Estimating Total Passage Survival For Fish Migrating Downstream At Hydropower Projects

Stephen Amaral, Celeste Fay, and George Hecker
Alden Research Laboratory

Abstract
Fish approaching hydropower projects can pass downstream through turbines, over spillways, or though bypasses specifically designed for safe passage. Unless effective fish guidance or exclusion systems have been installed, turbines are often the primary route of passage for downstream migrants, particularly during periods of low river discharge. Passage through turbines typically results in mortality rates between 5 to 30% depending on turbine design and fish size. Spillways and fish bypasses are generally considered safe routes of passage (> 97% survival). The proportion of downstream migrants using each available route will depend on several factors, but is likely correlated with the amount of flow discharged at each location. For fish approaching a powerhouse, turbine entrainment rates will be determined by the presence of fish guidance or exclusion technologies, including trash rack bar spacing and the location of fish bypasses. By estimating the proportion of fish passing through each route and applying route-specific survival rates, total project downstream passage survival can be calculated for any given site without conducting expensive field studies. This approach uses literature-based estimates for spillway and bypass survival rates and for bypass efficiency. A theoretical model for blade strike probability and mortality is used to estimate turbine passage survival, assuming other injury mechanisms (e.g., pressure and shear) are inconsequential. Using these methods, we estimated total passage survival for Atlantic salmon passing downstream at 15 hydroelectric projects on the Penobscot River in Maine, USA, over the historical range of river discharges that have occurred at each project.

Introduction

Atlantic salmon are a federally-listed endangered species in several rivers in Maine, USA. The National Marine Fisheries Service (NMFS), which oversees the recovery efforts for the listed populations, is in the process of developing a population model to assist with the determination of acceptable levels of incidental "take" of endangered salmon at hydro projects. For anadromous species, juveniles and adults must be able to pass downstream from spawning grounds to the open ocean, and adults must be able to return from the ocean to spawning grounds, both in a safe and timely manner. Atlantic salmon smolts and kelts (post-spawned adults) migrating downstream may be subject to mortality at hydropower facilities due to injuries sustained during passage through turbines and fish bypasses, or over spillways. In addition to direct mortality associated with these passage routes, indirect mortality may result from increased predation rates or reduced fitness associated with the stress of downstream passage and migration delays. Cumulative effects from passage at multiple projects may also lead to increased mortality and reduced fitness during the in-river migration and after fish reach the estuary and marine environment.

A major component of the Atlantic salmon population model that is being developed by NMFS will be estimates of the survival for smolts and kelts passing downstream at each hydropower project. To obtain this information, NMFS contracted Alden Research Laboratory, Inc. (Alden) to estimate downstream passage survival of Atlantic salmon smolts and kelts at 15 hydroelectric projects on the Penobscot River and its tributaries. These desktop survival estimates focus on direct mortality attributable to passage at dams, but indirect and cumulative (delayed) mortality associated with multiple dam passage are also addressed. The primary goal of Alden's analysis was to effectively estimate total project survival of Atlantic salmon smolts and kelts passing downstream at each of the specified hydro projects. To achieve this goal, the study objectives were to estimate the proportion of fish (smolts and kelts) using available downstream passage routes and to estimate direct and indirect survival associated with each route. An established turbine blade strike probability and mortality model was used to estimate direct survival of fish passing through turbines at each project. Survival rates for fish that pass downstream over spillways or through fish bypass facilities was estimated based on existing site-specific data or from studies conducted at other hydro projects with similar species (i.e., anadromous salmonids). The proportion of fish using each available downstream passage route was based on flow distributions and bypass efficiency estimates (either site specific or developed from the literature).

Study Sites

The Penobscot River has a drainage area of 22,196 square km and a mean annual discharge of 402 m^3/s. Basic design information for the 15 hydro projects included in the analysis of downstream fish passage survival is presented in Table 1. The Veazie Project is the first dam on the mainstem, followed by Great Works, Milford, West Enfield, and Mattaceunk. The Stillwater and the Orono projects are located on the Stillwater Branch and the Medway Project is on the West Branch. The remaining seven projects are located on various tributaries. Most of the projects have upstream passage facilities for anadromous species (river herring, American shad, and/or Atlantic salmon), as well as operate downstream bypasses for juvenile and adult outmigrants. Some of the projects have installed narrow-spaced bar racks or overlays to reduce fish entrainment through turbines.

Table 1. Project information for the 15 sites included in the analysis of Atlantic salmon downstream passage survival.

