# Introduction

Fish entrained through hydroelectric facilities are exposed to turbine passage mortality stressors. While mortality and entrainment rates are separately well-studied phenomena, their cumulative effects on aquatic populations are not. Unfortunately, resource managers often lack the necessary parameters to accurately model the fate of all impacted species, yet they are routinely required to assess the cumulative population-level effects of those species impacted. The 2022 Infrastructure Bill has set aside funding for the development of hydroelectric energy production facilities (Cite). Should this development occur, the hydroelectric industry will need to assess the cumulative impacts that are the result of fish entrainment.

Traditional risk analysis offers a potential solution for resource managers. An entrainment risk assessment or ERA 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 assess 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 to assess fishing risks for many species including elasmobranchs (Cortés et al. 2010; Furlong-Estrada, Galván-Magaña, and Tovar-Ávila 2017) and grouper (Pontón-Cevallos et al. 2020). Researchers have also developed risk assessment frameworks for fish entrainment. In 2012, Cada and Schweizer developed the qualitative traits-based assessment to evaluate the entrainment risk of data-poor species. In 2021, van Treeck et al. 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 due to entrainment, and overarching conservation goals for the river. They assessed entrainment mortality with empirically derived functions for Kaplan and Francis turbines.

Mortality through hydroelectric turbines has been well studied, with mathematical models able to predict the probability fish will get struck by a turbine blade (Von Raben 1957, Franke et al. 1997). The rate at which fish are entrained (fish per million [M] cubic feet [ft3] of water) through hydroelectric facilities is also a well-studied phenomenon, with results from field trials contributing to an entrainment database compiled by the Electric Power Research Institute (EPRI 1997). The 1997 EPRI database contains observations of 70 species at 43 facilities east of the Mississippi River. The EPRI dataset is particularly useful for quantitative analysis based on the assumption that when entrainment counts are standardized by discharge across facilities and holistically observed, the database will provide a reasonable estimate of entrainment rates for a watershed of a given size that are suitable for decision making purposes. Also, by describing entrainment rates with statistical distributions and simulating with Monte Carlo methods, it is possible to estimate average daily entrainment and mortality with measures of certainty, as well as estimating the likelihood an event of a given size will occur.

We developed the ERA to assess the cumulative impact of retrofitting a system of navigational locks and dams with hydro power generation. Retrofitting the existing dams will add an estimated XX MW of clean and reliable renewable energy to the regional grid. The operation of navigation facilities, operated by the United States Army Corps of Engineers, will remain unchanged. However, excess water that was once spilled will be routed through new powerhouses. Rerouting water through the new powerhouses will impact fish species within the Ohio River watershed and resource agencies have requested an assessment of cumulative impacts. Development of an Entrainment Risk Assessment is timely as the United States and other developed nations transition away from fossil fuels and towards renewable energy. There are many dams East of the Mississippi in the United States that can be retrofitted with hydropower generation (cite NID); and the cumulative effects of fish entrainment will need to be assessed at each. A transparent, repeatable, objective, and efficient method is needed.

# Methods

The Entrainment Risk Assessment (ERA) consists of two major components: (1) a simulation model that estimates the number of fish entrained and the number of expected mortalities; and (2) an objective method of assessing the resiliency of fish populations to the potential impact caused by entrainment.

## Study Area

## Selection of Target Species

We selected target species based on their relative abundance within the project, their recreational value, and/or their status as a species of concern. Further, target species were selected to represent a diversity of fish families with a range of life-histories, behavioral ecology, and habitat uses. The 26 target species selected included members of the Lepisosteidae (gars), Hiodontidae (mooneyes), Clupiedae (herrings), Cyprinidae (minnows), Catostomidae (suckers), Ictaluridae (catfishes), Atherinidae (silversides), Moronidae (temperate basses), Centrarchidae (sunfishes and black basses), Perchicae (perches), and Sciaenidae (drums) families. The target species selected account for the most abundant species in the Allegheny, Monongahela, and Ohio rivers based on available capture data from previously conducted surveys sourced by Pennsylvania Fish and Boat Commission (PFBC) and Ohio River Valley Water Sanitation Commission (ORSANCO) databases.

## Entrainment Simulation

We simulated entrainment mortality events with the open-source software package Stryke[[1]](#footnote-2). Stryke uses an individual based model (IBM), which follows the fate of individual fish within a population 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-3) to simulate routes of passage and Numpy[[3]](#footnote-4) for pseudo-random probability distribution draws. Kleinschmidt has validated Stryke with the USFWS Turbine Blade Strike Model or TBSM[[4]](#footnote-5). Stryke is scalable, such that it is possible to model complex movement through multiple facilities and assess cumulative impacts.

Fish migrate through a hydroelectric project where passage routes can be described with a network. For this assessment, we assume simulated fishes will move downstream as they approach the project. 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 network or dies.

