# Introduction

At hydroelectric facilities, both obligate and opportunistic migrants risk entrainment as they move downstream. 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.

Evaluating entrainment within a traditional risk assessment framework requires resource managers to anticipate the magnitude and frequency of potential future entrainment mortality events, and then assess the resiliency of the impacted populations. Patrick et al. 2009 quantified the risk of overfishing a pelagic fish stock as a function of its productivity (replenish rate) and susceptibility to the fishery. Their approach incorporated demographic parameters such as the maximum age and size of a fish, individual growth rates, natural mortality, fecundity, breeding strategy, recruitment pattern, and age at first spawn (Patrick et al. 2009). Multiple species have been assessed with these methods 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 at hydroelectric facilities. 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, and they assessed entrainment mortality with empirically derived functions for Kaplan and Francis turbines (van Treeck, 2021).

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. In 1995, the Federal Energy Regulatory Commission conducted a preliminary assessment of fish entrainment at hydropower projects and concluded that entrainment studies at a number of sites within a watershed may be used to extrapolate to other sites. In 1997, the Electric Power Research Institute compiled an entrainment database (EPRI 1997) that standardized 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 compared relative to others within the same hydrologic region; it is possible to construct a reasonable estimate of entrainment for a watershed of a given size that are suitable for decision making purposes. By describing entrainment rates with extreme value distributions (Weibull max, Pareto, Generalized Extreme Value) and simulating mortality with Monte Carlo methods, it is possible to estimate average daily entrainment and mortality events with measures of certainty, as well as estimating the likelihood an event of a given size will occur.

We developed the Fish Entrainment Risk Analysis (FERA) and the open source software package Stryke to assess the impact of entraining fish through hydroelectric facilities. We applied FERA at Townsend Dam on the Beaver River, a tributary to the Allegheny River in the state of Pennsylvania, United States. The Townsend Dam was chosen because an entrainment study was conducted in 1992, which offers the ability to validate the results of the Monte Carlo simulation. Development of FERA is timely as the United States and other nations transition away from fossil fuels and towards renewable energy. There are many dams East of the Mississippi River in the United States that can be retrofitted with hydropower generation (cite NID). If they are, then the cumulative effects of entrainment will need to be assessed at each. A transparent, repeatable, objective, and efficient method is needed.

# Methods

FERA 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 based the target species on those present at the project during sampling in the summer of 2022(?). They represent a diversity of fish families with a range of life-histories, behavioral ecology, and habitat uses. Species include: Clupiedae (herrings), Cyprinidae (minnows), Catostomidae (suckers), Ictaluridae (catfishes), Atherinidae (silversides), Moronidae (temperate basses), Centrarchidae (sunfishes and basses), Perchicae (perches), and Sciaenidae (drums) families.

## Entrainment Simulation

We simulated entrainment mortality events with the open-source software package Stryke[[1]](#footnote-2). Stryke employs an individual based model (IBM), that follows the fate of individual fish within a population as they migrate past a hydroelectric project. The software simulates the frequency and magnitude of entrainment events, a population of fish, movement, and survival with Monte Carlo methods.

### Daily Entrainment Event

The EPRI (1997) entrainment database contains observations from 73 facilities with multiple sampling events throughout a study period: usually once per month for one year. Not all species present at a facility were present in all samples. Therefore, it is possible to infer absence. For example, a particular species (‘A’) may be present at only 1 out of 12 sampling events at a facility. However, Species A may also be present at another facility for 4 out of 12 samples. Overall, Species A has been present in 5 of 24 possible samples for a presence rate of 21%. Stryke queries the EPRI database, observes many facilities within the same hydrologic region, counts the number of occurrences, infers the total number of samples the species could have been in, and returns the requested probability. To simulate presence with intent to migrate past the hydroelectric facility, Stryke iterates over a daily hydrograph, and then draws from a binomial probability mass function with presence rate X). If fish are present that day, the software then creates a population of fish and simulates an entrainment event.

An investigation of the 1997 EPRI entrainment database also 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 (# of individuals per Mft3) is of no concern for our model, we only need be able to simulate their relative magnitude and frequency of occurrence.

Stryke simulates the magnitude of the entrainment event with a sample from a Pareto distribution. The Pareto has been used to describe income inequality (Arnold 2014), the population of cities (Rosen and Resnick 1980), and the distribution of stock returns (Malevergne, Pisarenko, and Sornette 2006), among many other inequalities. Stryke also provides two more extreme value distributions that could be used to model entrainment rates. The Weibull Min 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.). Stryke also supports the Generalized Extreme Value distribution. Stryke uses a two-sided Kolmogorov Smirnov (KS) test implemented with *scipy.stats.ks\_test* to assist with distribution selection.

Figure 1 shows the observed and sampled entrainment rates for Yellow Perch in the months of March, April, and May in the Hudson River and Mid Atlantic drainages (HUC02 = 2). 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. Then, Stryke simulates a daily entrainment event (number of fish passing migrating past the hydroelectric facility), which is equal to the entrainment rate times the daily discharge rate.

Graphical user interface, chart

Description automatically generated

Figure observed and sampled entrainment rates for Yellow Perch in the Months of March, April ,and May compared with simulated distributions.

### Migration

Individual fish migrate through a hydroelectric project where passage routes can be described with a network model (Figure 2). 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. If there is more than one node available at their current location, then a pseudo random draw from a multinomial probability mass function () controls movement, where transition probabilities are determined *a priori*. The simulation ends for a fish when it arrives at the last node in the network or dies.

Diagram

Description automatically generated

Figure depicts the migratory network at Townsend Dam.

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. Most hydroelectric facilities in the United States have regulated minimum flow releases, usually in the form of spill. If river discharge is less than or equal to this minimum flow, than water is not routed through the units and no fish are entrained that day. 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.

### Survival

Stryke assesses survival for each fish at each node with a pseudorandom draw from a binomial distribution with probability mass function of . The survival rate of non-turbine nodes was determined *a priori*, sourced from similar studies, or from expert opinion. For simplicity, it was assumed that 100% of the fish that pass via spill survive, and that there is no natural mortality at any other node. Therefore, the only source of mortality in our simulation is entrainment.

The fish that move from the forebay node to either U1 or U2 (e.g., entrainment) are exposed to turbine mortality, which is modeled with the Franke et al. (1997) equations. These equations calculate the probability a fish of a given length will get struck by a turbine runner blade. If we know how long a given fish is, the amount of discharge, the type of turbine, the number of runner 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 fish length. All other input parameters are sourced from technical drawings of the facility.

### Fish Length

When fish are present, Stryke simulates a population of lengths by sampling a log normal distribution with probability density function :. Along with providing information on the frequency and magnitude of entrainment events, the EPRI (1997) entrainment database also provides information on fish lengths. These data describe the seasonal distribution of lengths for a species of fish entrained at hydroelectric facilities throughout the United States accounting for different lifestages at different times of the year. For example, entrainment of Alosids during autumn should only describe juveniles, whereas entrainment of Alosids in spring would likely describe adults.

### Simulation Scenarios

The intent of this exercise was to validate Stryke’s ability to recreate the frequency and magnitude of entrainment events. In 1992, an entrainment study was conducted at the project. The software iterated over the daily average hydrograph of USGS gage 03107500 and simulated a daily entrainment event for the ten most entrained species. We then compared Stryke to the 1992 study.

## Vulnerability to Entrainment

The second component of FERA 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

## Entrainment Rates

## Cumulative Entrainment Estimate

In total,

## Risk Assessment

## Validation

# 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)