Project	Number of Units	Rated Generation (MW)	Rated Flow (m^3/s)	Rated Head (m)
Veazie	17	3.70	95.2	5.8
Great Works	11	3.46	111.8	5.3
Milford	4	3.20	79.0	5.8
West Enfield	2	6.50	190.5	7.9
Mattaceunk	4	10.81	105.2	11.9
Orono	4	1.63	35.1	7.3
Stillwater	4	1.05	26.6	6.4
Howland	3	0.63	16.1	6.0
Medway	5	1.38	39.1	6.0
Browns Mills	2	0.72	13.4	7.3
Lowell Tannery	1	1.50	27.2	8.2
Moosehead	2	0.20	6.8	3.7
Milo	3	0.24	8.5	4.6
Sebec	2	0.87	22.4	5.2
Frankfort	1	0.40	15.6	4.9

STUDY APPROACH

The overall survival of fish passing downstream at hydropower projects is dependent on a variety of factors associated with available passage routes. Typically, there are three primary routes for fish passage: (1) over spillways and associated structures (e.g., spill or crest gates); (2) through bypasses (which may be designed and installed specifically for fish passage or may be existing ice or debris sluice gates); and (3) through turbines. The proportion of migrating fish passing through each of these routes will depend on project configuration and operation and the resulting hydraulic conditions experienced by fish as they approach a project. For the Penobscot River projects, it is important to note that not all of the sites have all three types of passage routes available at all river discharges. Also, some of the projects do not currently have dedicated downstream fish bypasses. Insufficient flow depth over spillways is assumed to prohibit passage (< 6 inches for smolts and < 12 inches for kelts) via this route, and low river flows may prevent the operation of one or more turbines. Certain levels of injury and mortality are expected to occur for fish passing through each available route, and survival of fish passing over spillways and bypasses is typically expected to be higher than for fish passing through turbines (Muir et al. 2001). Downstream passage survival depends on direct mortality resulting from lethal injuries, indirect mortality associated with increased predation and disease/infection from sub-lethal injuries, and cumulative effects of stress and injury associated with multiple dam passages.

Turbine Passage Survival Estimation

The probability of strike is derived from the distance that blade leading edges move as compared to the total distance between two leading edges in the time it takes a fish to be carried past the arc of leading edge motion. Therefore, the probability of strike is calculated with the following equation (Ploskey and Carlson 2004; Hecker and Allen 2005):

$$P = \frac{nNL \cos\theta}{60 V_{ax}} \tag{1}$$

Where:

P	=	probability of strike (non-dimensional)
n	=	runner rpm
N	=	number of leading edges (blades)
L	=	fish length (m)
θ	=	angle between absolute and axial (or radial) velocity vectors (degrees)
V_{ax} (or V_{rad})	=	axial (or radial) velocity (m/s)

Note that $\cos\theta = \sin\alpha$, where α is the angle between the absolute inflow velocity and a tangent line to the runner circumference. The parameter $L\cos\theta$ (or $L\sin\alpha$) is the projected fish length in the axial (or radial) direction. The wicket gate angle (Francis turbines) and flow angle (Kaplan/propeller turbines) are defined as the angle between the absolute velocity and tangential velocity, α. It was assumed that fish orient along the absolute inflow direction.

Although the physics of blade strike are the same for both radial and axial type turbine runners, the actual methods for calculating the probability of strike varies due to the geometric differences. Flow entering and making contact with the Francis turbine is in a radial direction, whereas flow entering a Kaplan or propeller turbine approaches the wicket gates in a radial direction before making a downward turn toward the runner in the axial direction. Consequently, the methodology used for calculating the various parameters of the strike probability equation differed between the two turbine designs.

Not all fish struck by turbine blades are killed. Therefore, strike probability estimates must be adjusted with a strike mortality coefficient to determine turbine passage survival (assuming little or no mortality occurs due other mechanisms like shear, turbulence, and pressure changes). Strike velocities (relative velocity of fish to blade leading edge) and fish length to blade thickness ratios were used to determine the mortality coefficient, K, based on data from blade strike tests conducted at Alden with rainbow trout and white sturgeon (Hecker et al. 2007; Amaral et al. 2008; EPRI 2008, 2011). Since K represents the probability that fish struck by a turbine blade will be killed, the probability of blade strike is multiplied by K and subtracted from one to estimate turbine passage survival:

$$S_T = 1 - (K)(P) \tag{2}$$

For each unique turbine design, turbine survival estimates were calculated for smolt lengths between 130 to 210 mm in 10 mm increments and kelt lengths from 650 to 800 mm in 25 mm increments. These are the expected length ranges of the two life stages based on biological data specific to the Penobscot River.

Bypass Efficiency and Survival

Downstream bypasses are installed at hydro projects specifically to provide fish with an alternative passage route that is safer than passage through turbines. Bypass efficiency is defined as the proportion of outmigrants that approach a powerhouse intake that are diverted and passed through a bypass. Fish that pass over a project's spillway typically are not included in the estimate of bypass efficiency. For example, if 100 fish approach a project and 40 pass over the spillway, 30 through the bypass, and 30 through the turbines, then bypass efficiency is 50% (number of fish bypassed divided by total number bypassed and entrained through turbines).

