# Introduction

Fish are entrained through hydroelectric facilities where they are exposed to turbine mortality stressors. While mortality and entrainment rates are well studied phenomenon on their own, their cumulative effects on fish populations are not. Unfortunately, we do not know the necessary parameters to accurately model the fate of all impacted species, yet we are routinely required to assess the cumulative population level effects of those impacted. A new approach besides population modeling is needed to assess cumulative system wide effects.

Risk analysis offers a potential solution. An entrainment risk assessment will identify and analyze potential future entrainment mortality events while making judgements on the resiliency of the population, i.e., its ability to tolerate the expected level of mortality. Applying a risk assessment framework to evaluate impacts to fisheries is not new. (Patrick, et al., 2009) developed the expanded productivity and susceptibility assessment (ePSA) to understand data-poor stocks. The ePSA assesses the risk of a pelagic fish stock becoming overfished as a function of its productivity (replenish rate) and susceptibility to the fishery. The ePSA incorporates demographic parameters like the maximum age and size of a fish, individual growth rates, natural mortality, fecundity, breeding strategy, recruitment pattern and age at maturity. The ePSA has been widely used to assess fishing risks for other species including elasmobranchs (Cortés, et al., 2010) and (Furlong-Estrada, Galván-Magaña, & Tovar-Ávila, 2017) and grouper (Pontón-Cevallos, et al., 2020). In 2021, (van Treeck, Radinger, Noble, Geiger, & Wolter, 2021) developed the European Fish Hazard Index to assess entrainment risk at hydropower projects. Their tool considered plant design and operation, the sensitivity and mortality of species to entrainment, and overarching conservation goals for the river. They assessed entrainment mortality with empirically derived functions for Kaplan and Francis turbines.

The United States has seen development of entrainment risk assessment methods as well. In 2012, Cada and Schweizer developed the traits-based assessment to assess the entrainment risk of data-poor species. This qualitative risk assessment …. However, qualitative methods that rely on expert opinion are not repeatable and lack transparency.

The analysis employed to assess entrainment risk at Rye projects … is quantitative. Mortality through hydroelectric turbines has been well studied, with mathematical models able to predict the probability fish will get struck by a turbine blade as they pass through (cite von raben, franke et al, etc), which have been backed up with years of empirical evidence (cite turbine mortality studies). The rate at which fish are entrained (fish per M ft3) through hydroelectric facilities is also a well-studied phenomenon, with over XX studies contributing to an entrainment database compiled by the Electric Power Research Institute (EPRI 1997). The EPRI 1997 contains XXXX observations of XX species at XXX facilities in XX states throughout the eastern United States.

# Methods

An Entrainment Risk Assessment has 2 major components

## Entrainment Mortality Event Simulation

Kleinschmidt simulated entrainment mortality events with the open-source software package stryke[[1]](#footnote-1). Stryke is an individual based model (IBM), which follows the fate of a population of fish as they migrate past a hydroelectric project. Movement and survival are simulated with Monte Carlo methods. The software is written in Python 3.7.x and utilizes Networkx[[2]](#footnote-2) to simulate routes of passage and Numpy[[3]](#footnote-3) for pseudo-random probability distribution draws. Kleinschmidt has validated stryke with the USFWS Turbine Blade Strike Model or TBSM[[4]](#footnote-4). Lastly, stryke is scalable; it is possible to model complex movement through multiple facilities and incorporate effects of migratory delay.

Fish move through a hydroelectric project where migratory routes are described with a network. Simulated fish are obligated downstream migrants. If fish survive their current node, they can move to the next one. If there is more than one node available at their current location, then Monte-Carlo role of the dice and *a priori* determined transition probabilities control their movement. The simulation ends for a fish when it arrives at the last node in the migratory network or dies.

For fish passing via entrainment, individuals are exposed to turbine strike, which is modeled with the Franke et. al. (1997) equations. For fish that pass via passage structures or spill, mortality is assessed with a roll of the dice using survival metrics determined *a priori*, sourced from similar studies, or from expert opinion. The Franke et al. (1997) equations calculate the probability a fish of a given length will get struck by a turbine runner blade. With these equations, if we know how long a given fish is, the velocity of the water as it travels through the turbine, the type of turbine, how many blades and how fast it is rotating, we can calculate, with certainty, the probability of being struck. Therefore, the only morphometric parameter one needs to assess blade strike is length, all other parameters are sourced from technical drawings of the facility.