For fish passing via entrainment, individuals are exposed to turbine blade 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 amount of discharge of through the turbine, the type of turbine, how many blades, and how fast it is rotating, then we can calculate with certainty the probability of being struck. Therefore, the only morphometric parameter needed to assess blade strike is length. All other input 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. Required inputs for the blade strike model include rated turbine head (feet [ft]), estimated maximum discharge (cubic feet per second [cfs]), discharge at maximum efficiency (cfs), percent discharge at maximum efficiency, runner speed (rotations per minute, [rpm]), runner diameter (ft), number of blades, and turbine efficiency (nameplate). These parameters were used to develop an initial blade strike model at the three projects (Table 1) for the range of fish lengths sourced from the 1997 EPRI database.

### Migratory Routes and Movement

At hydroelectric facilities, both obligate and opportunistic downstream migrants risk entrainment as they move downstream. For this assessment, 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 we only assessed mortality for those fish that pass via entrainment.

### Node Survival

Stryke assesses survival for individual fish at each node within the migratory network. For the forebay, tailrace, and river 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. When a fish is entrained, survival at a turbine is assessed with the Franke et al. (1997) equations for Kaplan 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. Then, we calculated the angle of absolute flow to axis of the rotation with Equation 4:

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

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

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

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. 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.

### Seasonal Entrainment Rate and Length Data

An investigation of the 1997 EPRI entrainment database found that the overall pattern of entrainment rates (expressed as fish per million cubic feet [Mft3]) for different species across the eastern United States were very similar. Across species and regions, a very small proportion of observations were large entrainment events that comprised most of the overall impact, while the majority of entrainment events constituted only a limited number of individuals. What leads to these large entertainment events is of no concern for our model, we only need be able to simulate their relative magnitude and frequency of occurrence. Distributions with such inequality are often modeled with a Pareto distribution, which has been used to describe income inequality (Arnold 2014), the population of cities (Rosen and Resnick 1980), and the distribution of stock returns among investors (Malevergne, Pisarenko, and Sornette 2006) among many other inequalities.

*Scipy.stats* provides two more extreme value distributions that could be used to model entrainment rates. The Weibull Max distribution is equivalent to a Frechet, which has been used to model extreme rain events (Koutsoyiannis 2004, Hawkes et al. 2008, Ramos et al. 2020) and river flows (El Adlouni, Bobée, and Ouarda 2008.). *Scipy.stats* also has support for the Generalized Extreme Value distribution. In either case, we compared the fit of the distribution to actual EPRI observations with a two-sided Kolmogorov Smirnov (KS) test implemented with *scipy.stats.ks\_test*.

Stryke comes pre-loaded with the EPRI database and convenience functions that allow the end user to describe entrainment rates with distributions fit to species-specific observations. When a species is missing from the EPRI entrainment database, Stryke allows the end user to pass queries and identify surrogate populations based on taxonomic linkages, functional feeding guilds, geographic location, habitat preferences, and/or seasonal migration patterns.

Figure 1 shows the observed and sampled entrainment rates for Yellow Perch in the months of March, April, and May. From a visual perspective, each distribution was able to recreate the extreme but rare entrainment events. To assist with distribution selection, we use the results of the KS test. When p <0.05, the simulated distribution is significantly different from empirical observations.

Graphical user interface, chart

Description automatically generated

Figure 1 observed and sampled entrainment rates for Yellow Perch in the Months of March, April ,and May

### Scenario Development

Entrainment events often occur on a seasonal cycle and are a function of the amount of water discharged through a facility. Therefore, it is important for our model to recreate potential hydrologic conditions and the operating scenarios for such conditions. For facilities with multiple units, it is assumed that a single unit would be operated up until its most efficient flow. At that point, water will then begin to flow through other units up until their most efficient flow or until the hydrologic capacity of the facility is met. Any more discharge is then spilled over the dam. If we assume fish proportionally follow the flow, we can estimate the rates at which fish will pass via each passage route. Thus, if we know the river discharge, we can simulate passage through the facility.

The last 10 years of data from the 100 nearest USGS stream gages to each dam were analyzed with the Python modules; *hydrofunctions* and *Pandas*. A linear relationship is evident when we graph exceedance flow as a function of drainage area. Stryke uses ordinary least squares regression with the Python module *statsmodels* to estimate seasonal exceedance flows (10, 50, and 90-percent exceedance) at each facility. Figure 2 shows one such example of the 50-percent spring exceedance flow at Allegheny Lock and Dam (red dot) on the Allegheny River in Pennsylvania. We created seasonal exceedance flow scenarios for winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November).