Downstream passage studies have been conducted at five of the 15 Penobscot River projects (FERC 2004; USASAC 2005; Fay et al. 2006), but only studies at two of these sites (Mattaceunk and Orono) had sufficient data to provide site-specific estimates of bypass efficiency for smolts, and only data from Mattaceunk was sufficient for kelts. To estimate bypass efficiency at the thirteen projects where studies have not been conducted or data were insufficient, data from studies conducted at Mattaceunk and Orono and from studies conducted primarily with Atlantic smolts and/or kelts at 40 hydro projects located in the U.S. (28) and France (12) were compiled and evaluated (Table 2). Similar to Penobscot River projects, most of the study sites are low head (< 15 m) and all but one of the U.S. projects are located in the Northeast. Most of the tests were conducted at sites with clear bar rack spacing of 37 mm or less (Table 2). Only four sites had bar spacings either less than 25 mm or greater than 37 mm. Consequently, the data were limited for bar spacings outside the 25 to 37 mm range and are considered insufficient to draw any reasonable conclusions on a broader scale. The data from tests with 25-mm bar spacing produced an average bypass efficiency of about 51% with a range of 17 to 100% (Table 2). Based on the analysis of existing data, bypass efficiency estimates were developed by bar spacing and assigned to the projects where studies have not been conducted or data were insufficient (Table 3). Bypass efficiencies for kelts were also based on physical exclusion from turbine entrainment as determined by length and body width data that demonstrated all fish of this life stage are likely too large to pass through racks with clear bar spacings of 63 mm and less.

Table 2. Summary of bypass effectiveness data from studies conducted with Atlantic salmon smolts and juvenile trout at low head hydro projects in the U.S. and France.

Bar Rack Spacing (mm)	Number of Tests	Bypass Efficiency (%)		
		Mean	Min	Max
13	1	81.5	81.5	81.5
25	20	51.3	17.0	100.0
31	7	66.6	32.0	92.5
37	7	52.2	17.0	73.0
50	1	7.0	7.0	7.0
125	7	56.7	24.0	88.0
50/88	1	18.0	18.0	18.0
Unknown	35	57.0	6.0	100.0
Totals	79	55.1	6.0	100.0

Table 3. Intake rack spacing and estimated bypass efficiencies for Atlantic salmon smolts and kelts passing downstream at 15 Penobscot River hydro projects.

Project	Bar Rack Clear Spacing (mm) (upper/lower)	Upper Rack Depth (m)	Kelt Entrainment	Smolt Bypass Efficiency (%)	Kelt Bypass Efficiency (%)
Veazie	25/57	4.6	no	40	70
Great Works	29	--	no	50	100
Milford	88	--	yes	10	25
W.Enfield	25/75	0.6	yes	25	70
Mattaceunk	25/67	4.9	yes	38	70
Orono	25/60	4.3	no	42	100
Stillwater	25/60	4.3	no	40	100
Medway	57	--	no	--	100
Howland	25	--	no	50	100
Brown's Mill	25	--	no	50	100
Lowell Tannery	50	--	no	25	100
Moosehead	37	--	no	--	--
Milo	50	--	no	--	--
Sebec	63	--	no	25	100
Frankfort	82	--	yes	10	25

Bypass survival data have only been collected at one of the fifteen Penobscot River projects (Mattaceunk). These data indicated that immediate survival of smolts passing through the bypass system was 99.8% (GNP 1999). Bypass survival estimates from studies conducted at other river systems in the Northeast ranged from 91 to 100.0% with a mean of about 97% (Table 4). Most of these studies were conducted at projects with head differentials greater than 12 m, whereas the Penobscot River projects have operating heads less than 9 m, with the only exception being Mattaceunk (11.9 m). Bypass survival rates are expected to be higher for lower head projects due to slower discharge velocities. Also, it is evident from the available data that survival may be at or near 100% at higher head projects which have bypass designs and discharge conditions that will minimize injury to fish. Given the high bypass survival observed at Mattaceunk, which is the highest head project in the Penobscot River basin, and the lower heads of the other 14 projects, bypass survival of Atlantic salmon smolts and kelts was assumed to be 99%.

Table 4. Summary of bypass survival data from studies conducted with Atlantic salmon smolts.

Project	Mean Fish Length (mm)	Project Head (m)	Bypass Flow (m^3/s)	Immediate Survival (%)	Total Survival (%)	Delayed Mortality Holding Period (hr)	Reference
Amoskeag	208	14	4.2	100.0	100.0	48	NAI 2006
Bellows Falls	252	18	8.7	96.0	96.0	48	RMC 1991
Garvin Falls	190	9	2.3	100.0	100.0	48	NAI 2005
Lower Saranac	245	23	1.0	--	100.0	72	NAI 1994, 1997
Vernon	156	8	1.1	93.3	93.3	48	NAI 1996
Wilder	212	16	8.5	99.0	91.1	48	RMC 1992
Wilder	212	16	5.7	99.0	97.0	48	RMC 1992
Wilder	212	16	14.2	98.0	97.0	48	RMC 1992

Spillway Survival

Spillways and associated discharge structures (spill, crest, and sluice gates) are common passage routes utilized by downstream migrating fish that encounter hydro power projects. Spill occurs when river discharge exceeds powerhouse capacity, but is often maintained at lower river flows specifically for downstream fish passage or to meet minimum flow requirements. Spillways and dam gates are typically considered a safe route of egress that can reduce the number of outmigrants passing through turbines, where the potential for injury and mortality is usually greater. Regulatory and resource agencies in the U.S. generally consider spillways as acceptable passage routes for downstream migrating fish. However, because fish passing over spillways or through dam gates can suffer injury and mortality (Bell and DeLacy 1972; Ferguson 1992; Heisey et al. 1996), many studies have been conducted to quantify injury and mortality associated with spillway passage. Most of these studies have focused on juvenile salmon passing downstream at Columbia and Snake River projects in the U.S. (Whitney et al. 1997; Muir et al. 2001; Ferguson et al. 2005). Fewer spillway survival studies have been conducted with Atlantic salmon smolts, and very little information is available for kelts of any species.

