Estimating Downstream Survival of Diadromous Fishes at Hydroelectric Facilities

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Table of Contents

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Executive Summary

Diadromous fish must complete migrations between freshwater and marine habitats to fulfill their life cycles. Hydroelectric facilities pose a significant risk to diadromous fish during downstream migration by potentially causing delay, increasing predation, and inflicting injuries that may lead to mortality. Safe, timely, and effective downstream passage at hydroelectric facilities is necessary to sustain viable commercial, recreational, subsistence, and Tribal fisheries in the U.S. The Federal Energy Regulatory Commission (FERC) is obligated under the Federal Power Act, the Endangered Species Act, the Magnuson-Stevens Fishery Conservation and Management Act, and the National Environmental Policy Act to consider the impacts of non-federal hydroelectric projects on diadromous fish species, however no contemporary resource guide or best practices document exists to inform study designs and incorporate lessons learned from decades of research and studies.

This technical memorandum, *Estimating Downstream Survival of Diadromous Fishes at Hydroelectric Facilities*, describes best practices for the hydroelectric industry to follow during licensing and compliance activities and provides a resource guide for FERC and natural resource agencies during their assessment of downstream survival study plans and results. We accomplish this by providing an introduction to diadromous species and the threats during downstream passage at hydroelectric facilities, followed by an in-depth description of a four step process to assess downstream survival: site characterization, field studies, data analysis and modeling, and evaluation of project effects. In the site characterization step, we describe the target species and life stages passing the hydroelectric facility within the context of the watershed, environmental, and operational conditions to identify the potential passage routes and threats encountered during and after passage. We also provide guidance on the suitability and applicability of existing information. In the field studies step, we outline the different types of studies that provide site-specific information regarding route selection, survival, delay, and predation. In the data analysis and modeling step, we describe the appropriate methods for interpreting field study data and desktop modeling exercises that quantify the impacts on downstream migrating fish. In the evaluation and mitigation step, we provide examples of how to derive a point estimate of project survival that integrates route selection and survival with operations at the facility. In addition, we elucidate how these survival estimates can be used to develop mitigation strategies in an adaptive management framework using performance standards.

Successful application of these best practices will improve the downstream survival effects analyses during licensing and compliance activities at hydroelectric facilities. This information will then guide the implementation of fish passage and protection measures that result in better outcomes for diadromous species and sustainable hydropower.

1 Purpose and Scope

The National Marine Fisheries Service (NMFS) is responsible for the stewardship of our Nation's marine fishery resources including the protection and passage of diadromous fish species during their migration in freshwater habitats. Diadromous fish must complete migrations between freshwater and marine habitats to fulfill their life cycle. Safe, timely, and effective upstream and downstream passage at hydroelectric facilities is imperative to recover threatened and endangered species and sustain viable commercial, recreational, subsistence, and Tribal fisheries in the U.S. In general, our conservation goal is to make hydroelectric projects "invisible" to migrating diadromous species meaning safe, timely, and effective passage that is equivalent to or approaches natural migration rates and survival.

The Federal Energy Regulatory Commission (FERC) is obligated under the Federal Power Act (FPA), the Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA) to consider the impacts of non-federal hydroelectric projects on diadromous fish species. Hydroelectric projects pose a significant risk to successful downstream migration by causing migratory delay, increased predation, and injury/mortality during passage (Algera et al. 2020). While NMFS provides comments and recommendations to FERC for assessing the effects of hydroelectric projects on diadromous fish species during compliance and licensing activities, no contemporary resource guide or best practices document is available to inform study designs and incorporate lessons learned. Therefore, this document serves as a resource guide, describing our expectations for the steps necessary to examine project effects on the downstream passage of diadromous fish.

The goal for the resource guide is two-fold: (1) the development of best practices for downstream survival and passage studies that the hydroelectric industry can follow during licensing and compliance, and (2) creation of standard procedures that FERC and resource agencies can use to evaluate study plans and findings to inform additional information requests from project proponents. This Technical Memorandum will facilitate consistency of evaluation methods across projects and a more representative quantification of project effects leading to better outcomes for our trust species and a more sustainable hydropower industry.

2 Background

Hydroelectric facilities create impediments and risks to migration that cause a range of effects on diadromous species (Waldman and Quinn 2022). Below is a high-level summary of the importance of successful downstream migration and threats at hydroelectric facilities.

2.1 Downstream Migration

Diadromous fish species (anadromous and catadromous) migrate between freshwater and marine environments to complete their life cycles. The construction of upstream fishways at conventional hydroelectric facilities has allowed access to habitats for diadromous species with varying levels of success (Bunt et al. 2012, Noonan et al. 2012, Brown et al. 2013, Hershey 2021). One reason for the lack of a positive biological response to upstream passage is inadequate downstream passage and protection measures (McLaughlin et al. 2013, Ohms et al. 2022). Bidirectional longitudinal connectivity is essential for sustainable fisheries and responsible hydroelectricity production (Stich et al. 2019). The downstream fish passage and protection requirements at a hydroelectric facility will depend on the facility's effects on the species and life stage using that migratory corridor. An applicant for a hydroelectric project license (Applicant) cannot identify safe, timely, and effective downstream passage and protection measures without fully understanding the hydroelectric facility's impacts on downstream migration.

2.1.1 Anadromous

Anadromous fish spawn in freshwater habitats where juveniles rear for varying amounts of time (weeks to years) depending on the species, before migrating to marine environments to grow and mature. Semelparous anadromous adults die after spawning. Therefore, these species are more likely to pass downstream at hydroelectric facilities only as juveniles. Iteroparous species may undergo multiple spawning migrations, so both adult and juvenile life stages need safe, timely, and effective downstream passage at hydroelectric facilities.

2.1.2 Catadromous

Catadromous fish migrate from fresh or brackish water to spawn in marine environments. The semelparous American eel *Anguilla rostrata* is the only catadromous fish in North America, exclusively on the Gulf of Mexico and Atlantic Coasts. American eel require safe, timely, and effective downstream passage at hydroelectric facilities at two adult life stages (yellow- and silver-phase). Yellow-phase American eel actively migrate between freshwater habitats to forage for prey and disperse. Silver-phase American eel migrate to the Sargasso Sea to spawn.

2.2 Downstream Passage Threats

In the absence of anthropogenic stressors, downstream migrations are stressful journeys with the potential for a high mortality rate for diadromous fish. The addition of hydroelectric facilities in the migratory corridor exacerbates this already arduous journey. The effects of hydroelectric facility passage are compounded in watersheds with multiple developments (Budy et al. 2002). The following sections describe the threats encountered by diadromous fish at hydroelectric facilities during downstream migration.

2.2.1 Delay

Diadromous fish encounter numerous impediments passing a hydroelectric facility during emigration. These impediments elicit a behavioral response that may overwhelm the drive to migrate back to the ocean causing a migratory delay (Huusko et al. 2018). During their downstream migration, diadromous fish first swim into the reservoir shifting from a lotic (flowing water) to a lentic (still water) environment. Lentic environments do not provide the same hydraulic migratory cues, thereby slowing migration rates (Acou et al. 2008, Tiffan et al. 2009). Reservoirs often thermally and chemically stratify which may create impediments that alter habitat use (Nestler et al. 2016) and affect migration (Ohms et al. 2022). Once fish reach the infrastructure (e.g., dam, powerhouse), further delays may occur due to unfavorable hydraulics (Haro et al. 1998, Enders et al. 2012) or poor egress locations (Venditti et al. 2000, Keefer et al. 2012b). The effect of hydroelectric facilities can range from minimal delay (Welch et al. 2008) to significant delay (Holbrook et al. 2011, Huusko et al. 2018). In general, run-of-river hydroelectric facilities have less of an impact on delays in migration than storage facilities, but even small, non-powered dams can have measurable effects (Gauld et al. 2013). Delays in migration can increase predation (Rieman et al. 1991) and cause physiological stress (Leonard and McCormick 1999, Durif et al. 2005) leading to decreased passage success (Nyqvist 2016). Significant delay at one facility, or cumulatively in a watershed, can have large detrimental effects by interfering with life cycle timing and seasonal habitat usage. If sufficiently delayed, some salmonids, such as steelhead *Oncorhynchus mykiss*, may permanently cease migration (i.e., desmoltification) and become resident (Rousseau et al. 2011). Thus, the effects of delay may be far more significant to populations than it appears at the individual level.

2.2.2 Predation

Predation is a natural phenomenon that is exacerbated by hydroelectric facilities (Schilt 2007). Hydroelectric facilities create aggregation areas for predators of diadromous fish. Reservoirs provide lentic habitats for various native and non-native predators that can consume large amounts of juvenile anadromous fish (Beamesderfer and Rieman 1991, Rieman et al. 1991, Petersen 2001, Erhardt et al. 2018, Murphy et al. 2021). Likewise, immediately downstream from a hydroelectric facility, predation may be high due to prey disorientation, injury, and concentration (Mesa 1994, Blackwell and Juanes 1998, Beland et al. 2001, Ferguson et al. 2006, Sabal et al. 2016, Andrews et al. 2018, Tidwell et al. 2019). In addition, reservoirs and tailraces are active locations for avian predation (Collis et al. 2002, Evans et al. 2012, Evans et al. 2022). Similar to most habitat discontinuities (Kennedy et al. 2016), hydroelectric facilities increase predator-prey interactions.

2.2.3 Mechanical Injuries

When diadromous fish pass over or through hydroelectric facilities, mechanical injuries occur when the fish collides, scrapes, impinges, or grinds against facility infrastructure. These injuries can result in instant or delayed mortality (Budy et al. 2002, Ferguson et al. 2006) and are manifested in a variety of maladies (Mueller et al. 2017a). In general, larger fish have a higher probability of colliding with infrastructure, but juvenile and small fish are more sensitive to mechanical injury (Pflugrath et al. 2020b). Common components of hydroelectric infrastructure that cause mechanical injuries include, but are not limited to, guide vanes, wicket gates, turbine runner blades/buckets, gates, trash racks, and spillways. Facilities in poor condition often present more hazards such as exposed structural supports (e.g., protruding rebar) and roughened surfaces (e.g., spalled concrete).

2.2.4 Fluid Injuries

Fluid injuries occur when diadromous fish experience fluid shear forces from two water masses that are flowing in different directions and/or at disparate velocities. These fluid injuries are similar and often indistinguishable from mechanical injuries (Mueller et al. 2017a). Susceptibility to fluid shear injuries varies based on species and life stage with scaled, rigid-bodied fish and juveniles being less resilient to shear forces (Pflugrath et al. 2020b). Common components of hydroelectric infrastructure that cause fluid injuries include, but are not limited to, stilling basins, draft tubes, wicket gates, turbine units, and hydraulic gates.

2.2.5 Barotrauma Injuries

Barotrauma injuries are caused by rapid decompression during turbine passage as diadromous fish are transported through the low (nadir) pressure region immediately downstream from the turbine unit (Brown et al. 2012). Common maladies arising from barotrauma include burst swim bladder, exophthalmia, hemorrhage, emphysema, and emboli (Boys et al. 2016). Sensitivity to barotrauma varies greatly with species and life stage as a result of the existence and functioning of the swim bladder (Pflugrath et al. 2020b). Barotrauma is less of a concern for low-head hydroelectric facilities (Boys et al. 2018), but the risk of barotrauma is site-specific relating to the acclimation pressure before being entrained, the turbine operating conditions, and the sensitivity of the species (Trumbo et al. 2013).

2.2.6 Gas Supersaturation

Downstream of some hydroelectric facilities, water can become supersaturated with atmospheric gases during times of spill potentially causing gas bubble disease in anadromous fish (Weitkamp and Katz 1980). Gas bubble disease is similar to the bends suffered by human divers. Gas exchanges across the skin and gills in water with supersaturated dissolved gas levels that then form bubbles in the blood and other body tissues without maintaining compensation depth (i.e., adequate partial pressure). Gas bubble disease causes emphysema and emboli among other maladies. All species and life stages are susceptible to gas bubble disease if unable to swim to regions of normal gas saturation to limit their exposure. Total dissolved gas levels below 110% result in less than 10% mortality for studied fish species for 100 hour exposures and levels below 130% result in 10% mortality for 10 hour exposures (Pleizier et al. 2020). However, species tolerances vary widely.