### Turbine Parameters

The blade strike models derived by Franke et al. (1997) require accurate measurements of a suite of turbine parameters. The Project has three axial flow fixed blade propeller turbines of similar design (U1-U3) and a smaller unit for min flow releases (U4). Required inputs for the blade strike model include: rated turbine head (ft), estimated maximum discharge (cfs), discharge at maximum efficiency (cfs), percent discharge at maximum efficiency, runner speed (rotations per minute, rpm), runner diameter (ft), runner diameter (ft), number of blades, and turbine efficiency (nameplate). These parameters were used to develop an initial blade strike model at units 1-3 and unit 4 (Table 2‑1) for the range of fish lengths found at Cornell.

Table 2‑1 Cornell Kaplan Unit Parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Units** | **U1-U3** | **U4** |
| Rated Turbine Head |  | ft | 37 | 37 |
| Max. Discharge |  | cfs | 3750 | 400 |
| Efficient Discharge |  | cfs | 2625 | 360 |
| Percent Discharge at Max. Efficiency |  |  | 70% | 90% |
| Runner Speed |  | RPM | 100 | 450 |
| Runner Diameter |  | ft | 15 | 4 |
| Number of Blades |  |  | 5 | 5 |
| Turbine Efficiency |  |  | 0.9 | 0.714 |

### Migratory Routes and Movement

The Cornell project is a traditional hydroelectric facility, where both obligate and opportunistic downstream migrants risk entrainment as they move downstream. Fish moving downstream start in the forebay where they can either be entrained or pass via spill. Survival is assessed at every node. If a fish survives the passage state, they transition to the tailrace. However, this assessment was simplified. Since we are only concerned with unit entrainment stressors and not whole project survival for the purposes of this assessment, we routed 100% of the fish through the units. This allows us to understand potential impact among a range of fish lengths.

### Node Survival

Stryke assesses survival for individual fish at each node within the migratory network. For the forebay and tailrace nodes, the survival probability was assumed to be 1.0. Since we are not concerned with effects of migratory delay, like we would with an obligated anadromous fish (e.g., juvenile alosine), we do not need to model natural mortality (e.g., predation). During times of high discharge, fish may spill over the dam. However, the effects of spill were not modeled for this assessment as 100% of the fish were routed through the unit. When a fish is entrained, survival at a turbine is assessed with the Franke et al. (1997) equations for Propeller runners. The first step calculated the energy coefficient and is given with Equation 1:

|  |  |
| --- | --- |
|  | 1 |

where is the energy coefficient, is the acceleration due to gravity (), is the turbine net head (ft, is the rotational speed of the runner (, and is the diameter of the runner (ft). Next, we calculate the discharge coefficient ( with Equation 2:

|  |  |
| --- | --- |
|  | 2 |

where is the diameter (ft) of the runner cubed. The relative flow angle () is given with Equation 3:

|  |  |
| --- | --- |
|  | 3 |

where is the turbine discharge at best efficiency () and is the radius ratio, or where along the radius of the turbine runner struck the fish. Stryke simulates the radius ratio with a draw from a uniform probability between 0.3 and 1.0. Then, we calculated the angle of absolute flow to axis of the rotation with Equation 4:

|  |  |
| --- | --- |
|  | 4 |

Finally, the probability of mortality from blade strike is given with Equation 5:

|  |  |
| --- | --- |
|  | 5 |

Where is a strike mortality correlation factor, is the number of blades, and is the length of the fish (ft). A correlation factor (λ) was utilized in the Advanced Hydro Turbine (Franke et al. 1997) model to adjust the predictive model results to correspond with documented empirical results. This correlation factor was originally introduced by Von Raben (cited by Bell 1981) because the contact of a fish with a turbine component does not always result in injury or mortality (Bell 1981; Cada 1998). Therefore, Von Raben introduced the correlation factor to adjust the predicted turbine strike results to more closely match empirical results. This factor also extends the applicability of these predictive equations to all injury mechanisms related to the variable NL/D (see above for definition of parameters). As stated in Franke et al. (1997) "*such mechanisms could include mechanical mechanisms leading edge strike and gap grinding as well as fluid induced mechanisms related to flow through gaps or other flow phenomena associated with blades.*" Based on a substantial number of test results obtained from studies conducted with salmonids on the west coast, Franke et al. (1997) recommends that the correlation factor be set between 0.1 to 0.2.

### Entrainment Rate and Length Data

### Model Validation

Validation with a known standard is a critical step for any simulation-based predictive model such as stryke. Kleinschmidt validated our approach against the Turbine Blade Strike Model (TBSM) developed by the USFWS. To validate stryke with TBSM, we routed 100% of 1000 simulated fish (mean length = 20 inches, st. dev. = 2 inches) through unit 1, 50 times . We then described each iteration, where the overall probability of entrainment survival is the number of successes (survival) divided by the total number entrainment events. This resulted in two beta distributions of entrainment survival; one for the TBSM (n = 50) and the other stryke (n = 50). These distributions were then compared with a two-sided Kolmogorov-Smirnov test, which has a null hypothesis that each distribution was drawn from the same continuous distribution. Acceptance of the null hypothesis means stryke is validated with the TBSM standard, thus simulations at remaining flow and fish length scenarios should be considered valid.