A summary of data from 136 tests conducted at Columbia River projects produced a mean spillway passage survival rate of 97.1% for juvenile salmonids, with a range of 76.2 to 100.0% (Table 5). Also, sluice gate passage survival rates reported for Atlantic salmon smolts at six projects in the Northeast averaged 96.8 for total survival (48-hr). The Penobscot River projects have lower heads and typically experience less spillway discharge than many of the sites where spillway and sluice gate studies have been conducted, suggesting that passage conditions would be less injurious on the Penobscot River. In general, lower head projects are expected to provide safe passage over spillways due to lower velocities leading to less damaging impact with water surfaces and solid structures, as well as less severe shear and turbulence levels. Applying a spillway survival rate to Penobscot River projects that was approximately equivalent to the average of rates reported from past studies was considered a prudent and reasonable. Consequently, a direct spillway survival rate of 97% was used in the calculations of total survival for smolts and kelts passing downstream at each of the Penobscot River projects.

Table 5. Summary of spillway survival data from studies conducted with juvenile salmonids (primarily Chinook salmon) at Columbia River projects.

Project	Tests	Head (m)		Spill/Gate Flow (cfs)		Average Survival (%)	Min Survival (%)	Max Survival (%)
		Min	Max	Min	Max			
Bonneville	10	15.2	19.8	116.0	339.6	97.1 (88.6-100.0)	88.6	100.0
Ice Harbor	23	28.0	30.5	96.2	384.9	97.6 (90.1-100.0)	90.1	100.0
Little Goose	18	28.7	29.9	50.9	362.2	98.8 (95.3-100.0)	95.3	100.0
Lower Granite	4	29.6	30.8	96.2	198.1	98.3 (97.5-100.0)	97.5	100.0
Lower Monumental	4	29.6	29.6	240.6	240.6	97.7 (94.9-100.0)	94.9	100.0
North Fork (OR)	8	41.1	41.1	19.8	56.6	87.0 (76.2-99.9)	76.2	99.9
Rock Island	8	11.9	14.9	53.8	283.0	98.7 (95.1-100.0)	95.1	100.0
The Dalles	44	22.6	25.6	127.4	594.3	97.5 (85.1-100.0)	85.1	100.0
Wanapum	17	21.6	25.0	56.6	353.8	97.5 (92.0-100.0)	92.0	100.0
All Projects	**136**	**11.9**	**41.1**	**19.8**	**594.3**	**97.1 (76.2-100.0)**	**76.2**	**100.0**

Indirect Survival

In addition to direct mortality, which represents smolt and kelt losses resulting from lethal injuries suffered during passage over spillways and through bypasses and turbines, indirect mortality may occur due to sub-lethal injuries, increased stress, predation, and/or disorientation. Indirect mortality resulting from passage at hydro projects can be difficult to isolate and estimate because it typically occurs over longer time frames and greater distances. A large portion of indirect mortality may involve predation on disoriented fish exiting turbines, bypasses, or spillways (Mesa 1994; Ward et al. 1995; Ferguson et al. 2006), whereas other fish may experience mortality much further downstream due to secondary effects related to disease, infection, and overall reduced-fitness. Indirect mortality has been examined in depth on the Columbia River, primarily for salmon smolts and juveniles. Fewer studies of indirect mortality suffered by juvenile salmonids have been conducted on smaller river basins similar in size to the Penobscot, but some studies have reported heavy predation by birds and/or piscivorous fishes on Atlantic salmon smolts that may be linked to passage through hydropower impoundments and tailraces (Blackwell and Juanes 1998; Jepsen et al. 1998; Aarestrup 1999; Koed et al. 2002).

From an analysis of 33 survival studies conducted at Columbia River projects, Bickford and Skalski (2000) reported an average direct turbine survival rate of 0.933 and an average total survival rate of 0.873. These data indicated indirect survival was 0.936 (0.873/0.933). Muir et al. (1996) examined balloon tag (direct survival) and PIT tag (total survival) data from studies conducted with chinook salmon that were released at the same location in a turbine intake at Lower Granite Dam. They reported direct and total survival rates of 0.940 and 0.927, respectively, indicating that the indirect survival for turbine-passed fish was 0.986. Ferguson et al. (2006) also found evidence of indirect mortality when comparing relative survival rates of PIT and radio-tagged juvenile salmon to direct survival rates of balloon-tagged fish released into turbine intakes at McNary Dam and recovered in the tailrace. Based on their analysis, Ferguson et al. (2006) concluded that indirect mortality accounted for about 45 to 70% of total mortality for fish that traveled 15 to 46 km downstream of the dam. Total relative survival estimates reported in this study ranged from 0.814 to 0.871 and direct survival rates ranged from 0.930 to 0.946. When matched to the turbine flow tested with each tagged fish release, the resulting range of indirect survival rates for this study 0.860 to 0.937. Combining the results of these three studies produces an average indirect (delayed) survival rate of 0.930 (Table 6).