Chart, scatter chart

Description automatically generated

Figure 2 Spring 50-Percent Exceedance at Allegheny Lock and Dam 2

With three-month seasons, we simulated daily entrainment events (fish per M ft3)for 90 model-days (30 per month). Then expanded that to a daily entrainment estimate (fish) by multiplying the entrainment rate by the total amount of discharge through the project. Stryke simulates a daily entrainment event as a function of species and season with a pseudo-random draw from a Pareto, Weibull Max, or Generalized Extreme Value distribution using *Scipy.stats*. After Stryke iterates through each seasonal scenario and species combination, it then summarizes results.

## Vulnerability to Entrainment

The second component of an ERA objectively assesses the vulnerability of those species subjected to entrainment. Large impacts to highly vulnerable species carry the most risk, but what makes one species any more vulnerable than another? In 2012, Cada and Schweizer developed a traits-based assessment (TBA) to estimate fish population sustainability for data poor fish populations. This qualitative assessment extended experimental results from tested fish species to predict passage survival of other untested species based on phylogenic relationships or ecological similarities (Cada and Schweizer 2012). Kleinschmidt used the concepts of the Cada and Schweizer (2012) TBA and the Patrick et. al. (2009) PSA as a framework for assessing vulnerability. However, we used a straightforward quantitative approach for assessing fish population sustainability. Specifically, we used estimates of fish population growth rates for each species to evaluate a population’s ability to make up for turbine passage losses with compensatory mechanisms. If these compensatory mechanisms are not enough to overcome losses, the fish population is vulnerable to entrainment stressors.

The sustainability of fish populations is influenced by a number of demographic traits. These traits include natural life span, natural mortality rates, generation time or interval between reproductive events, the number of reproductive events per year, and the number of offspring per reproductive event (Cada and Schweizer 2012). Species that have a low natural mortality rate, short generation time, and produce a large number of eggs are less likely to experience population level effects. Patrick et al (2009) also incorporated the individual growth rate (von Bertanlaffy) and trophic level in their assessment of vulnerability. These mentioned traits all impact how quickly a population will increase in number when it is depleted, meaning when the population is not nearing the carrying capacity in the local environment. Both the PSA and TBA methods used a set of traits and combined them into a qualitative categorization of vulnerability. However, quantitative estimates of the combined impact of these population traits are available in the literature for many species in the form of population growth rates or doubling rates for depleted populations. By using these estimates directly, we avoid subjective selection of traits to include and subjective methodology for weighting the importance of each individual trait.

Population growth for a harvested (or in this case, potentially entrained) population of fish can be described on annual increments using the Schaeffer Model:

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where

Nt = population size in year t;

K = carrying capacity of population;

Et = entrainment losses in year t; and

r = discrete population growth rate

If we assume the population is depleted relative to the carrying capacity, then this equation simplifies to:

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If we reparametrize entrainment loss as the fraction of the population lost (PL; Et = PL x Nt,), then:

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Thus, if the entrainment loss rate (PL) is greater than the discrete population growth rate (r), the local population may decline over time.

The discrete population growth rate (r) for each species of concern was derived from information on FishBase (Froese and Pauly 2021), from model-derived resilience factors for the exact or in some cases, a surrogate species (Table xx). In the FishBase “Estimates based on models” section, we used:

1. “K”, which we presume to be the intrinsic population growth rate for depleted populations. The intrinsic growth rate (K) is related to the discrete growth rate as follows:

K is not reported for all species; when not reported for a species of concern, Kleinschmidt identified surrogates that were primarily based upon taxonomic linkages (Table xx).

1. “Population doubling time”, which is reported as a categorical range for all species (i.e., three presumed ranges for low resilient, moderate resilient, and high resilient species). The population doubling time (D) is related to the discrete population growth rate as follows:

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We report both of these estimates for (1+r) in Table xx and use the most conservative result from each range of values, the lower discrete population growth rate, as an estimate for species vulnerability.

## Assigning Risk

With quantitative measures estimating the number of fish entrained and the expected number of mortalities, and a quantitative index expressing the relative vulnerability of those species impacted, it is possible to objectively assign risk categories and identify the species most at risk. Following entrainment simulations, the annual proportion of the population in each river lost to entrainment (PL) was estimated by dividing the annual entrainment mortality by the annual population passing the facility.

We report (1+r-PL) in tabular form for each facility and flow scenario. Values of (1+r-PL) of exactly one would indicate steady population, >1 indicates population growth, and <1 would indicate the population is being impacted by entrainment.

# Results

## Validation

## Discharge Scenarios

## Entrainment Rates

## Cumulative Entrainment Assessment

# Discussion and Conclusion

Future improvements

* Simulate hydrograph rather than simplistic dry, average, and wet years.
* Let’s collect some new data – why the hell are we using 30 year old information

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1. <https://github.com/knebiolo/stryke> [↑](#footnote-ref-2)
2. <https://networkx.github.io/> [↑](#footnote-ref-3)
3. <https://numpy.org/> [↑](#footnote-ref-4)
4. <https://www.fws.gov/northeast/fisheries/fishpassageengineering.html> [↑](#footnote-ref-5)