3 Step One – Site Characterization

The first step in determining the impacts of a hydroelectric facility on downstream migrating fish is to characterize the site. Each of the sections describe different aspects of the hydroelectric facility that are important for determining impacts on diadromous fish.

3.1 Target Species and Life Stages

State and federal resource agencies typically identify the target species and life stages that will encounter a hydroelectric facility during downstream migration. These species and life stages are often part of state and/or federal diadromous species management or recovery plans. Due to the diverse and complex life histories of diadromous species, the threats posed by a hydroelectric facility may include multiple infrastructure components and a range of operations throughout the year.

3.2 Watershed Context

NMFS manages downstream passage and protection at a hydroelectric facility in the context of watershed and ecosystem processes. The location of a hydroelectric facility within a watershed determines what target species and life stages are most likely to require passage and protection. In addition, facilities located in the lower watershed may need much different downstream passage and protection requirements, timing, and duration than facilities located in the upper watershed. For example, a hydroelectric facility lower in the mainstem will have to provide safe, timely, and effective downstream passage for diadromous fish migrating from headwaters, tributaries, and mainstem habitats; whereas a facility located on a tributary will only have to pass diadromous species using that tributary habitat. The location of a facility in a watershed also affects the number and types of diadromous species needing passage and the timing and duration of the migratory period. In addition, the number of hydroelectric facilities in a watershed that a population of diadromous fish must pass influences the survival and delay performance standards (Marschall et al. 2011, O’Connor et al. 2022).

3.3 Environmental Conditions

Photoperiod, temperature and discharge have a major influence on the timing of migration for diadromous species (Quinn and Adams 1996, Gahagan et al. 2010, Otero et al. 2014, Teichert et al. 2020). Therefore, understanding the environmental conditions at both the watershed and hydroelectric facility scales is necessary to complete a downstream passage effects analysis. Characterization of the hydrology during periods of downstream migration is necessary to understand the potential effects to diadromous fish. A licensing or compliance monitoring study should include the calculation of a migrational flow duration curve (FDC) based on daily average flows of the last 10 to 30 years (or other agency-approved hydrologic method) for each species and life stage anticipated to pass the hydroelectric facility. Due to climate change effects on river discharge and species phenology, the Applicant should update the flow duration curves at the start of each licensing or compliance study. A common mistake is to utilize monthly flow duration curves instead of the full migratory period (i.e., multiple and/or partial months). Migratory periods are often ephemeral and may cover only a few weeks or months during the year. Characterization of the migrational hydrology will determine potential operating regimes of the hydroelectric facility during diadromous fish emigration. After identifying the duration and likelihood of the operating regimes, the Applicant can identify and quantify the likely passage routes and threats to safe, timely, and effective downstream passage at a project.

In addition to understanding the hydrology, the Applicant should be aware of the potential for water quality to affect downstream passage. For example, the temperature in the upper water column of the reservoir may be elevated during the warm months of the year. If this temperature is outside the preferred range of emigrating fish, the likelihood of those fish using a surface bypass system will decrease. Alternatively, if the only viable route of passage is through a low-level outlet and the reservoir develops a chemocline with low dissolved oxygen, emigrating fish may not sound to use that route of passage. The Applicant should understand the potential implications water quality parameters may have on the successful passage of diadromous species at their project.

Diadromous fish exhibit circadian patterns, with their activity influenced by photoperiod and the diel cycle. Patterns vary by life stage, habitat, and other factors. For example, American eel are nocturnal, with increased movement occurring at night (Haro et al. 2000, Eyler et al. 2016). The Applicant will have to understand the circadian rhythms of the target species and life stages to understand how operations will potentially affect downstream passage. However, circadian behavior is plastic and may change based on the effects of barriers to migration such as challenging hydraulic conditions or increased predation (Keefer et al. 2012a).

3.4 Passage Routes and Threats

Hydroelectric facilities may have one or multiple possible routes for downstream passage. The environmental conditions (e.g., flow, temperature), migration timing, fish behavior, and the configuration and operational scheme of the facility influence which route the fish selects to pass the facility. The three primary categories of downstream passage are through the turbines, via spill, or through a designated fish bypass system (**Figure 1**). A secondary means of downstream passage are navigational locks. The threats posed by each of these routes are highly variable and site specific. For every hydroelectric facility, the Applicant must evaluate each passage route by identifying and quantifying the threats to downstream migrating fish.

3.4.1 Turbines

The turbine is a route of downstream passage at hydroelectric facilities when there is no physical exclusion by a screen or other means (e.g., trash rack). There are many different turbine technologies designed for various dam heights and river flows. The three main types of hydraulic turbines installed in the U.S. are impulse, reaction, and gravitational turbines. Pelton, Turgo, and Cross-Flow units are impulse turbines designed for low flow sites with high-, medium-, and low head, respectively. Francis and Kaplan units are reaction turbines designed for variable flow sites with high- and low-head, respectively. Deriaz, bulb, and propeller units (among others) are variations of the Kaplan turbine. Archimedes Screw units are gravitational turbines used at low-head sites. Each of these turbine technologies maximizes energy production and minimizes cost for the dam height and river flow conditions specific to the hydroelectric plant location at the time of development. Rarely do two hydroelectric plants have the same turbine type, size, age, or operation and often there is a combination of different turbine types within a single facility. This diversity in turbine infrastructure makes each hydroelectric plant unique with respect to turbine passage.

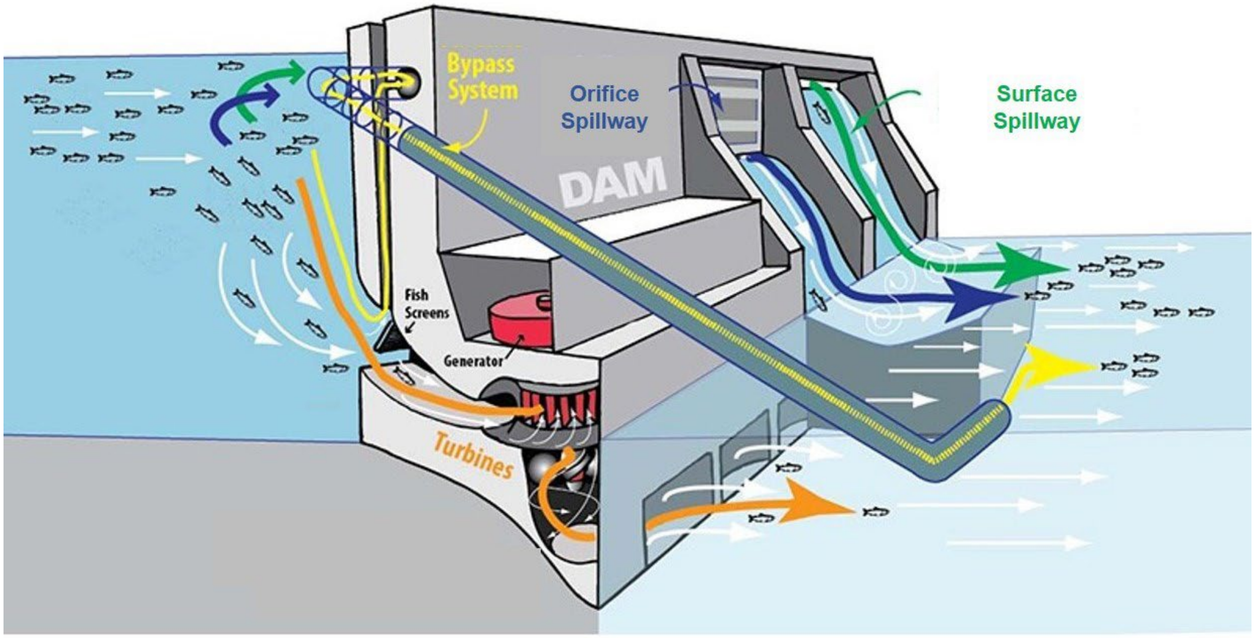

Figure 1. Primary routes of downstream passage at a hydroelectric facility.

Based on previous studies of downstream passage at hydroelectric facilities with reaction turbines, Francis and Kaplan turbines have variable effects on fish. For example, American and European eel *Anguilla anguilla* survival was lower [mean survival = 80.7 ± 6.4% (90% CI)] with a higher injury rate (25.7 ± 7.9%) for Kaplan turbines compared to Francis turbines [mean survival = 95.1 ± 5.3% (90% CI); injury rate = 12.5 ± 10.5%] (Heisey et al. 2019). In general, the opposite is true for salmonids and other fusiform fish that exhibit higher survival in Kaplan turbines (Pracheil et al. 2016). However, not all Kaplan and Francis turbines are equally dangerous for downstream fish passage. The hydroelectric industry has designed fish friendlier reaction turbines that have shown promise for making turbine passage a safer route for diadromous fish at hydroelectric facilities with upgraded infrastructure (Hogan et al. 2014, Amaral et al. 2020, Romero-Gomez et al. 2020, Kassanos et al. 2022, Watson et al. 2022, Watson et al. 2023).

In general, impulse turbines are not a safe route of passage for diadromous fish. Pelton and Turgo turbines require screened intakes as those technologies involve high velocity impact on turbine runners. Likewise, two Cross-Flow (a.k.a., Ossberger) units of different capacity exhibited high mortality and injury rates for juvenile Atlantic salmon *Salmo salar*, American shad, and striped bass *Morone saxatilis* in upstate New York (Gloss and Wahl 1983, Kostecki et al. 1987, Dubois and Gloss 1993). However, the turbine type is poorly studied and the results from that site may not be applicable to other Cross-Flow sites (EPRI 1992, Pracheil et al. 2016).

Mortality and injury rates passing through an Archimedes screw turbine are poorly understood, though data from Europe suggests that these rates are low, but vary by species (Bracken and Lucas 2013, Okland et al. 2016, Havn et al. 2017b, Okland et al. 2017, Pauwels et al. 2020). Currently, the only Archimedes screw turbine installed in the United States is at the Hanover Pond Project (P-14550) located in Meriden, Connecticut. Compliance evaluations of downstream passage suggest 100% survival for adult American eel and adult American shad (Kleinschmidt 2019, Normandeau Associates 2019). However, the American eel study used small adult eels (average length of 325 mm) and the American shad study involved a very small sample size (n=20) with an incomplete telemetry receiver array.

Collectively, average mortality passing through all turbine types was 22.3% (95% CI 17.5–26.7%) using empirically-derived estimates from a global dataset corrected for common uncertainties (Radinger et al. 2022).The threats to downstream migrants passing through turbines include delay, mechanical, fluid, and barotrauma injuries (Pflugrath et al. 2020b). We provide more detail for each of these threats in the following subsections focusing on the better understood, ubiquitous reaction turbines.

3.4.1.1 Turbine Passage Delay

A downstream migrating fish may experience delay before entrainment through turbines. For pelagic species such as salmonids and alosines, delay may occur because the hydroelectric intake is below the fish depth preference. In these situations, a fish may search for routes of egress at their preferred depth range before sounding and entering the intakes. For hydroelectric plants that are not spilling or do not have bypass systems, this searching delay will be exacerbated. Impoundments that chemically and thermally stratify may delay entrainment by acting as a chemical barrier between the preferred habitat conditions and those near the intake. Delay may also occur when trash rack clear spacing is large enough to allow passage but behaviorally inhibits entrainment. For example, some American eel and American shad exhibited searching behavior at hydroelectric plants on the Connecticut River with bar rack clear spacing that allowed entrainment (Kynard and O'Leary 1993, Brown et al. 2009).