## Vulnerability to Entrainment

## Scenarios

# Results

## Updated Simulation Results

Generally, as fish length increases, survival decreases. Figure 3‑1 displays the results of a simulation of an arbitrary species, where total length was incrementally increased (1 to 50 inches). A 1-inch fish has a nearly 100% chance of survival, while a 50-inch fish has around a 70% chance of survival. Survival at best gate for Propeller units decreases linearly with an increase in length.

Chart, scatter chart

Description automatically generated

Figure 3‑1 Arbitrary Species Simulation

We then calculated median turbine passage survival at the Cornell Project for our species of interest. The mean length and standard deviation within each size class was calculated from a WIDNR electrofishing dataset. As depicted in Table 3-1 and Table 3-2, median survival rates decrease as length increases for all species. The largest size classes of muskellunge and lake sturgeon experienced the lowest survival rates of 71% each. Smaller size classes of these two species experience 88-89% survival. The larger size classes are excluded in the 2.5 inch trash rack spacing scenario. Thus, survival is 100% for these size classes in these scenarios, as the larger fish cannot be entrained. Survival rates were at least 86% for large walleye and redhorse size classes, and are 95-96% for fish in the 0-10 inch size class (Table 3‑1, Table 3‑2).

Table 3‑1 Turbine Blade Strike Survival Estimates for Target Fish Species with 5.38-in. Trash Racks

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Species** | **Mean Length** | **St. Dev. Length** | **Median Turbine Survival** | **Standard Deviation** |
| **Muskellunge** |  |  |  |  |
| Muskellunge: 10-25 inches | 18.6 | 4.7 | 0.88 | 0.01 |
| Muskellunge: 26-35 inches | 31.2 | 2.5 | 0.81 | 0.01 |
| Muskellunge: 36-45 inches | 39.8 | 2.8 | 0.75 | 0.01 |
| Muskellunge: > 45 inches | 47.3 | 2.5 | 0.71 | 0.02 |
| **Lake Sturgeon** |  |  |  |  |
| Lake Sturgeon: 11-20 inches | 17.5 | 2.3 | 0.89 | 0.01 |
| Lake Sturgeon: 21-30 inches | 26.7 | 2.3 | 0.83 | 0.01 |
| Lake Sturgeon: 31-40 inches | 36 | 2.9 | 0.78 | 0.01 |
| Lake Sturgeon: > 40 inches | 46.3 | 2.1 | 0.71 | 0.02 |
| **Walleye** |  |  |  |  |
| Walleye: 0-10 inches | 8.21 | 1.48 | 0.95 | 0.01 |
| Walleye: 11-20 inches | 15.4 | 2.4 | 0.91 | 0.01 |
| Walleye: > 20 inches | 22.8 | 2.1 | 0.86 | 0.01 |
| **Redhorse** |  |  |  |  |
| Redhorse: 0-10 inches | 7.1 | 1.5 | 0.96 | 0.01 |
| Redhorse: 11-20 inches | 16.5 | 2.1 | 0.90 | 0.01 |
| Redhorse: > 20 inches | 21.9 | 1.4 | 0.86 | 0.01 |

Table 3‑2 Turbine Blade Strike Survival Estimates for Target Fish Species with 2.5-in. Trash Racks

| **Species** | **Mean Length** | **St. Dev. Length** | **Median Turbine Survival** | **Standard Deviation** |
| --- | --- | --- | --- | --- |
| **Muskellunge** |  |  |  |  |
| Muskellunge: 10-25 inches | 18.6 | 4.7 | 0.89 | 0.01 |
| Muskellunge: 26-35 inches | 31.2 | 2.5 | 0.81 | 0.01 |
| Muskellunge: 36-45 inches |  |  |  |  |
| Muskellunge: > 45 inches |  |  |  |  |
| **Lake Sturgeon** |  |  |  |  |
| Lake Sturgeon: 11-20 inches | 17.5 | 2.3 | 0.89 | 0.01 |
| Lake Sturgeon: 21-30 inches | 26.7 | 2.3 | 0.83 | 0.01 |
| Lake Sturgeon: 31-40 inches |  |  |  |  |
| Lake Sturgeon: > 40 inches |  |  |  |  |
| **Walleye** |  |  |  |  |
| Walleye: 0-10 inches | 8.21 | 1.48 | 0.95 | 0.01 |
| Walleye: 11-20 inches | 15.4 | 2.4 | 0.90 | 0.01 |
| Walleye: > 20 inches |  |  |  |  |
| **Redhorse** |  |  |  |  |
| Redhorse: 0-10 inches | 7.1 | 1.5 | 0.96 | 0.01 |
| Redhorse: 11-20 inches | 16.5 | 2.1 | 0.90 | 0.01 |
| Redhorse: > 20 inches |  |  |  |  |