The smaller impoundments and lower heads of Penobscot River projects compared to those on the Columbia River are expected to result in less indirect mortality of smolts and kelts that can be attributed to passage at a single dam. Predation in impoundments and tailraces and below spillways and bypass outfalls is expected to be the primary source of indirect mortality at each project, with the effect of sub-lethal injuries, scale loss, and stress having more influence on cumulative indirect survival rates associated with multiple dam passages. Although information from studies conducted on the Columbia River indicate that indirect mortality may be less for fish passing over spillways and through bypass systems (Bickford and Skalski 2000; Muir et al. 2001), it is not clear if this would also be the case for Atlantic salmon smolts and kelts at Penobscot River projects. Based on the available information, it was assumed for the calculation of total project survival that indirect mortality for a single dam passage by smolts and kelts is 0.95 for each available passage route (spillway, bypass, and turbines) at each of the 15 projects.

Table 6. Total and direct survival rates reported for turbine-passed fish evaluated at dam on the Columbia River and indirect survival rates calculated for set of data (i.e., total survival divided by direct survival).

Study	Total Survival	Direct Survival	Indirect Survival
Bickford and Skalski (2000)	0.873	0.933	0.936
Muir et al. (1996)	0.927	0.940	0.986
Ferguson et al. (2006)	0.814	0.946	0.860
Ferguson et al. (2006)	0.871	0.930	0.937
Average	**0.871**	**0.947**	**0.930**

Assignment of Flow and Fish to Available Passage Routes

Total passage survival of smolts and kelts moving downstream at each Penobscot River project is dependent on the proportion of fish passing through each available route (spillways, bypasses, and turbines) and the corresponding survival rates for these routes (as discussed above). The flow and fish distributions are a function of total river flow. As long as crest depth is sufficient to allow passage, the number of fish passing over spillways and approaching a powerhouse is assumed to be proportional to discharge. For fish approaching a powerhouse, turbine entrainment is based on trash rack bar spacing and the estimated efficiency of available bypasses.

For any given river flow, the distribution of flow among available discharge locations was assigned using the following sequence: (1) bypass flow (fixed flow rate based on requirement for downstream passage); (2) powerhouse flow (based on operation of one or more units at partial or full load); and (3) spillway flow (flow depth of spillway crests must exceed 6 inches for smolt passage and 12 inches for kelt passage). The proportion of fish passing through each discharge location (spillway, bypass, turbines) was determined primarily by the proportion of flow passed over the spillway and approaching the powerhouse. The number of fish passing over the spillway is assumed to be proportional to flow. The number of fish approaching the powerhouse is also proportional to flow (bypass and turbine flow combined), but other factors determine what proportion of these fish are either bypassed or entrained through a project's turbines (i.e., bypass efficiency and bar rack spacing, as discussed previously).

Fish approaching a powerhouse that are not bypassed are assumed to be entrained through powerhouse turbines (i.e., entrainment = 1- bypass efficiency). However, for projects with bar rack spacings less than 2.5 inches, it was assumed that all kelts would be large enough to be physically excluded from turbine entrainment, resulting in a bypass efficiency of 100%. The distribution of entrained fish passed through individual turbines was assumed to be proportional to the amount of the total generating flow passed through each unit. Turbine flow and subsequent proportions of total generating flow through each operating unit will vary as a function of the total river flow, but will be constant when the flow capacity of all turbines is reached.

Three of the Penobscot River projects (Moosehead, Milo, and Medway) do not operate downstream bypasses for Atlantic salmon smolts and kelts and have bar racks with spacing less than 63 mm. Consequently, at river flows that result in spill with less than 30 cm of depth over the dam crests at each project, there is no available downstream passage route for kelts (i.e., no bypass, complete exclusion from turbine entrainment due to narrow bar spacing, and insufficient spill depth for passage). In these situations, it was assumed that kelt survival was 0%. Lack of a downstream passage route for kelts has the potential to occur during the spring and fall migration periods at Moosehead and Milo, but only in the spring at Medway due to the operation of a downstream bypass for American eel in the fall which can be used by kelts.

Development of Flow Probability Distributions

In order to estimate survival probabilities for each project over the expected range of river flows for the specified migration periods of each life stage, the probability of occurrence for average monthly flows must be known. That is, the probability that any given survival rate will occur is equivalent to the probability of the corresponding flow to occur. Consequently, using historical gaging station data, flow probability distributions were developed for the average monthly flows of May for smolts and April, May, and November for kelts. The estimation of flow probabilities required that an appropriate distribution be identified and applied to the data for each site. Daily flow values are typically skewed to the right and are approximated by a log-normal distribution. The central limit theorem states that regardless of the sampling distribution, the distribution of the sample mean approaches a normal distribution as sample size approaches infinity (Bickel and Doksum 1977). Thus for an intermediate sample size mean, such as a monthly mean, the distribution is likely to be intermediate to the log-normal and the normal distributions. A power transformation was proposed by Box and Cox (1964) that covers a continuous family of distributions between the normal and the log normal and yields an approximately normal random variable. Using these statistical techniques with the available historical flow data for each project, flow probability distributions were generated for each project.