3.4.1.2 Turbine Passage Mechanical Injury

Turbine passage involves confined spaces with structural and mechanical infrastructure that pose a threat of mechanical injury to fish. The first threat encountered is the trash rack of the facility that may have a clear space that physically prevents fish entrainment (**Figure 2**). In some instances, the normal velocity (the velocity component perpendicular to the trash rack face) may exceed the swimming capability of the fish and the migrant may become impinged on the trash rack or screen. This threat is particularly acute for post-spawn, iteroparous adult anadromous fish who are energetically depleted (Haro and Castro-Santos 2012).

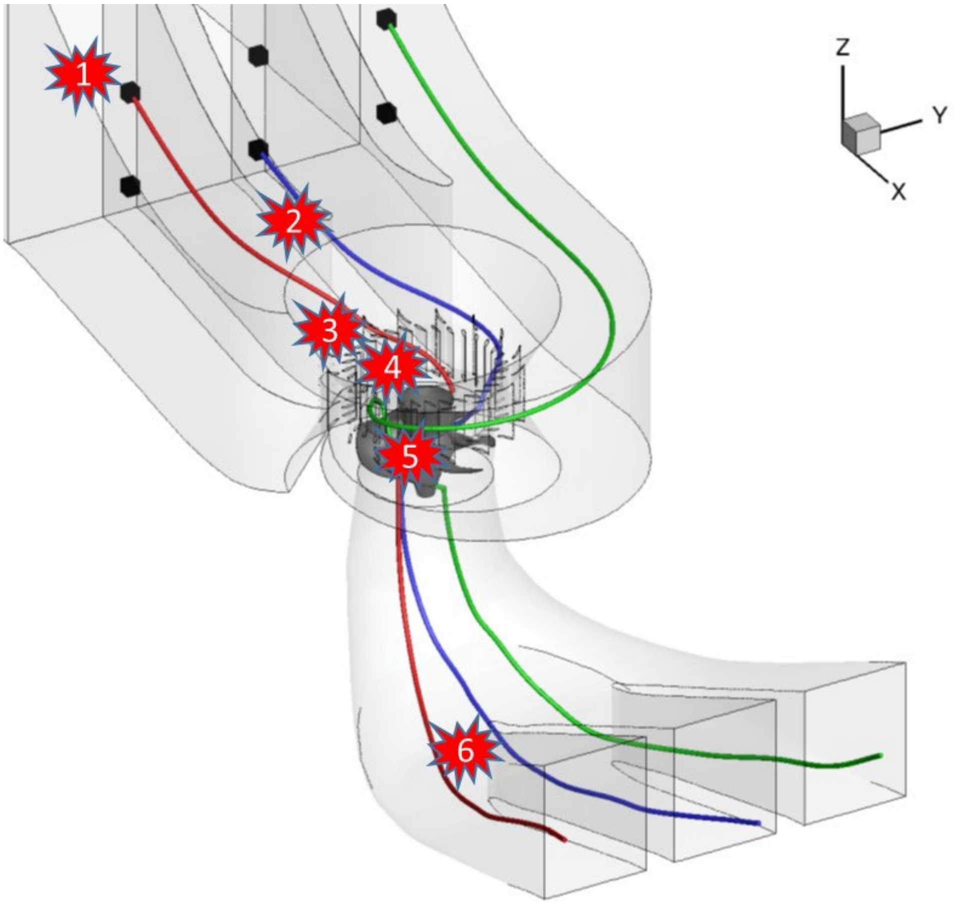

Figure 2. Transparent, isometric view of a Kaplan turbine passage route highlighting possible mechanical injury threats during passage: (1) trash/rack screen, (2) intake structural pier, (3) stay vane, (4) wicket gate, (5) turbine, and (6) draft tube structural pier. The red, green, and blue flow lines represent potential pathways for emigrating fish. Image modified from Richmond and Romero-Gomez (2014).

Once entrained, fish may experience collisions or abrasions with intake/draft tube walls, stay/guide vanes, and wicket gates (**Figure 2**). This internal infrastructure is site specific, so some hydroelectric plant designs may pose more of a threat of mechanical injury. For example, some hydroelectric plants have long penstocks, turns in the flow path, more stay vanes, or intake/draft tube bifurcations that all pose additional threats compared to a short, linear intake. In addition, wicket gate and guide vane positioning will change under different operating conditions, thus increasing or decreasing the probability of the fish colliding or abrading against the wicket gate (Martinez et al. 2019a). Especially at small projects, the relationship between fish size and the physical structures may preclude safe passage and result in high injury and mortality rates.

Turbine runners are moving parts that may cause collisions or grinding of the fish with the blade (Kaplan) or bucket (Francis). For many decades, this mode of injury has been the focus of research and the assumed most likely cause of turbine passage injury and mortality (von Raben 1957, Bell et al. 1967, Bell 1981, 1991, Cada 1991, Franke et al. 1997, Turnpenny et al. 2000, Bevelhimer et al. 2017). However, each mechanical injury threat should not be ignored by the Applicant as other facility components can be as dangerous, if not more dangerous, than the runner region. For example, Hou et al. (2018) measured more collisions in the stay vane/wicket gate region compared to the runner region at some facilities and operation regimes. In general, the following factors influence the threat of injury and mortality from a turbine runner:

- Larger fish are more likely to experience blade/bucket strike.
- The number of buckets/blades on a runner increases the probability of strike.
- Blade/bucket leading edge velocity directly correlates to the severity of strike. Because the runner is rotating, the velocity proximal to the hub is less than near the blade/bucket tip meaning the severity of injury is typically less when fish pass near the hub of the runner.
- The angle and location of strike on the fish body directly relates to the severity of the injury.
- Larger turbines tend to be safer because there is usually more space in the flow path for safe conveyance of fish.
- Thicker blades/buckets produce strikes with less mortality.
- For Kaplan runners, smaller gaps between the blade and the hub, and the discharge ring produce less grinding injuries.

3.4.1.3 Turbine Passage Fluid Injury

Turbine passage is a harsh, complex, hydraulic environment with numerous locations where shear forces may injure downstream migrating fish (**Figure 3**). The locations where fluid shear forces may injure fish include areas of rapid flow acceleration or deceleration, areas with secondary flow development, and areas of high velocity proximal to infrastructure (e.g., walls, structural members). In Kaplan turbines, the main areas of concern are the stay vanes and wicket gates, runner, and draft tube (Cada et al. 2006). The stay vanes, wicket gates, and runner are all areas of rapid acceleration producing potentially lethal and injurious turbulence; whereas the draft tube is an area of rapid deceleration resulting in macro-scale turbulence that disorient fish (Cada and Odeh 2001). In Francis turbines, the main areas of concern are the same as Kaplan units, but Francis runners tend to produce more severe shear events due to the conversion of radial flow to axial flow in the runner region (Fu et al. 2016). Cada et al. (2006) conclude the risk of fluid injuries increases when the turbine operational settings are above or below maximum efficiency because the hydraulic phenomena causing the inefficiency may result in fish injury (e.g., cavitation, micro- and macroscale turbulence).

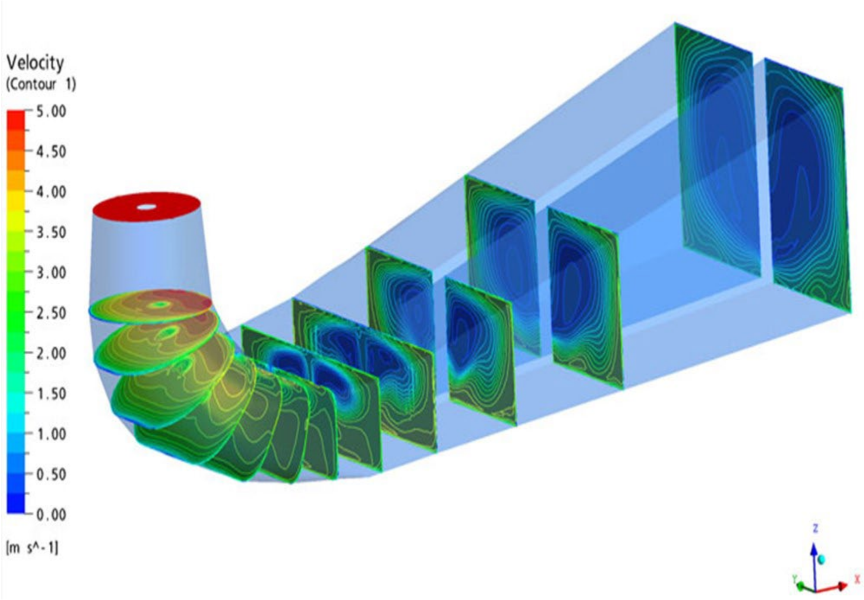

Figure 3. Transparent, isometric view of the hydraulic environment in a draft tube simulated by a three-dimensional computational fluid dynamic model showing multiple locations with high shear stresses that may injure fish. Image courtesy of the Institute of Hydraulic Fluid Machinery, Graz University of Technology www.hfm.tugraz.at.

3.4.1.4 Turbine Induced Barotrauma

Downstream migrating fish passing through turbines experience rapid pressure changes (Deng et al. 2014). The impact of barotrauma on diadromous species passing through turbines at a hydroelectric facility is governed by the depth of acclimation before entrainment and the presence/functioning of the swim bladder (Pflugrath et al. 2020b). Salmonids, alosines, eels, and sturgeon are all diadromous fish with open swim bladders (physostomes) that can regulate air in the swim bladder through the alimentary canal. During turbine passage, as fish move rapidly from high pressure to low pressure regions, the air in the swim bladder will expand according to Boyle's Law (Brown et al. 2012). The fish's ability to expel the expanding gas during turbine passage will mitigate the risk of swim bladder rupture or other related maladies. Not all physostomes regulate air equally with American shad (Pflugrath et al. 2020a) being much more susceptible to barotrauma than American eel (Pflugrath et al. 2019). We do not fully understand the reasons for these differences, but fish behavior and physiology prior to passage are likely important factors. Physoclistous fish (e.g., striped bass) do not have a connection between the swim bladder and alimentary canal making them more susceptible to barotrauma injuries. Finally, lamprey are fish without swim bladders that are likely unaffected by barotrauma during turbine passage (Colotelo et al. 2012).

The specifics of the hydroelectric facility also determine the risk of barotrauma during turbine passage (**Figure 4**). Turbine operation is a factor because the pressure differential increases with turbine discharge (Richmond et al. 2014). The water depth in front of the intake is an important variable because acclimation pressure increases with depth. Fish entrained at depth are more susceptible to injury and mortality passing through the nadir pressure regions downstream from the wicket gates/guide vanes and runner because the absolute pressure difference is greater. In addition, fish acclimated at depth are transported to a tailrace that may not be deep enough or quiescent enough for them to gradually acclimate to near surface pressure regions causing barotrauma according to Henry's Law (Brown et al. 2012).

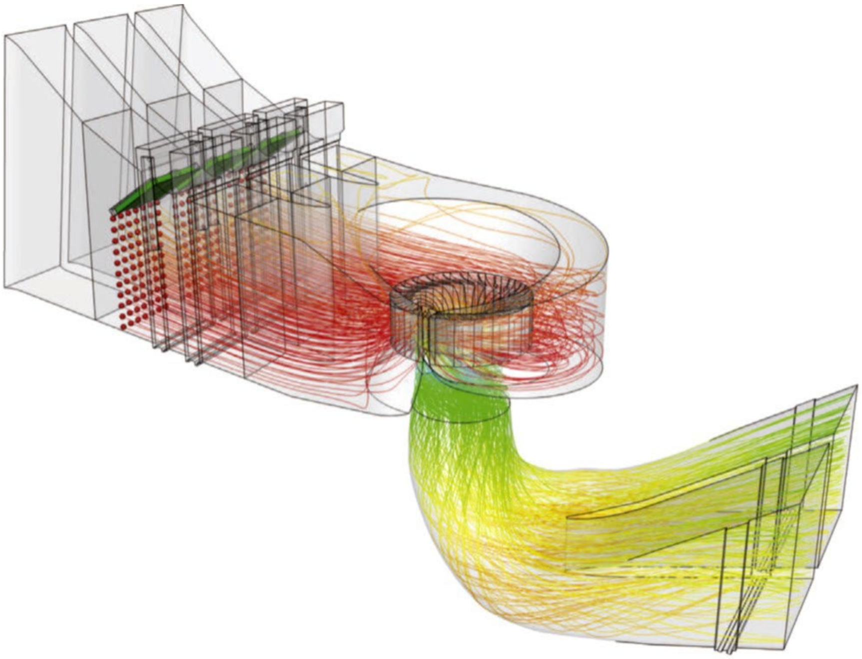

Figure 4. Transparent, isometric view of the pressure environment in a draft tube simulated by a three-dimensional computational fluid dynamic model showing stream traces originating from 180 uniformly spaced seeds at the intake. Warm colors (e.g., red) represent high pressure and cool colors (e.g., blue-green) represent low pressure. Image courtesy of Richmond and Romero-Gomez (2014).