## Validation with TBSM

Stryke was well validated with the TBSM. The mean and variance of the 50 stryke simulations was 0.876 and 0.0001 respectively, while the 50 TBSM runs produced a mean of 0.88 and variance of 0.000008. Both models had low variance and nearly identical survival estimates. However, the shapes of the distributions varied. Figure 3‑2 shows a beta distribution of stryke simulations while Figure 3‑3 shows the TBSM. Note, the TBSM had a much stronger central tendency. That being said, the KS was not significant (p = 0.06), both distributions were drawn from the same beta distribution.

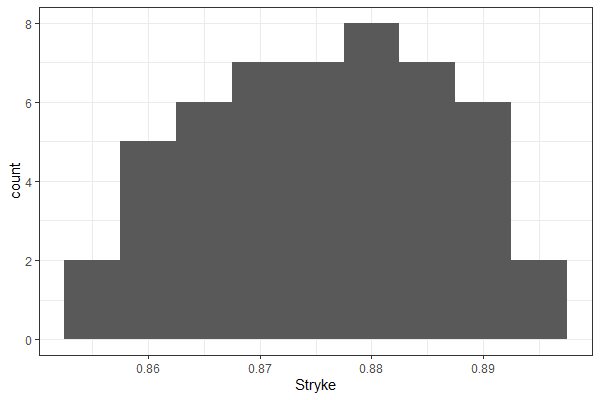


Figure 3‑2 Beta Distribution Of Stryke Simulations

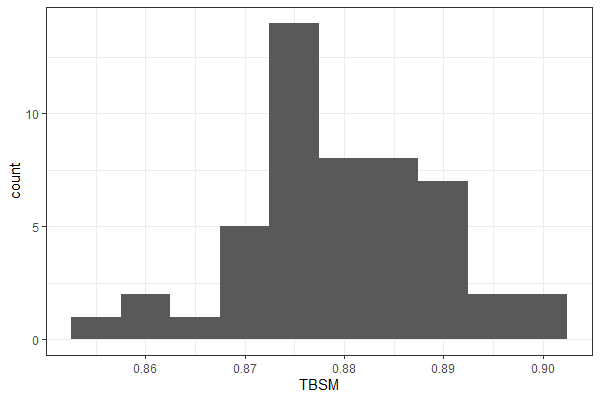


Figure 3‑3 BETA DISTRIBUTION OF TBSM SIMULATION

# Discussion and Conclusion

Overall, survival through Cornell is expected to be high, with the largest muskellunge and lake sturgeon having a 71% chance of surviving entrainment. These results represent a significant departure from our previous assessment, that showed lower survival rates, especially in larger size classes. Kleinschmidt conducted a thorough forensic analysis and have identified a number of faults with the original analysis and within the background open source code. Small samples, coupled with use of the mean rather than median when describing the resulting beta distribution, explains the discrepancies between analyses.

First, the original analysis employed small sample sizes with only 10 fish for 10 iterations. The present analysis sampled 1,000 fish 50 times for each scenario. When sample sizes are small, the probability of obtaining an extreme value is much higher than with large sample sizes. For example, the probability of obtaining 7 heads out of 10 flips of a fair coin is 12%. Not high, but neither is it improbable. If we were to repeat the experiment of flipping a fair coin 1000 times and got 700 heads, the probability of that occurring is practically zero (5.06 x 10-38). Note, with the adequate sample sizes used in this analysis, the range of expected values is very small (0.83 – 0.91). With small sample sizes it is much more likely to produce poor simulated survival rates.

The second fault was from the use of the mean rather than the median when describing the central tendency of a beta distribution. The beta distribution is not symmetrical; therefore, the mean is susceptible to bias when outliers are present. If small sample sizes are more likely to produce extreme values, and extreme values bias the mean, we have an explanation for the low survival rates noted in the first assessment.

Kleinschmidt is confident with the current analysis because of the rigorous validation exercise we employed. Archived simulation runs and summaries can be provided upon request. The resulting beta distributions were not significantly different (p = 0.06). Stryke produced a survival rate of 87.6% for a 20 inch fish, while the TBSM produced a survival rate of 88.0%.

# References

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1. <https://github.com/knebiolo/stryke> [↑](#footnote-ref-1)
2. <https://networkx.github.io/> [↑](#footnote-ref-2)
3. <https://numpy.org/> [↑](#footnote-ref-3)
4. <https://www.fws.gov/northeast/fisheries/fishpassageengineering.html> [↑](#footnote-ref-4)