kg before turbine operation were *c.* 84% annually. By 1986 the catch of legal *M. saxatilis* declined to 15.2% and by 1987 12.5%. Granted there were some better years of angling for the Kennedy family after 1985, but some of the large fish they captured could have been migrants from other Bay of Fundy rivers or the U.S.A. Large *M. saxatilis* tagged in the Annapolis River have been recaptured in the Shubenacadie River, NS spawning run (M. Dadswell, unpub. data). Harris (1988) reported four recaptures of tagged *M. saxatilis* from the Hudson River, NY which occurred at the Annapolis causeway during 1987. Similarly, two *M. saxatilis* tagged in the Potomoc River, MD were recaptured in Annapolis Basin (Nichols & Miller, 1967). Since migrant *M. saxatilis* have been found to exhibit a strong year-to-year fidelity to their summer foraging grounds (Ng *et al.*, 2007; Pautzke *et al.*, 2010), it seems probable that some of the large *M. saxatilis* captured by the Kennedy family before and after 1990 probably came from distant stocks. Because of their fidelity to the Annapolis region, however, even this contingent was apparently extirpated by turbine mortality. The Kennedy family angling catches displayed a continuous decline of large *M. saxatilis* between 1986 and 1999; after 1999 they captured no fish > 4.0 kg.

The Dunromin angling contest closed after 2008 because of lack of large fish and lack of angler interest. As G. Kennedy states in his 2008 fishing diary entry, "this year, very few fishermen fished for bass at the causeway". This statement contrasts sharply with 1978 when catch reports were received from 2,430 anglers (B. M Jessop, 1980) or 1987 when Harris (1988) interviewed 898 anglers at the causeway. Conversely, no decline of large fish has been observed in the *M. saxatilis* population from the nearby Shubenacadie River (Paramore & Rulifson, 2001; Bradford *et al.*, 2012). The Shubenacadie River does not have a causeway or tidal turbine. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2012) and the Canadian Department of Fisheries and Oceans (DFO, 2014) consider the Annapolis River population of *M. saxatilis* extirpated. They list the Annapolis Royal tidal turbine as one of the possible causes and we agree with their assessment. The demise of the Annapolis River *M. saxatilis* population has been so complete that only one fish was reported angled in the river during 2016 and none during 2017 (L. Cliché, pers. com).

Earlier studies in the Annapolis River have indicated that there may be an alternate hypothesis for the decline in the *M. saxatilis* population. From 1976 to 1983 a series of investigations indicated that spawning success was low (Williams, 1978; Williams *et al.*, 1984) or unsuccessful (Daborn *et al.*, 1979b). With the construction of the causeway in 1960 the estuary was changed from a vertically homogeneous, high tidal range habitat to a salt wedge environment with a tidal range of only 0.5 m (Daborn *et al.*, 1979a). Since *M. saxatilis* spawning success is sensitive to environmental conditions (Reinert & Peterson, 2008; Setzler *et al.*, 1980) these changes may have caused a decline in egg and juvenile survival. Other studies on the river, however, during 1971–1972 and again in 1987 illustrate periods of strong recruitment of age 3–6 fish to the angling fishery (Williamson, 1974; Harris, 1988). Populations of *M. saxatilis* often exhibit long periods of scarcity between periods of good recruitment (Setzler *et al.*, 1980; Richards & Rago, 1999). After a period of low recruitment of age 3–6 fish to the Annapolis River angling fishery during the 1970s (Jessop & Doubleday, 1976), catches of 1–3 kg (age 3–6) fish comprised 35% and 58% of those entered in the Dunromin contest during 1986 and 1987 and these catches were mirrored in the Kennedy family records with 44% of their 1986–1989 landings from this size class. Additionally, the Kennedy family continued to catch small fish at a relatively consistent catch per unit effort up to 1999.

If reproductive failure was the cause of the *M. saxatilis* extirpation in the Annapolis River these younger fish would have disappeared from the angling fishery first. Instead it was catches of older, larger fish which declined rapidly after 1985.

### 9.3 | *Acipenser oxyrinchus*

*Acipenser oxyrinchus* was unknown in the Annapolis River before the tidal turbine began operation (Leim & Scott, 1966; Daborn *et al.*, 1979b; Scott & Scott, 1988). The river, however, had excellent ecological habitat for the species (Dadswell, 2006) and it was not surprising that turbine mortalities began to appear seaward of the turbine immediately after it commenced generation. *Acipenser oxyrinchus* adults are large (1.5–4.0 m; Dadswell, 2006) which puts them at extreme risk during turbine passage. Fish of this length have a potential mechanical strike rate of 47–100% in the Annapolis STRAFLO turbine.

Since 1985, 21 *A. oxyrinchus* mortalities have been found seaward of the turbine. Observed mortalities consisted of two juveniles and 19 adult fish. Twelve of these fish were killed by mechanical strike having been decapitated or severed somewhere in the body. Three of the observed *A. oxyrinchus* were killed by cavitation; the rest were not autopsied or were too decayed to determine the cause of death. The juveniles were probably killed while leaving the river to begin their growth phase at sea (Dadswell, 2006). The adults were killed while returning to the Annapolis to spawn (June–July; Dadswell *et al.*, 2017) or departing the river after spawning (August–October).