3.4.2 Spill

When water is spilling at a hydroelectric facility through a controlled spillway (i.e., gated) and/or over an uncontrolled spillway, these become potential routes of downstream passage for diadromous fish. Spillways consist of three components: the outlet, conveyance, and discharge sections. The spillway types that are most germane to fish passage at hydroelectric facilities include drop, ogee, chute, and conduit spillways. As the name implies, the drop spillway involves water free falling over the crest onto the ground below or into a plunge pool. An ogee spillway has an S-shaped profile designed to maximize discharge at the design head. Flow over an ogee spillway maintains contact with the surface from the crest to the discharge section. Chute spillways are prismatic channels that convey water to a downstream reach. Conduit spillways are pressurized pipe or tunnel flow from submerged orifices or siphons. Controlled spillways have gates that are overflow (pneumatic, flashboard, or hydraulic) or orifice flow (tainter, roller, or sluice).

Spill can be a safe, timely, and effective means of downstream passage (Økland et al. 2019, Skalski et al. 2021), but not all spillways and gates are appropriate passage routes. Some spill outlets may not attract downstream migrants because of poor location (Trancart et al. 2020) or unfavorable hydraulics (Silva et al. 2016) causing migrational delay. Other spillways cause fish injuries from abrasive surfaces, energy dissipation baffles, accumulated debris, shallow or absent receiving waters, excessive turbulence, and/or rapid acceleration/deceleration (Bell and DeLacy 1972, Ruggles and Murray 1983). Water passing over spillways and through gates can entrain bubbles containing atmospheric gases that dissolve at depth in proportion to the partial pressure in the receiving water resulting in elevated total dissolved gases (gas supersaturation). If downstream migrants get overexposed or trapped in these environments, they may develop gas bubble disease (Algera et al. 2022).

The threats to downstream migrants passing via spill include delay, mechanical, fluid, and gas supersaturation exposure injuries (Pflugrath et al. 2020b). We provide more detail for each of these threats in the following subsections.

3.4.2.1 Spill Induced Delay

Location is a key factor when evaluating a hydroelectric facility for migratory delay caused by spill. Poorly located outlets will require searching behavior by migrating fish. For example, a facility may have a spillway separated from the bulk flow (typically turbine discharge) causing a searching behavior that is unnatural for downstream migrating fish who tend to travel with bulk flow to save energy (Haro 2003, Castro-Santos et al. 2010). In addition, the location of the spill may be distant from the preferred migratory path of the target species. For example, a migrating fish may swim within the thalweg of the channel that may not lead to the spillway, thereby increasing delay. Another example of spill-induced delay may occur at a facility with a surface outlet and the downstream migrating fish are demersal or vice versa (low-level outlet and pelagic species). In these instances, searching behavior outside of the natural depth preferences is required to pass a facility via spill. Spillway passage improved on the Columbia and Snake Rivers by modifying the spillway gates. These dams are large, with bottom (orifice) spill intakes located at 40 feet or greater depths. The species of concern, primarily salmon and steelhead, tend to be more surface oriented and resist sounding to find fish passage. Modifications were made by installing a weir in one or two spillways in each dam which allow water be drawn from the surface rather than the deeper bottom spill. Fish delay in the forebay decreased dramatically and the efficiency of passing fish by spill increased as well (Axel et al. 2007).

The hydraulics of the outlet is another important factor to determine potential migratory delay at a hydroelectric facility. Rapidly accelerating flow inhibits timely fish passage as it elicits an avoidance response for migrating fish (Haro et al. 1998, Kemp et al. 2005, Enders et al. 2009, Enders et al. 2012, Vowles et al. 2014, Piper et al. 2015). Therefore, spill routes that produce gradually accelerating flow (ogee spillways, broad-crested weirs, bell mouth orifices) will minimize delay, whereas sharp-crested weirs (e.g., overtopped flashboards, downward opening gates) and orifices (e.g., low-level outlets, tainter gates) will exacerbate migratory delay. The depth of water at surficial outlets is also important for migrating fish to commit to spill routes. In general, the water depth should be greater than two times the body depth of the migrating species to be a viable route of egress.

Finally, predation may be a contributing factor to migratory delay during spill passage. Hydroelectricity facility outlets concentrate downstream migrating fish, which attract predators (birds and fish) that may inhibit the approach of downstream migrating fish to the outlet. In these instances, downstream migrating fish may look for other routes of egress or wait until conditions improve (e.g., nighttime) to pass the facility. Predation is also a concern in the spillway tailrace, and the Applicant should implement measures to ensure that fish move rapidly out of the tailrace to mitigate the risk from these high predation areas.

3.4.2.2 Spill Induced Mechanical Injury

Fish entrained in the flow through spillways may experience mechanical injury from two main mechanisms: impact with a hard surface or abrasion against a rough surface. At the outlet, fish may hit a pier or other protuberance in the flow path. In addition, for outlets with overflow gates, fish may experience a drop over the crest gates (typically flashboards, but also pneumatically or hydraulically actuated) that results in an injurious impact on the concrete spillway or other hard surface. As a fish travels downstream, it may hit lodged debris in the flow path or abrade against surfaces if the depth of water is too shallow or the flow path takes sharp turns. When the fish reaches the discharge area, the receiving water may not be deep enough to prevent impact injuries or debris may accumulate increasing the probability of injury (Castro-Santos et al. 2021). In addition, many spillways have energy dissipation baffles that likely result in fish mortality at impact.

Research that informs guidance for evaluating the risk of mechanical injuries via spillways is sparse. Seminal work with Pacific salmon determined juvenile salmonids survived a free fall at velocities up to 50 feet per second (fps). In the same compendium of studies, the authors concluded that juvenile salmon will not survive impacts with solid objects at velocities of 20 fps (Bell and DeLacy 1972). These values were adjusted to 100% survival after a free fall up to 60 fps and solid impact up to 15 fps (Bell 1990). However, the researchers did not evaluate non-lethal injuries, nor were other diadromous species studied.

3.4.2.3 Spill Induced Fluid Injury

Fish entrained in spillway flow may experience fluid injury from shear stresses. Because the maladies caused by shear forces are often indistinguishable from mechanical injuries (Mueller et al. 2017a), evaluation of the risk is estimated in combination with mechanical injuries with species-specific laboratory studies, computational fluid dynamic (CFD) modeling, and field studies (Richmond et al. 2009, Duncan 2013, Duncan et al. 2018, Hou et al. 2018, Pflugrath et al. 2020b). The most likely location where shear stresses may injure fish is the discharge section as the spill flow rapidly decelerates. In some instances, a submerged orifice (e.g., low-level outlet) may produce rapid acceleration that result in shear forces that injure a fish.

3.4.2.4 Spill Induced Gas Bubble Disease

For hydroelectric facilities with adequate depth and plunging flow in the discharge section of a spillway, the receiving water may have gas supersaturation following Henry’s law that may create large plumes of water that are potentially dangerous for fish. Installation of flow deflectors, (which limit plunging flows) in spillways can greatly reduce the level of dissolved gas in the tailrace, though not to zero (Li et al. 2023). Fish that pass the facility through the turbines, or chaotic spill environments, are at a higher risk of gas bubble disease because of disorientation and/or non-related injury that prevent active movement away from supersaturated water. Dependent on flow, wind, and atmospheric pressure, supersaturation decreases as water flows downstream from the dam. However, in systems with multiple dams gas saturation may not drop to, or below, 100% before reaching the next dam.

3.4.3 Fish Bypass

For decades, hydroelectric facilities have been constructing designated bypass systems for downstream migrating fish (Schilt 2007). In theory, these facilities are designed to be the safest and timeliest routes of passage at a hydroelectric facility (USFWS 2019, NMFS 2022). In reality, many of these facilities are under-sized, poorly designed, neglected, and/or incompetently operated leading to substandard efficiency and, sometimes, a downstream passage threat (Kynard and O'Leary 1993, Wertheimer and Evans 2005, Croze et al. 2008, Noonan et al. 2012, Nyqvist 2016, Ovidio et al. 2017, Klopries et al. 2018, Knott et al. 2019, Kock et al. 2019). Like spillways, fish bypasses consist of three main components: an entrance (i.e., outlet), conveyance, and discharge section. The Applicant should evaluate the fish bypass for the same threats outlined in the spill section (3.4.2) to ensure the system provides safe, timely, and effective passage for downstream migrants.

3.4.4 Navigational Locks

Navigational locks may be associated with hydroelectric facility infrastructure. The Applicant usually does not operate these facilities, so navigation locks are often not part of the FERC licensing and compliance process. In the rare cases that a navigation lock is under FERC jurisdiction, there is very little known about the potential threat to downstream migrating fish (Vergeynst et al. 2019). However, as a potential route of egress, the Applicant should evaluate these facilities for threats based on the principles outlined for the primary routes of passage. Depending on the fish species, navigational locks may lack the necessary cues for fish to locate the passage routes or the potential passage routes may elicit an avoidance response. However, when lock operations overlap with migratory seasons, the Applicant will need to evaluate the risk that navigational locks pose to downstream migrating diadromous species. When the risk of delay or injury is high, navigation locks may require screening of intakes/outlets and/or other measures to avoid affecting fish.

3.5 Existing Information

Hydroelectric facility owners usually possess substantial information that they can incorporate into their downstream passage effects analysis during a licensing/exemption process or compliance activity. Before collecting more information through field studies and modeling, a thorough review and compilation of relevant information is required. Data describing site-specific details (e.g. infrastructure, operational protocols, and local conditions) and relevant studies from other facilities will be useful for estimating downstream passage impacts. This effort should identify data gaps and the probable risks to safe, timely, and effective downstream passage at a facility; thus saving the Applicant time and money with future field studies (Step Two) and data analysis and modeling (Step Three).

3.5.1 Site-Specific Information

Hydroelectric facility owners should have basic information including facility drawings and specifications. For old facilities, this information may need to be updated, and, in some instances, may be unavailable. At a minimum, the drawings will meet the Commission's standards for Exhibit F drawings (18 CFR §4.39). However, these drawings likely do not include enough information to fully identify and evaluate the risks and threats during downstream passage. For example, Exhibit F drawings do not contain adequate information to evaluate turbine passage (e.g., trash rack clear spacing, turbine rotational speed, runner blade thickness).