Total Project Survival

Based on the methods described previously for estimating route-specific survival rates and determining the proportion of fish passing through each route based on river flow and turbine operations, the calculation of total project survival (S_{TP}) can be summarized for a given fish length as follows:

$$S_{TP} = [(P_{SW} \times S_{SW}) \times (P_{BYP} \times S_{BYP}) \times (P_T \times S_T)] \times S_I \quad (3)$$

where:

P_{SW} = proportion of fish passing over the spillway;

S_{SW} = literature-based estimate of direct survival for fish passing over the spillway (0.97 for all projects);

P_{BYP} = proportion of fish passing through the bypass (assigned value based on life stage, bar rack spacing, and site-specific studies or literature-based data; Table 2);

S_{BYP} = literature-based estimate of survival for fish passing through the bypass (0.99 for all projects);

P_T = proportion of fish passing through operating turbines;

S_T = estimated survival rate of fish passing through operating turbines;

S_I = literature-based estimate of indirect (delayed) survival (0.95) assigned to all passage routes.

Total passage survival rates were calculated at increments of 0.14 m^3/s for the flow probability distributions developed for each site. Turbine passage survival rates (S_T) were estimated for specified length intervals covering the expected size ranges provided by NMFS for smolts and kelts in the Penobscot River. Frequency probabilities provided by NMFS for each length interval were multiplied by corresponding project survival rates and summed across intervals to provide a total passage survival rate for all lengths combined. Although turbine survival is length-specific, it was assumed that direct survival over spillways and through bypasses does not vary with length or life stage.

At lower flows when there is no spill, the operation of turbines usually had the greatest influence on total survival rates because entrainment increases as more units come on line and turbine survival rates fluctuate with partial and full load operation. As flow increases and spill begins to occur, total survival rates typically increase gradually as a greater proportion of fish avoid turbine entrainment and pass over spillways, for which survival is typically higher. The flow probability distributions developed for each site basically determine the probability that any given total project survival rate will occur. With respect to turbine entrainment and survival, and as described previously, some assumptions were made with regard to turbine operation, including the order of unit operation, the distribution of flows to individual turbines, and operating ranges. Therefore, turbine entrainment and survival fluctuate with flow and the operation of available units. The influence of turbine survival on total project survival will be greatest when there is no spill and will decrease with increasing river flow after sufficient spill becomes available for fish to pass over a spillway.

RESULTS

Total passage survival rates were successfully calculated across the expected flow ranges for smolts and kelts migrating downstream at each of the 15 Penobscot River projects. Mean, minimum, and maximum survival rates estimated for both life stages by month are presented in Table 7. Mean smolt survival rates ranged from 0.857 to 0.925 for smolts and 0.447 to 0.937. Total project survival for kelts was typically higher than it was for smolts at projects where bar rack spacing was sufficiently narrow (< 63 mm) to completely exclude kelts from turbine entrainment. Also, even at the sites where bar spacing was large enough for kelts to be entrained through turbines, bypass efficiencies were set higher for kelts than for smolts due to greater swimming ability and reluctance of the larger fish to pass through intake rack structures. At Medway, Moosehead, and Milo, minimum kelt survival rates reached 0% during at least one month when there was no viable outlet for passing downstream (i.e., no spill, no fish bypass, and complete exclusion from turbine entrainment).

Flow and survival probabilities were plotted by life stage for each project to demonstrate the relationship between the two parameters (see Figures 1 and 2 for example distributions for smolts and kelts, respectively). In general, total project survival rates for smolts fluctuate at lower river flows as turbines are brought on line and alternate between partial and full load. Smolt survival rates level off after river flows are high enough to allow all turbines to be operated at full load and there is sufficient spill depth for downstream migrants to pass over the spillway. At sites where kelts were completely excluded from turbine entrainment by narrow bar rack spacing, total project survival rates did not vary considerably across the range of expected flows for each month. For these sites, the highest kelt survival rates were observed at the lowest flows when all or most fish were passing through the bypass (i.e., downstream route with highest survival rate).

Table 7. Mean, minimum, and maximum total project survival for smolts and kelts passing downstream at 15 Penobscot River projects. Survival rates were calculated for the range of average monthly river flows estimated from probability distributions developed for each site. The months listed represent the primary migration periods for the two life stages.