*Acipenser oxyrinchus*, like *A. sapidissima*, display strong fidelity to their natal river (Wirgin *et al.*, 2000; Grunwald *et al.*, 2008) and most of the mortalities were large adults returning to spawn. Many of the autopsied females had ripe, stage 5 gonads, males were either spent or had come earlier in the spawning season and their gonads were in stage 4. Autopsied females were 180–203 cm $L_F$ and 26–53 years old, males, 146–168 cm $L_F$ and 22–27 years old; which is similar to the length and age of *A. oxyrinchus* breeding adults captured in the commercial fishery in the Saint John River across the Bay of Fundy from the Annapolis River (Dadswell *et al.*, 2017).

Unfortunately there is little other information available on the Annapolis River *A. oxyrinchus* stock making it impossible to determine if turbine mortality has affected its population characteristics or viability. Since some of the fish were killed while leaving the river after spawning and because *A. oxyrinchus*, like other *Acipenser spp.*, has intermittent spawning (spawn once every 2–5 years; Dadswell, 2006; Dadswell *et al.*, 2017), turbine mortalities may have had less effect on their population than on the other anadromous species in the Annapolis River. On the other hand, since sturgeons are large slow-growing fish with low lifetime fecundity, very low rates of increased mortality, especially on the larger adults, could cause population collapse (Boreman, 1997).

## 10 | CONCLUSION

The effect of a tidal propeller turbine on the three anadromous fish species from the Annapolis River has apparently been to alter the population characteristics of *A. sapidissima*, extirpate *M. saxatilis* and cause increased mortality of *A. oxyrinchus.* If these results can be extrapolated to instream axial-flow, hydraulic lift propeller tidal turbines in the ocean we would expect to see some valuable fisheries altered, some probably decreased in yield and some perhaps extirpated. Also cetaceans or other marine mammals may be adversely affected because with large size they have the highest potential for mechanical strike.

Instream axial-flow hydraulic-lift propeller turbines have the same potential for causing mortalities in the open ocean as the STRAFLO turbine in the Annapolis Estuary because they operate by the same physical laws of hydraulics that cause these turbines to rotate and produce electricity (Hammer *et al.*, 2015; Zangiabadi *et al.*, 2016). We are not discussing other hydrokinetic devices. Although instream propeller turbines are not associated with a barrage or causeway and fishes are thought to have greater probability of avoidance (Viehman & Zydlewski, 2015; Shen *et al.*, 2016; Bevelhimer *et al.*, 2017). The probability of turbine encounter in the open ocean depends on numerous conditions such as the number and distribution of turbines, turbine size, probability of behavioral avoidance, benthic or pelagic species relative to turbine position in the water column, year, month and tidal stage (Shen *et al.*, 2016). In one open ocean location, the probability of fish encountering a single device was estimated to be 0.43 and the probability of only encountering device foils was 0.058, results which can perhaps be scaled up to multiple devices (Shen *et al.*, 2016). Although behavioral avoidance of hydrokinetic structures due to sound generation apparently varies among species evidence indicates it does exist (Shen et al. 2016; Shramm et al. 2017). Unfortunately, plans are to mass the turbines in regions of high power potential (Lewis *et al.*, 2015; Walters *et al.*, 2013) resulting in a large portion of the water column becoming potentially dangerous for fish migration. Also, unlike the Annapolis Estuary turbine, which only generates on ebb tide or *c.* 11 h $day^{-1}$, instream propeller turbines generate on both ebb and flood tide or *c.* 23 h $day^{-1}$ (FORCE, 2017). This mode of operation means that a 16 m diameter propeller turbine in a 5 m $s^{-1}$ tidal flow will pass 45 $km^3$ of sea water during a 12.4 h tide cycle and the fishes and other marine animals therein will be affected by the physical changes and machinery in the draft tube if they pass through it. Potential mortalities may be lower than they are with a barrage turbine (Amaral *et al.*, 2015) but a long-term, cumulative effect is probable. The ocean is already at or past its sustainable yield (Pauly *et al.*, 2002; Shao, 2009) and further depletion of its resources will not improve the situation.

Will the necessary pre-operational and operational studies be undertaken on the effects of instream propeller turbines on marine organisms or will their remoteness in the sea delay or defy detailed scrutiny? A portion of our knowledge about the effects of the Annapolis turbine on the river's fish populations came from volunteers. This was possible because the Annapolis River has a small estuary surrounded by people. In Minas Passage and at other instream turbine sites the pre-operational environment and the effects of test turbines on fishes are being studied (Tollit *et al.*, 2011; Redden *et al.*, 2014; Lewis *et al.*, 2015; Bevelhimer *et al.*, 2017) but the remoteness, depth and properties of the physical environment makes environmental monitoring difficult (Sanderson & Redden, 2015; FORCE, 2017). The effects of instream propeller turbines will be difficult to observe and may not be obvious until too late to reverse. Will they be out of sight and out of mind?

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