In addition, each facility has an operation protocol for various river flow and energy market conditions. A clear understanding of how the facility operates is necessary to determine the effects on downstream passage. This includes much more detail than is typically provided in the application documents. Examples of site-specific operational information include, but are not limited to:

- Debris management – debris types, loads, frequency, control measures, and removal strategies
- Spill management – spillway locations, types, prioritization, capacities, energy dissipators, and reliability (e.g., flashboards)
- Turbine operation – types, prioritization, ramping, reliability, flow range, cavitation, efficiency curves, number of stay vanes, number and operational settings of wicket gates
- Fish bypass management – operating season, modes of operation, target species and life stages, effectiveness, efficiency, and safety
- Hydrologic and hydraulic rating curves – migratory flow duration curves, headpond rating curves, and tailwater rating curves (with and without generation)

In consultation with NMFS and other agencies, site-specific information collected in previous licensing/exemption and compliance studies may be valid for determining the present-day effects on trust species during downstream migration. However, the methodology used in the previous studies needs to meet equivalency standards when compared to contemporary methods. In addition, the baseline environmental and operational conditions must be equivalent between the past and present studies. For example, a facility with an old turbine passage study with tailrace netting may provide useful information on the safety of turbine passage, but netting methodology has advanced since the early studies and past inferences from the data may no longer be relevant. Similarly, if past studies were conducted when the river system had a different regulation (e.g., peaking versus run-of-river), then old study conclusions may no longer be relevant. In some instances, this may require a new, comprehensive study, but more likely, previous studies will identify unknowns and focus new studies on those unknowns.

3.5.2 Information from Other Facilities

The use of study results from one hydroelectric facility for another has been common practice during compliance and the licensing process for decades (EPRI 1992). We encourage the use of previous studies to inform new ones, but consider the usefulness of non-site-specific studies to be limited for determining project effects during licensing or compliance. Each hydroelectric facility is unique and the study results from one facility are unlikely to reflect the effects on downstream migrants at another facility. This goes beyond the differences in facility infrastructure and operations as diadromous species' migratory behavior and condition will vary from site to site based on exogenous and endogenous factors. For example, a study of Atlantic salmon smolt passage at a facility in the upper watershed will produce a survival estimate that is unlikely to reflect passage survival at an identical facility with the same operation in the lower watershed. This is because a smolt may be experiencing osmotic or temperature-related stressors near the end of their freshwater emigration (McCormick et al. 1998, McCormick et al. 1999) and be more sensitive to project impacts at the downstream facility. In addition, a downstream passage effects analysis in the upper watershed may not reflect the cumulative effects in the lower watershed.

Some may argue that studies from similar facilities that estimate an average survival of 85% with a range of ±10% is as good as an estimate derived from a site-specific study producing the same estimate and range. NMFS disagrees; inherent in the execution of a site-specific study is the ability to use the results as diagnostic information to explain the variance in the estimate. For example, if an Applicant was estimating spillway survival and conducted field studies under multiple flow conditions that determined survival meets management goals only at a specific flow, this is useful information, whereas an average estimate from multiple other facilities does not provide this same type of information. Therefore, NMFS values understanding the variance in the survival estimate associated with site-specific studies that help identify potential mitigation measures to reduce the impacts. Then additional field studies or modeling exercises will focus on ways to improve the facility survival. The amalgamation of study results from disparate facilities will produce an average estimate and range, but assessments of site-specific studies are necessary to understand the unique operations and facility infrastructure that leads to appropriate mitigation strategies.

Others may argue that a site-specific study is not worth the cost if survival estimates are qualitatively high (e.g., the average survival estimate from surrogate facilities are 90%, and the actual site-specific survival estimate is 95%). However, while the difference in survival estimates may only be 5%, multiplying that estimate out to the watershed scale has significant fisheries management implications. For example, if that facility is one of eight in the watershed, the 5% difference in survival results in a basin wide emigration success rate of 43% instead of 66%. Therefore, accurate downstream passage survival estimates are crucial to the sustainable management of diadromous species. Cumulative effects from multiple hydroelectric facilities in the watershed are well-established fisheries management issue (Fraser et al. 2015, Harrison et al. 2019, Stich et al. 2019, Algera et al. 2020, Haxton 2021, Mensinger et al. 2021, Skalski et al. 2021, Zydlewski et al. 2023).

NMFS supports the development of downstream passage survival databases as this provides valuable information on existing impacts and future study design. However, there is no substitute for a site-specific study. When utilizing studies from other facilities, the Applicant will need to identify the project nuances and be able to describe how these differences may affect the survival estimate. The burden of proof will be on the Applicant to justify the use of data from other facilities; NMFS will question surrogate facility data without strong supporting justification. In addition, NMFS will question desktop modeling exercises that do not have calibrated and validated inputs.

4 Step Two – Field Studies

The second step in determining the impacts of a hydroelectric facility on downstream migrating fish is to conduct field studies that directly estimate survival or elucidate key unknowns to model survival. The Applicant can best accomplish this after a full characterization of the site (Step 1) including threat identification and synthesis of existing information.

4.1 Surrogate Fish

The use of surrogate fish may be necessary when species of interest are unavailable or protected. In selecting surrogate fish one should consider factors including behavior, size, general morphology (deep bodied, anguilliform, etc.), physical capacity (swim speed, swim duration), presence or absence of a swim bladder, and life stage. The more of these factors that are similar between species, the more likely the surrogate is to produce results that will be valid for the species of interest.

Taxonomically similar fish usually have the same physical characteristics and behavior (though important differences may exist). Fishes occupying similar ecological niches often have similar physical and behavioral characteristics as well. A typically fruitful strategy in determining a surrogate is to begin by considering closely related species then gradually working outwards until identifying a suitable candidate. If no closely related species are available then fish fulfilling similar niches are another possibility. Due to convergent evolution, they frequently display similar characteristics and behavior (Saylor et al. 2020).

The validity of using surrogates is also dependent on the information needed. If the situation involves fish moving passively, then a surrogate of similar body size, mass, and buoyancy may prove sufficient. However, if the situation involves active movement through passage routes, or selection of a particular route, then the physical capabilities and behavior of the fish are more likely to play a significant role. Before embarking on a field study using surrogate fish, the Applicant should consult with NMFS and other resources agencies on the selection.

4.2 Route Survival

Each route of downstream passage at a hydroelectric facility requires assessment for survival and injury rate using one or more of the following methodologies: radio telemetry (Skalski et al. 2002), PIT telemetry (Skalski et al. 1998), acoustic telemetry (McMichael et al. 2010), balloon tags (Heisey et al. 1992), netting (Mueller et al. 2017a), and Sensor Fish (Deng et al. 2014).

4.2.1 Telemetry

Telemetry involves affixing a tag onto a fish that emits a pulsed signal detected by aerial or underwater antennae at fixed receivers or via mobile tracking. Telemetry allows investigators to track where and when fish move through the zone of influence of a hydroelectric facility. There are two main types of telemetry used in fisheries studies: radio and acoustic technology (Brownscombe et al. 2019). Radio tags send electromagnetic energy in the radio frequency range (30 to 300 MHz) and are effective in shallow freshwater (< 10 m) environments. Acoustic tags transmit a periodic acoustic signal detected by hydrophones and are effective at depth in both salt and freshwater environments, which can be informative (e.g., head-of-tide dams, determining latent survival) for diadromous species that traverse both environments during downstream migration. However, acoustic receiver arrays may miss detections in shallow, turbulent, and noisy deployments. An added advantage of acoustic tags is the ability to detect fine-scale (~1 m) three-dimensional locations of fish with multiple receiver arrays and data processing (Martinez et al. 2021, Lennox et al. 2023). An added advantage of radio antennae are flexibility with deployment (i.e., underwater and above water) and the directionality of the receiver allows for more effective determination of route selection. Due to the complementary strengths and weaknesses of each technology, dual tags that use both signal technologies are available. In addition, specialized tags can estimate mortality by changing the tag signal when the tagged individual becomes stationary or a predator consumes the fish. The study design should also include mobile tracking and multiple downstream receivers to account for dead drift (Havn et al. 2017a). A full description of telemetry methodology (i.e., tagging, tracking, analysis, and interpretation) is beyond the scope of this document, so we recommend the reader refer to reviews in the literature (Cooke et al. 2013, Brownscombe et al. 2019).

Another tag type frequently used in telemetry studies at hydroelectric facilities are passive integrated transponders (PIT). PIT technology is essentially radio telemetry in reverse: the receiver array emits a low frequency radio signal (125 to 450 kHz) that reads an encoded, passive transponder implanted into a fish. PIT tags are the longest lasting, cheapest, and least obtrusive of the tagging technologies in common use, but are constrained by detection range and signal collision (Cooke et al. 2013). To identify specific routes of passage with PIT tags, each route must be equipped with PIT tag detection antennas. These antennas are typically loops that the fish pass through or flat plates the fish pass next to or over. Deployment of these antennas in passage routes can be challenging because the fish must pass relatively close to the detector, and the detectors are very sensitive to interference from metal structures. However, researchers have developed and implemented numerous successful antenna array strategies to overcome these limitations (Harnish et al. 2020, Tiffan et al. 2021, Ohms et al. 2023). Areas where fish pass through a pipe or other small orifice, such as bypasses or fish ladders are the most suitable for installing PIT antennas.

Often times, estimating route survival with telemetry methods requires large sample sizes to produce statistically significant results for less common routes or at facilities with many passage routes. In these instances, supplemental study methodology (e.g., balloon tags – see Section 4.2.2) may strengthen the route survival estimation. Alternatively, though not promoted through existing licensing processes, expanding telemetry studies to larger spatial extents (i.e., full or partial watersheds) dramatically increases the cost-benefit of conducting these studies. For example, recently on the Merrimack River in Massachusetts, the owner of three facilities conducted a comprehensive downstream American eel survival study with release locations in the impoundments of the two upstream facilities that had required compliance and licensing studies. The owner chose to deploy an antenna array at the downstream project though none was required at the time of the study, the data collected was used in the subsequent licensing proceeding at the downstream facility providing sufficient information according to FERC to do a downstream passage effects analysis for American eel (FERC Accession No. 20240510-3049).

This approach is highly recommended for small hydroelectric facilities that struggle to pay for the requisite studies and/or watersheds where multiple projects are undergoing licensing and compliance monitoring within a short timeframe. We encourage Applicants to collaborate with resource agencies and other hydroelectric facility owners in their watershed to conduct large-scale telemetry studies. For facilities that are not in the licensing process, proactively participating in these studies will not preclude the need for future studies, but if needed, future studies will be focused and more cost-effective.

4.2.2 Balloon Tags

Balloon tags were specifically developed as a mark-recapture method for turbine survival studies (Heisey et al. 1992). During this procedure, a technician tags a fish with a time-release balloon before releasing the test specimen into the turbine intake. Once the fish passes the turbine environment, the balloon inflates allowing for rapid recapture of the test specimen in the tailrace. Application of this technology to other routes of downstream passage at hydroelectric facilities has been successful (Mathur et al. 1996, Johnson et al. 2003). There are multiple benefits to this technology. First, the technicians can evaluate the specimens before and after the test for lethal and non-lethal injury with post-passage holding time that allows for estimation of latent mortality. In addition, the test specimens can undergo necroscopy or x-ray imaging allowing for identification of internal injuries (Mueller et al. 2020). Second, the rapid and high recapture rate decreases field effort, data processing, and the need for larger sample sizes; which along with the relatively low tag price, lowers the overall study cost. Third, this technique often produces more conclusive route-specific injury and mortality results than telemetry, particularly when studying juveniles, though recent advances in telemetry tag technology are reducing the tagging effect on juveniles (Deng et al. 2015, Mueller et al. 2017b, Mueller et al. 2019, Deng et al. 2021). Drawbacks of this technology include limited availability due to patent protection, the resulting data provide no information on delay or route choice, and the methodology involves destructive testing which has implications for protected species. Applicants may sometimes use a surrogate species (see Section 4.1) to avoid impacts to protected species.

4.2.3 Netting

Before balloon tags were developed for route-specific survival studies at hydroelectric facilities, netting the discharge of a turbine or another downstream passage route was the common capture method (Cramer and Donaldson 1964, EPRI 1992). However, hydroelectric facilities in the U.S. over the last few decades typically have not used this method during the study process. Likely reasons for this include cost, confounding catch effects, and poor catch efficiency. In Germany, where netting is still practiced, a standardized protocol has been developed that can be used by U.S. hydroelectric facilities where appropriate and desired (Mueller et al. 2017a). The main benefit of netting is a turbine entrainment rate can be calculated for a fish assemblage (Sorenson et al. 1998). However, this information is less important for obligatory migrating diadromous fish compared to resident species. Another benefit of netting is the ability to evaluate a wider range of fish sizes and life stages as some marking methods preclude tagging small fish.