	Smolt Survival	Kelt Survival		
Project	**May**	**April**	**May**	**November**
Veazie	0.897 (0.827 - 0.913)	0.928 (0.926 - 0.932)	0.932 (0.927 - 0.941)	0.929 (0.924 - 0.941)
Great Works	0.857 (0.777 - 0.893)	0.930 (0.925 - 0.941)	0.930 (0.925 - 0.941)	0.933 (0.927 - 0.941)
Milford	0.917 (0.903 - 0.920)	0.862 (0.693 - 0.893)	0.847 (0.693 - 0.895)	0.818 (0.658 - 0.884)
West Enfield	0.925 (0.923 - 0.936)	0.910 (0.902 - 0.916)	0.910 (0.902 - 0.916)	0.908 (0.902 - 0.941)
Mattaceunk	0.860 (0.772 - 0.898)	0.827 (0.758 - 0.877)	0.852 (0.758 - 0.895)	0.853 (0.758 - 0.896)
Orono	0.894 (0.809 - 0.912)	0.925 (0.923 - 0.933)	0.927 (0.923 - 0.941)	0.929 (0.924 - 0.941)
Stillwater	0.918 (0.881 - 0.921)	0.926 (0.923 - 0.941)	0.927 (0.923 - 0.941)	0.930 (0.924 - 0.941)
Medway	0.912 (0.884 - 0.919)	0.609 (0.000 - 0.922)	0.856 (0.000 - 0.922)	0.932 (0.927 - 0.941)
Howland	0.915 (0.896 - 0.927)	0.926 (0.923 - 0.941)	0.928 (0.923 - 0.941)	0.929 (0.924 - 0.941)
Brown's Mill	0.865 (0.615 - 0.918)	0.927 (0.924 - 0.941)	0.929 (0.924 - 0.941)	0.931 (0.924 - 0.941)
Lowell Tannery	0.887 (0.847 - 0.949)	0.933 (0.927 - 0.941)	0.934 (0.928 - 0.941)	0.937 (0.930 - 0.941)
Moosehead	0.880 (0.686 - 0.910)	0.922 (0.922 - 0.922)	0.926 (0.923 - 0.941)	0.763 (0.000 - 0.922)
Milo	0.890 (0.852 - 0.909)	0.542 (0.000 - 0.922)	0.591 (0.000 - 0.922)	0.447 (0.000 - 0.922)
Sebec	0.887 (0.834 - 0.909)	0.933 (0.926 - 0.941)	0.932 (0.925 - 0.941)	0.934 (0.927 - 0.941)
Frankfort	0.920 (0.908 - 0.944)	0.740 (0.535 - 0.908)	0.709 (0.535 - 0.941)	0.724 (0.535 - 0.941)

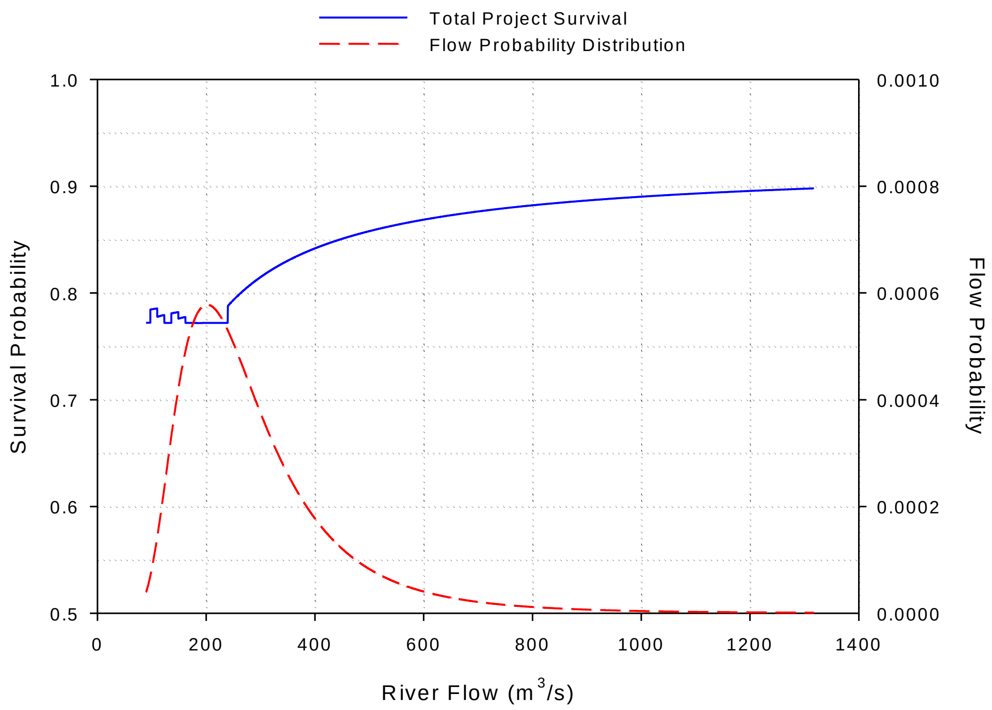

Figure 1. Total project survival for smolts and the probability distribution of average monthly flow for May at one of the 15 Penobscot River Projects. Flow probabilities were estimated and plotted in 0.14 m^3/s increments.