4.2.4 Sensor Fish

In 1998, scientists at the Pacific Northwest National Laboratory developed an autonomous sensor called a Sensor Fish that measures the hydraulic environments that fish experience when passing a hydroelectric project (Carlson and Duncan 2003). Over the last few decades, the developers have tested, modified and improved the Sensor Fish technology (Dauble et al. 2007, Richmond et al. 2009, Deng et al. 2010, Duncan 2013, Deng et al. 2014, Fu et al. 2016, Boys et al. 2018, Duncan et al. 2018, Hou et al. 2018, Martinez et al. 2019c). Now it is commercialized and available for use in downstream passage studies. The commercialized version of the Sensor Fish is a 3.5-inch-long by 1-inch-diameter device weighing 1.5-ounces that measures temperature, acceleration, pressure, and angular velocity. The Sensor Fish is neutrally buoyant when deployed and automatically floats to the water surface after deployment to be recovered using radio antenna tracking. Similar to balloon tags, the investigator introduces the Sensor Fish to the route of passage at the depth and location needing evaluation. After recovery, the data is downloaded and compared to empirically-derived dose-response thresholds of mechanical, fluid, and barotrauma stressors to predict fish injury and mortality during passage (Hou et al. 2018, Pflugrath et al. 2020b). Sensor fish act as a passive particle during deployment, so the data collected is not always representative of actively swimming and larger fish.

4.3 Route Probability

“Fish go with the flow” is the common assumption when estimating route probability (i.e., 75% of the fish will go with 75% of the flow). This oversimplification may be correct, but requires field study at each hydroelectric facility to validate the assumption. Multiple years of study may be required if the facility operates abnormally (e.g., a turbine unit is in maintenance) or the hydrologic year is unrepresentative of typical migratory environmental conditions (e.g., drought year with no spill). The recommended methodology for these studies is radio or acoustic telemetry using Mark-Recapture analysis (Perry et al. 2012). Another potential methodology may be the use of sonar imaging to estimate route selection, if the passage routes are limited and the fish can be reliably identified (Ransom et al. 1996, Johnson et al. 2004, Grote et al. 2014, Caumartin et al. 2020, Keeken et al. 2020, Smith et al. 2020).

Conducting a full-scale telemetry study on all diadromous species and life stages may be cost- and time-prohibitive at some sites, so the Applicant should consult with NMFS staff and other resource agencies to determine the appropriate species and life stages that will adequately characterize the facility for route probability. For example, a traits-based assessment may be useful at sites with many diadromous species migrating past the facility (Cada and Schweizer 2012).

4.4 Migratory Delay

The preferred method of estimating route-specific migratory delay at hydroelectric facilities is radio or acoustic telemetry with Time-to-Event analysis (Castro-Santos and Haro 2003, Castro-Santos and Perry 2012). This involves deploying an array of receivers in series and parallel upstream, downstream, and throughout the zone of influence of a hydroelectric facility. At a minimum, receiver arrays must cover the following locations:

- Upstream extent of the zone of influence of the project to establish a time stamp for when the individual enters the study area.
- Upstream location from facility infrastructure before any route choices are made by the individual to establish a time stamp for the near-field approach to the facility and the route choices
- At each of the possible route choices (i.e., spill, turbine, fish bypass) to determine the time stamp for each route of passage.
- Immediately downstream from the facility infrastructure to confirm passage.
- Downstream extent of the zone of influence of the project to establish a time stamp for when the individual leaves the study area.

At each receiver station, a high detection efficiency is required (Perry et al. 2012). Therefore, to avoid inconclusive results, multiple receivers may be required to ensure a high detection probability at a station.

4.5 Predation

Predation has been a confounding factor when evaluating safe, timely, and effective downstream passage at hydroelectric facilities (Gibson et al. 2015). Though difficult to determine the extent a facility has on predation rate, anything that causes delay or concentration of prey species is likely to increase predation mortality. Predators have evolved to detect, and exploit concentrations of prey species caused by both anthropogenic and natural factors (Furey et al. 2018). Actual levels of predation are also likely to vary with predator populations, seasonal patterns of predator activity (feeding young), and environmental effects on predators such as temperature. Changing a flowing river to a lacustrine environment favors predators that prefer those conditions (Rieman et al. 1991, Zydlewski et al. 2023, Mensinger et al. 2024). The ability to distinguish the difference between natural predation and facility-induced predation is difficult. However, recent advances in telemetry technology with tags designed to detect predation (Bouletreau et al. 2020, Hanssen et al. 2021) or post-study analyses (Daniels et al. 2018, Chavarie et al. 2022) may be able to estimate facility-induced predation. In addition, non-tagging methods including dietary analyses (Schmitt et al. 2017) and species assemblage studies (Whittum et al. 2023) will provide insight to the predator-prey dynamics at hydroelectric facilities. Finally, where applicable, a nearby reference reach of sufficient length may be included in the telemetry study to estimate a background (natural) mortality rate for emigrating species for comparison with the mortality rate through the impoundment or tailrace (Mensinger et al. 2024).

5 Step Three – Data Analysis and Modeling

The third step in determining the impacts of a hydroelectric facility on downstream migrating fish is to analyze the data and use modeling approaches to estimate route selection probability, route survival, project survival, and evaluate mitigation strategies.

5.1 Mark-Recapture Studies

Mark-recapture studies involve capturing a sample of a population (or suitable surrogates), marking them, and releasing them into the study area. Based on the number of marked fish recaptured, or detected in the case of active tags (e.g., radio, PIT, acoustic), the Applicant can generate estimates of survival, population size and other parameters. Mark-recapture studies are the most common method for estimating project survival because of the difficulty ascertaining the true number of fish at the start and end of the survival test. Other methods such as hydro-acoustics, video, and fyke nets may estimate parameters such as the numbers of unmarked fish using a particular route of passage, but are unable to estimate survival.

Investigators have developed numerous experimental designs and statistical models for mark-recapture studies (Adams et al. 2012, Brownscombe et al. 2019). The extensive salmonid survival studies conducted on the Columbia and Snake Rivers provide some examples (Giorgi et al. 2010). Practical considerations include the availability of fish from the population (or suitable surrogates) to mark with tags and the opportunities for recapture, or detection, of active tags. Confidence intervals surrounding parameters derived from mark-recapture studies depend on the number of tags released and the number recaptured or detected. Thus, if probability of detection is low, more tagged fish releases will need to occur to provide a survival estimate of acceptable precision. Likewise, if a project has multiple routes of passage and operations affect the usage of those routes, then the sample size will need to be large enough with an adequate number of release dates to provide information for each route of passage and operational condition. An excellent discussion of biological and statistical standards used in FERC licensing of hydropower facilities is in Molina-Moctezuma and Zydlewski (2020). Well-designed mark-recapture studies can provide estimates of multiple parameters including project survival, travel times, passage route selection, and specific route or sub-reach survivals. The following sections describe some common analytical and experimental designs that estimate fish passage survival and other relevant parameters.

5.1.1 Cormack-Jolly-Seber

The Cormack-Jolly-Seber (CJS) model is a statistical method for estimating survival when recapture/detection probabilities are significantly less than 100% (Cormack 1964, Jolly 1965, Seber 1965). Since that seminal work, there has been substantial literature elaborating on this approach and exploring applications (Adams et al. 2012, Cooke et al. 2013, Brownscombe et al. 2019). CJS has become a standard model for use in fish and wildlife mark-recapture and other tagging studies.

The CJS methodology partitions the probability of detection from the estimate of survival. With regard to downstream passage studies, the CJS method estimates survival from point A to point B where the survival estimate is actually the probability of detection multiplied by the number of fish detected. The experimental design of a CJS study requires at least one detection/recapture location beyond the study reach to calculate a detection probability for the last station within the study reach. For a downstream survival study, this last detection/recapture location should be immediately downstream from the study reach to prevent ambiguous results. The downstream extent of the study reach is defined as the longitudinal point in the river where conditions (e.g., hydraulics, water quality) are unaffected by facility operations.

5.1.2 Paired-Release

The paired release methodology (Skalski et al. 2010) attempts to separate dam-related mortality from background levels of mortality by adjusting the survival of test fish that pass the dam by the survival of control fish released downstream of the dam. The paired-release-recapture design has a minimum of two release locations, one above and one below the zone of inference (Test Release and Control Release), and two downstream monitoring sites (Peven et al. 2005). The use of only a single downstream monitoring station is inadequate to distinguish differences in survival from differences in downstream detection probabilities between the two release groups (Perry et al. 2012). The focus of this design is to estimate survival in the reach between the two release points, which typically includes a hydropower dam. The model adjusts the survival estimate by dividing the survival of the test fish by the survival of the control fish.

A requirement of the paired-release methodology is that both release groups share common survival processes in the reach below the downstream release site (Giorgi et al. 2010). Valid estimation of survival depends on the assumption that survival processes are constant over the course of the study. The study design needs to ensure that both release groups experience the same degree of handling and transportation effects. When paired release groups are close in proximity, the likelihood of downstream mixing increases and makes it more probable that post-release handling mortality will be equal between the two release groups. This can be accomplished by placement of the first downstream monitoring station far enough away from the release locations that any post-release handling mortality has already been expressed in both release groups (Giorgi et al. 2010). In any survival study, it is essential that the monitored study reach be sufficiently long to capture all mortality attributable to dam passage.

Paired release methodology inflates the error associated with any survival estimate and, thus, overestimates survival when sample sizes are small (Zydlewski et al. 2017). Zydlewski et al (2017) concludes, “Paired release is generally not advantageous at release sizes less than 1000.” The paired release methodology is widely utilized at hydroelectric projects on the Columbia River using larger sample sizes.

5.1.3 Multistate

Similar to CJS models, multistate models partition survival and detection probabilities. In addition, multistate models allow grouping of individuals to estimate survival and detection parameters for each group (i.e., state). Multistate models describe the process of fish passing a project as a series of “states”. The investigator generally arranges these states in a series based on time or location. The probability of a fish transitioning from one state to another derives from empirical observations (i.e., detection). Examples of transitions include from live fish to dead fish or from location to location. Each transition has a probability of occurring that may change depending on fish location or the operational/environmental condition at the time of transitioning.

For every model, there is a "state space" which defines all the states that are possible such as alive or dead, in the reservoir, passing via spill, passing via turbines, etc. For example, during downstream fish passage at a hydroelectric facility, the first state is typically the upstream extent of the reservoir where there is a probability of the fish transitioning from a live fish to a dead fish (i.e. survival) and a probability of moving downstream in the reservoir. The second state is upstream from the dam/powerhouse where there is a probability of the fish transitioning back to the upper reservoir (State 1), a spillway route (State 3), a turbine route (State 4), a bypass route (State 5), or perishing while in the second state. Each route of passage at the dam/powerhouse will have a probability of survival corrected by the route-specific detection probabilities. The route-specific survival multistate model requires replicate telemetry arrays for each route of passage to determine route detection probabilities (Skalski et al. 2002). An example of this type of model is the comprehensive passage (COMPASS) model used on the Columbia River (Zabel et al. 2008, Perry et al. 2010, Aeberhard et al. 2018, NMFS 2019, Stock and Miller 2021).

5.1.4 Time-to-Event

Time-to-event analysis presents a more detailed picture of fish passage behavior at hydroelectric projects. The forebay is divided into an approach zone (outside the direct detection range of a route of passage), entry zone (where fish can detect physical cues of the passage route such a flow) and the passage route itself. Fish may pass from approach zone to the entry zones of the available routes of passage and back to the approach zone, but once they have entered the route of passage they move to the tailrace requiring a telemetry array set up that can validate this assumption. The amount of time spent in each zone, in addition to the possible number of rejections of a route of passage provides information on possible delays, as well as the attraction and capture effectiveness of a particular route. In addition, the model can incorporate covariates that affect passage success and delay (e.g., river flow, temperature, operations) into the model structure. This analysis provides more useful information than multistate or paired release studies that cannot account for covariates that affect passage. For example, a model that only accounts for the final route of passage and survival may fail to identify issues such as significant loss of fish due to long forebay residence times (Nyqvist et al. 2017).

These studies typically require acoustic or radio tags and a detection network that can identify the fish within the various zones and routes of passage. Castro-Santos and Perry (2012) provide a good overview of this model.

5.2 Blade-Strike Models

Deterministic blade-strike models have been utilized to estimate fish mortality passing through the turbine region of a hydroelectric facility for over 65 years (von Raben 1957). The original derivation assumed the probability of blade strike is the ratio of time for the length of fish to pass the leading edge of a turbine blade divided by the time successive blades pass the same point in the streamline the fish travelled. The original model assumed all fish align lengthwise with the streamline and every strike results in mortality. The original model over predicted strike mortality compared to observed mortality, so the author suggested adding a mutilation factor to account for the discrepancies. Additional modifications of the blade strike model include:

- more accurate assumptions of the internal flow field with a correlation factor (λ) to account for other passage threats related to the body length to blade spacing ratio (Franke et al. 1997),
- adding a mutilation ratio that is dependent on fish body mass (Turnpenny et al. 2000), and
- modifying the correlation factor (λ) to account for the fish length to blade thickness ratio and relative strike velocity (NEN 2020).

Further improvements to the blade-strike models should include fish orientation during blade strike (Saylor et al. 2020) and the strike location on the fish body (Amaral et al. 2020). However, these deterministic models cannot currently account for these improvements because of the stochastic nature of fish swimming behavior during turbine passage.

Recently, the U.S. Fish and Wildlife Service repackaged the Franke et al (1997) model as an Excel-based Visual Basic for Applications program called the Turbine Blade Strike Analysis (TBSA) tool (Towler and Pica 2019). The model adds bypass and spill route inputs allowing for a Monte Carlo simulation of a fish population to estimate project survival, not just turbine survival. Since that time, the use of deterministic blade-strike models in licensing and compliance studies of hydroelectric facilities has increased. Unfortunately, the increased use of blade-strike models has led to an increased misuse of blade-strike models. The modeler needs to understand that the inputs for the TBSA tool must be specific to the site and validated with field data for each passage route at a facility. Like all models, a poorly parameterized TBSA model will produce poor estimates of facility survival. Appropriate usage of the TBSA model (or variations thereof) include the following:

- The modeler tunes the correlation factor (λ) for the species and life stage as well as the facility infrastructure and operations using field studies at the site or from an agency-approved analogous site. The correlation factor (λ) must account for all blade strikes that are fatal as well as all other turbine passage threats (e.g., wicket gate and fluid shear mortality).
- The modeler bases the spillway and fish bypass survival estimates on field studies at the site or from an acceptable analogous site.
- The modeler bases the route selection probability on telemetry studies at the site that estimate route selection under at least two distinct operating conditions to evaluate whether operating condition is a covariate that effects the route selection probability.
- The modeler conducts a sensitivity analyses for any input parameter that is uncertain or does not have field data validation.

We conducted an exercise to highlight the potential error in output from a TBSA model that lacks appropriate input data. We selected nine hydroelectric projects with different turbine types that covered different regions of the United States capturing a range of diadromous species (**Table 1**). For each of these projects, we applied the TBSA model and compared the output with field-based survival estimates. The comparison included a turbine survival and a project survival estimate as described below. In both cases, we used the recommended correlation factor (λ) values, which are 0.2 for salmonids and alosines and 0.4 for American eel.

Table 1. Hydroelectric projects used in the comparison of the TBSA model and field-based survival studies.

Project	**River**	**State**	**Turbine**	**Species Group**
Vernon	Connecticut	NH/VT	Kaplan/Francis	Salmonids, Eel, Alosines
Lowell	Merrimack	MA	Kaplan	Salmonids, Eel, Alosines
Mine Falls	Nashua	NH	Kaplan	Alosines
West Enfield	Penobscot	ME	Kaplan	Salmonids, Eel, Alosines
Conowingo	Susquehanna	MD	Kaplan/Francis	Alosines
Ellsworth	Union	ME	Kaplan/Propeller	Salmonids, Eel, Alosines
McNary	Columbia	OR/WA	Kaplan	Salmonids
Little Goose	Snake	WA	Kaplan	Salmonids
Willamette Falls	Willamette	OR	Kaplan	Salmonids

For the turbine survival comparison, the precision of TBSA survival estimates with field-based methods, as measured by the difference between TBSA and field-based estimates was variable across turbine types and fish species (**Figure 5**). The precision of TBSA turbine survival estimates for Kaplan turbines was highly variable, with survival estimates ranging from large overestimates to large underestimates compared to field-based survival estimates. The precision of Francis turbine survival estimates were more consistent with field-based methods, but sample sizes were smaller. In general, the TBSA model underestimates the turbine survival of American eel and overestimates the survival of salmonid species compared to field-based methods. For alosines, the results of the TBSA model was generally similar to the field-based estimates. The comparison does not reflect the uncertainty in the field-based and TBSA estimates (length to blade thickness ratio, strike orientation, operating conditions, tagging effects, heterogeneity in mark/recapture methods etc.), but this demonstrates the need to tune the correlation factor (λ) to better reflect the unique characteristics of turbine passage at each hydroelectric project. Because the blade strike model is deterministic, the correlation factor (λ) is the only adjustable input to improve precision between methodologies.

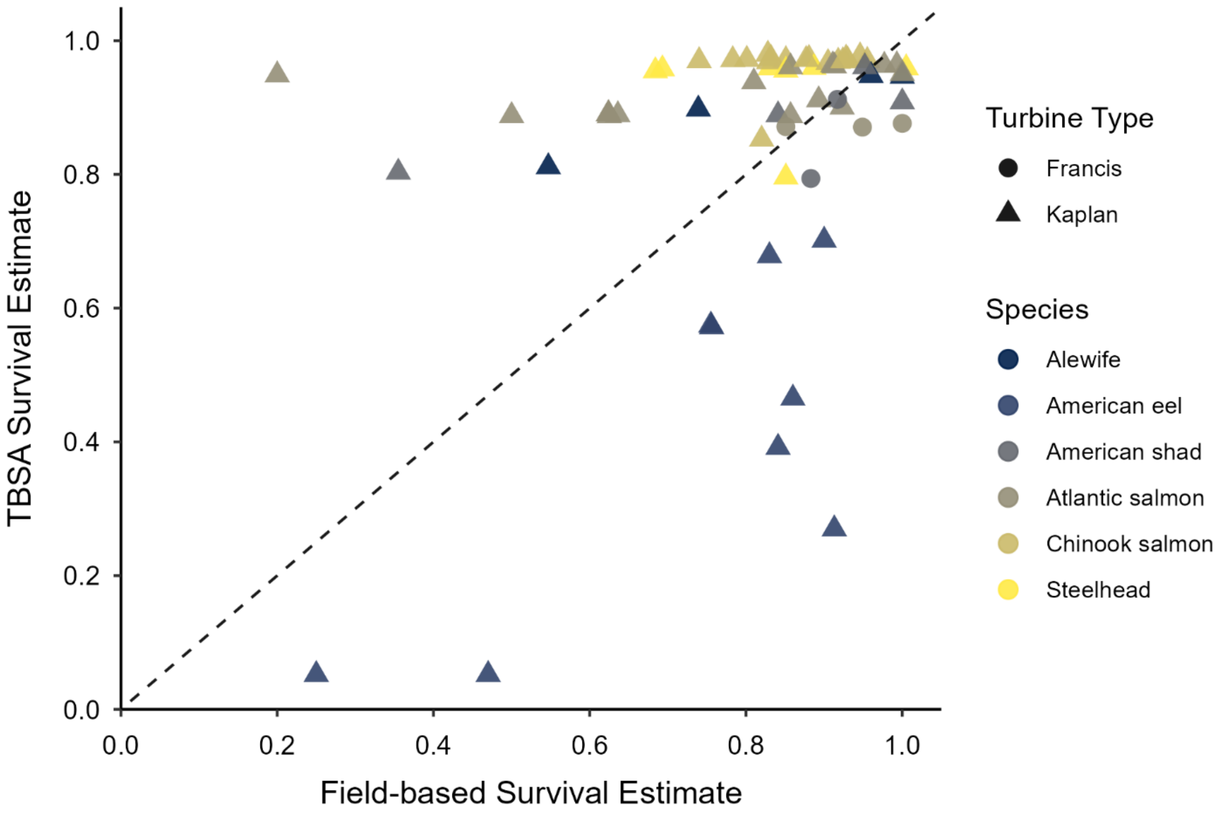

Figure 5. TBSA model versus field-based turbine survival estimates.

The precision of the TBSA project survival estimate compared to field-based methods were better than for turbine survival estimates (**Figure 5** and **Figure 6**). In general, the TBSA model underestimated project survival for American eel and slightly overestimated project survival of all other species (**Figure 6**). The improved precision in the simulated TBSA-derived project survival is attributable to field studies informing non-turbine route survival and the proportion of fish using those non-turbine routes, which reduces the effect of the turbine survival deviation (i.e., an unrepresentative correlation factor). Further analysis could include tuning the correlation factor (λ) so the turbine survival portion of the TBSA model better reflects field-based turbine survival estimates. In addition, as other hydroelectric facilities collect more field-based turbine survival data, modelers can calibrate and validate blade strike models further to better characterize relationships between particular infrastructure and operations with turbine survival.

In summary, a site-specific, calibrated, and validated TBSA model (or equivalent) is a powerful tool for examining Project effects on downstream migrating diadromous fish. Models, such as TBSA, are best used for expanding upon field-based study results, as it is unlikely that field studies fully characterize all environmental and operational conditions under the time limitations of compliance and licensing activities. As shown above, a TBSA model (or equivalent) that is not calibrated and validated will produce tenuous results.

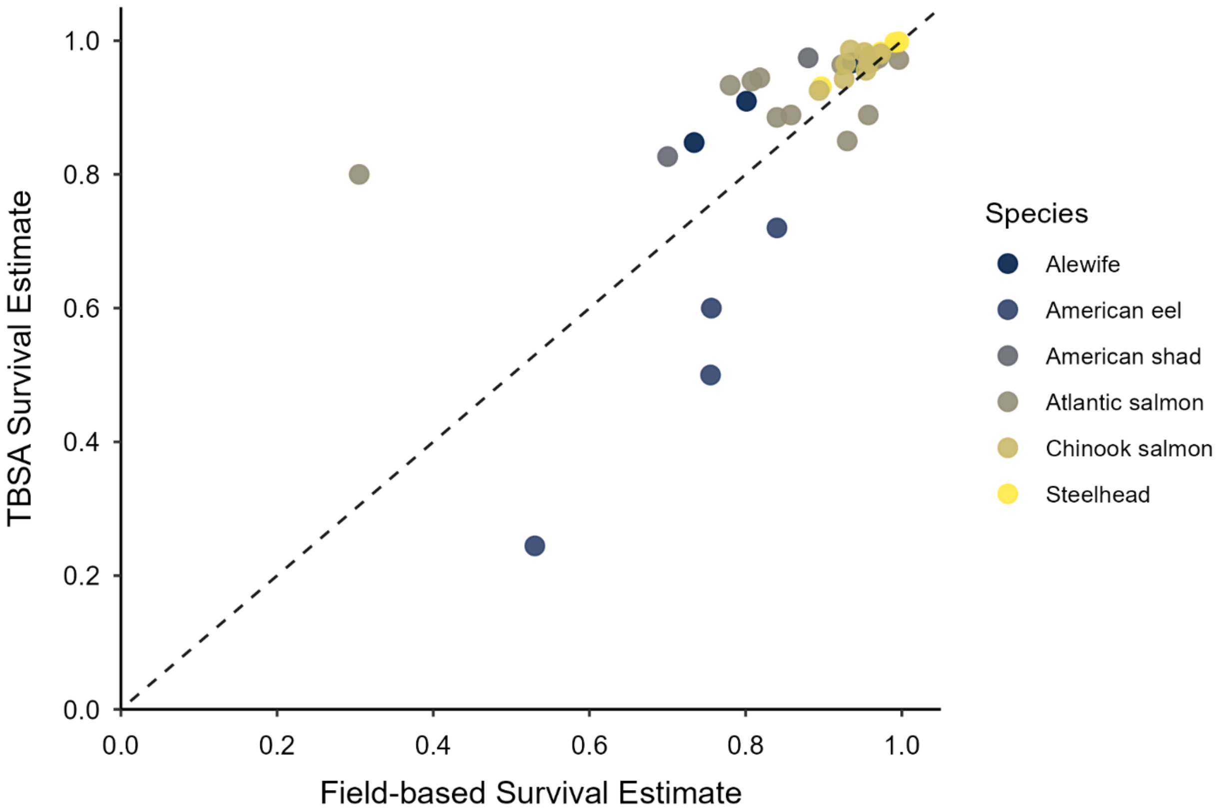

Figure 6. TBSA model versus field-based project survival estimates.