SUMMARY

An effective method for estimating total downstream passage survival at hydropower projects was developed and successfully applied to Atlantic salmon smolts and kelts encountering dams on the Penobscot River in Maine, USA. The study approach included theoretical estimates of turbine passage survival and literature-based estimates of bypass and spillway survival for the range of river flows expected to occur at each project during the migration periods of both life stages. These estimates also accounted for fish passing through every turbine at the 15 projects under partial and full load operation as river flows changed. Additionally, the turbine survival estimates covered the range of expected fish lengths (in 10-mm increments for smolts and 25-mm increments for kelts) and the proportion of fish in each size interval was incorporated into the total survival model based on actual measurements of fish lengths from field sampling. The results of the survival analysis provided data in a level of detail that would have been extremely expensive and difficult to accomplish with field studies. Typically, turbine passage survival studies conducted in the field only evaluate one or two turbines operating at one or two gate settings (i.e., flow rates), and additional field studies would be needed to provide information on the proportion of fish using each passage route and their associated survival rates.

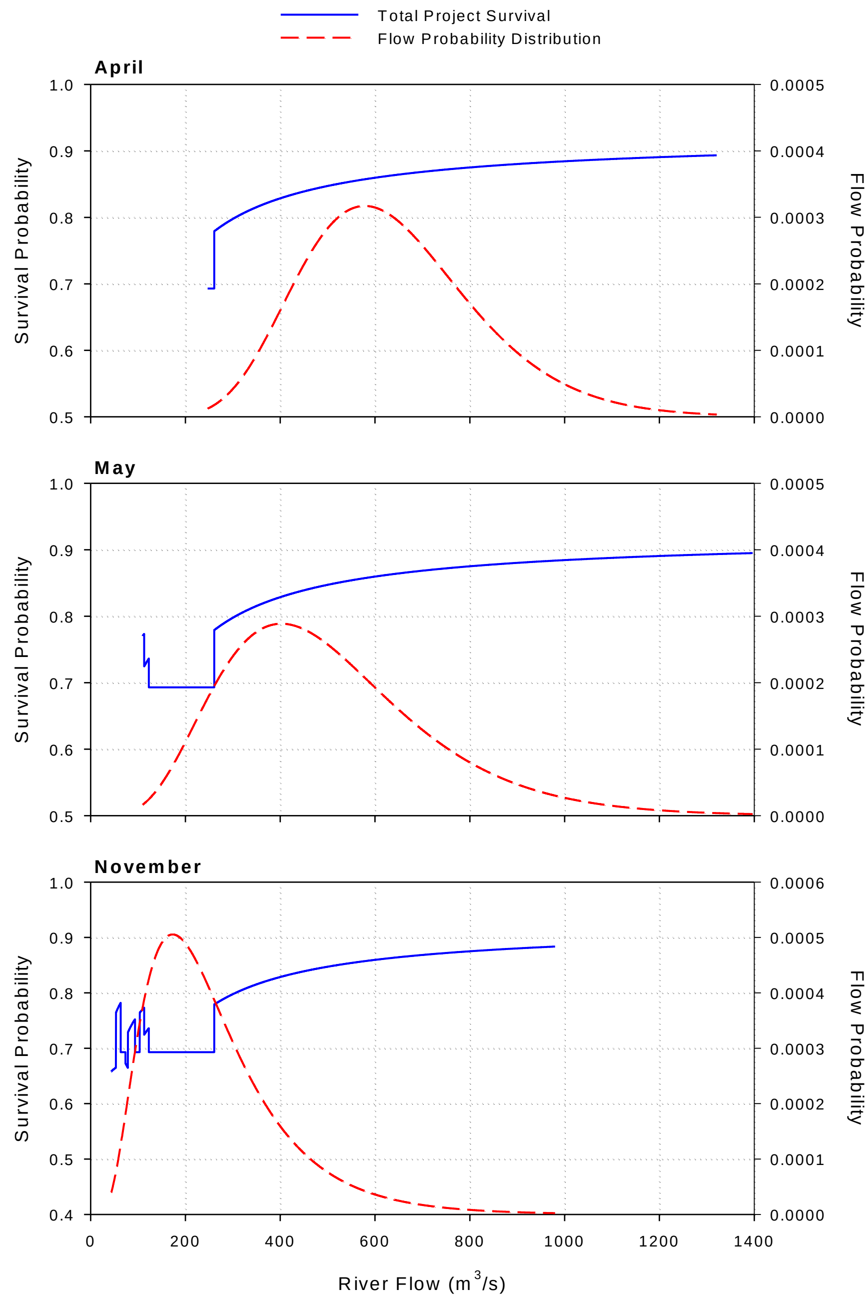

Figure 2. Total project survival for kelts and the probability distributions of average monthly flows in April, May, and November at one of the Penobscot River hydro projects. Flow probabilities were estimated and plotted in 0.14 m^3/s increments.

The methods and model developed for Atlantic salmon on the Penobscot River are transferable to other river systems and species. The theoretical model for predicting strike probability is applicable to most species and the blade strike mortality data for rainbow trout are considered representative of many other species. Although bypass and spillway passage and survival data collected for salmonids may be representative of other species (e.g., shads, herrings, and some freshwater species), a review of existing literature may be required to obtain data more relevant to downstream passage of non-salmonid species in the U.S and other parts of the world.

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