5.3 Biological Response Models

Since 2014, the Water Power Technology Office (WPTO) in the U.S. Department of Energy has developed 99 biological response models for mechanical, fluid, and barotrauma injuries for 31 different species of fish (Pflugrath et al. 2020b). Biological response models are analogous to dose-response relationships used in environmental rsk assessment that predict the incidence, probability and magnitude of adverse health effects to individuals or populations exposed to toxicants. **Table 2** lists the biological response models available for diadromous fish originating from laboratory studies that systematically evaluate mechanical, fluid, and barotrauma injuries and mortality through simulated stressors on test specimens in controlled environments. For example, mechanical injury is induced by a test apparatus that simulates the strike of a turbine blade on an anesthetized live fish (see Pflugrath et al. (2020b) for full explanations of laboratory testing). The dose variables used in these relationships are blade strike velocity (m s^{-1}) for mechanical injury, the ratio of pressure change (acclimation/nadir) for barotrauma injury, and strain rate (s^{-1}) for fluid injury. The response variables are the probability of injury, major injury, and mortality. The categories of injury and major injury are subjective with the difference presumably the likelihood of full recovery from the injuries.

Table 2. Biological response models for diadromous fish.

Species	**Life Stage**	**Model**	**Citation**
American Eel	Adult	Mechanical	Saylor et al. (2019)
American Eel	Adult	Barotrauma	Pflugrath et al. (2019)
American Eel	Adult	Fluid	Pflugrath et al. (2021)
American Shad	Juvenile	Mechanical	Saylor et al. (2020)
American Shad	Juvenile	Barotrauma	Pflugrath et al. (2020b)
American Shad	Juvenile	Fluid	Pflugrath et al. (2020b)
Atlantic Salmon	Smolt	Fluid	Turnpenny et al. (1992)
Blueback Herring *Alosa aestivalis*	Juvenile	Mechanical	Saylor et al. (2020)
Chinook Salmon *Oncorhynchus tshawytscha*	Juvenile	Barotrauma	Brown et al. (2012)
Chinook Salmon	Juvenile	Fluid	Neitzel et al. (2004)
Coho Salmon *Oncorhynchus kisutc*h	Juvenile	Fluid	Johnson (1972)
Gizzard Shad *Dorosoma cepedianum*	Adult	Mechanical	Saylor et al. (2020)
Pacific Lamprey *Entosphenus tridentatus*	Juvenile	Barotrauma	Colotelo et al. (2012)
Pacific Lamprey	Juvenile	Fluid	Moursund et al. (2000)
Rainbow Trout/Steelhead	Juvenile Adult	Mechanical	EPRI (2011) Saylor et al. (2020) Amaral et al. (2020)
Rainbow Trout/Steelhead	Juvenile	Barotrauma	Beirão et al. (2021)
Rainbow Trout/Steelhead	Juvenile	Fluid	Neitzel et al. (2004)
White Sturgeon *Acipenser transmontanus*	Juvenile	Barotrauma	Brown et al. (2016)

These dose-response relationships are most advantageous during the design process for new, rehabilitated, or retrofitted facilities. The WPTO has developed the Biological Performance Assessment software (https://www.pnnl.gov/projects/hydropassage/biopa) to assist designers and operators to optimize their design or existing equipment for fish safety. We support the use of these tools and encourage developers to consider fish safety in all aspects of hydroelectric facility design. During compliance monitoring and the licensing process, the Applicant may not produce computational fluid dynamic (CFD) models of all routes and operational conditions during downstream passage at a facility. However, if a CFD model exists; biological response models could help diagnose potential causes of poor route survival using the model simulation results.

Another tool developed by the WPTO is the Hydropower Biological Evaluation Toolset (HBET) that links Sensor Fish (Section 4.2.4) data to a remotely accessible database through a user-friendly interface. The objective of HBET is to facilitate Sensor Fish studies focused on characterizing the hydraulic conditions at hydropower infrastructure (e.g., turbines, spillways, bypasses). HBET allows Applicants to design studies, analyze collected Sensor Fish data, perform statistical analyses, and predict (not measure) biological responses. To date most of the field-based data and application using HBET and Sensor Fish originates from the developers (Deng et al. 2010, Fu et al. 2016, Duncan et al. 2018, Hou et al. 2018, Martinez et al. 2019a, Martinez et al. 2019b, Martinez et al. 2019c). Alone, Sensor Fish and HBET are not adequate for determining project effects on downstream migrating diadromous fish at hydroelectric facilities because the technology infers, rather than actually measures, the biological response from laboratory studies. There is a significant leap from controlled laboratory studies to real-world project effects, as lab studies cannot adequately incorporate physiological status, behavior, and environmental conditions that effect safe, timely and effective passage. In addition, the Sensor Fish does not behave (e.g., active swimming against the current) or have the same dimensions as an actual fish that may lead to incorrect inferences. However, Sensor Fish and HBET are excellent diagnostic tools to augment more traditional study designs (e.g., telemetry, balloon tags) for some fish species. For example, Sensor Fish provide evidence for where the stressor affecting the migrating fish is occurring during passage. Mark-recapture methods and desktop blade strike models integrate these stressors during passage and it is unlikely the Applicant will be able to tell from recapture data whether the injury is from a wicket gate, turbine blade, fluid shear, or all stressors combined. A properly designed and executed Sensor Fish study will provide useful information that will help develop mitigation strategies.

6 Step Four – Evaluation and Mitigation

The final step for an Applicant examining the impacts of a hydroelectric facility on downstream migrating fish is to estimate project survival and other project effects (e.g., delay) based on the best available information. Survival estimates and other project effects can be compared to a performance standard in an adaptive management framework that informs potential mitigation strategies at a hydroelectric facility and species management goals in the watershed.

6.1 Performance Standards

A performance standard establishes a measurable level of success needed to ensure safe, timely, and effective passage for diadromous fish migrating past hydroelectric facilities. The Applicant should evaluate these three characteristics quantitatively for downstream passage through the framework outlined in this Technical Memorandum. During the licensing process, performance standards are irrelevant because the Applicant needs to determine their project effects for FERC to complete their NEPA analysis and a biological assessment under the ESA section 7 consultation, where applicable. The Applicant must identify and quantify the project effects on diadromous resources in the licensing process regardless if there is a set performance standard or conservation management goal for that species.

As part of NMFS' mandatory conditioning authority in Section 18 of the FPA or as a reasonable and prudent measure in NMFS' incidental take statement of a biological opinion under the ESA, performance standards for downstream migrating diadromous fish may be a requirement of a license. Therefore, performance standards are necessary to determine whether a hydroelectric project is compliant with the license order and/or an incidental take statement. For endangered and threatened species, NMFS may publish performance standards in recovery plans as directed by section 4(f) of the ESA. For non-listed species, NMFS may publish performance standards as part of comprehensive plans filed with FERC under Section 10 of the FPA or as fisheries management plans in coordination with states and other federal agencies. We derive our performance standards from the best available science, which varies by species and life stage.

6.2 Project Survival

Mortality resulting from hydroelectric facility passage can be direct and indirect. Direct mortality results from injury during passage that leads to simultaneous death or death immediately after passage (Čada 2001, Amaral et al. 2012). Indirect mortality occurs through several mechanisms, such as increased predation risk in modified habitats and increased health risk from sub-lethal injuries (Čada 2001, Amaral et al. 2012). Indirect (a.k.a., latent or delayed) mortality is defined as fish that pass a project that are lost during the migration at some point downstream due to sub-lethal injuries, increased stress, or passage delay. Loss of fish through indirect mortality may result from infections and disease associated with sub-lethal injuries (including excessive scale loss) and increased stress or higher predation risk due to injury and/or disorientation following dam passage (Čada 2001). By estimating the proportion of fish passing through each route and applying route-specific direct and indirect survival rates (i.e., one minus the mortality rate), the Applicant can calculate the project survival during downstream passage as a point estimate during a particular operating regime at their hydroelectric facility. The Applicant will need to calculate the project survival for each target species and life stage that migrate past the project.

The general equation to estimate project survival is:

$$S_P = \sum_{R_n}^{R_{n+1}} (R_P * R_{DS} * R_{IS})$$

Project survival (S_P) equals the summation of the product of all route probabilities (R_P), route-specific direct survival (R_{DS}), and route-specific indirect survival (R_{IS}). A well-designed survival study estimates both direct and indirect mortality, and thus survival, for a particular route of passage. However, indirect mortality through each route of passage at a facility requires extensively studied sites, species, life stages, and watersheds that may not be available at the time of the compliance activity or within the five-year licensing timeframe. In consultation with NMFS and other resource agencies, the Applicant may apply an indirect survival estimate to the project survival after summation of the route-specific probabilities and direct survival terms. The project survival estimation should account for project effects in the impoundment and tailwater. Therefore, the project survival estimation should include the impoundment and tailwater of the project with a route probability (R_P) of one.

6.2.1 Simple Project Survival Example

In a simple example, an Applicant evaluates the project effects for only one migrating species and life stage at a run-of-river hydroelectric project. For this hypothetical project, the routes of passage are through a single turbine, over an uncontrolled spillway, or via a designated fish bypass system. The project has a trash sluice gate that operates intermittently and there is no evidence suggesting that this is a viable route of passage for the target species. The fish guidance efficiency (FGE) of the bypass system is 40% regardless of turbine operating condition with the remaining 60% of fish passing through the turbine. Fish do not use the spillway route until a certain spill threshold, when 50% of the fish emigrated over the spillway regardless of the amount of spill. Survival through the fish bypass system is 98%. Survival through the turbine is 87% and there was no evidence that this survival changed with turbine operating condition. Survival over the spillway is 95% and this estimate did not change with spill magnitude. At the project, there is no documented predation on the target species in the reservoir or the tailrace. Finally, migration delay is minimal and there is no other evidence of indirect mortality. In this hypothetical scenario, the Applicant has two project survival estimates to calculate: a non-spill condition and a spill condition.

For the non-spill condition the project survival estimate is:

$$S_{Non-Spill} = (Bypass_P * Bypass_S) + (Turbine_P * Turbine_S)$$

$$(0.4 * 0.98) + (0.6 * 0.87) = 91.4\%$$

For the spill condition the project survival estimate is:

$$S_{Spill} = (Bypass_P * Bypass_S) + (Turbine_P * Turbine_S) + (Spill_P * Spill_S)$$

$$(0.2 * 0.98) + (0.3 * 0.87) + (0.5 * 0.95) = 93.2\%$$

6.2.2 Complex Project Survival Example

Hydroelectric projects often involve complex infrastructure and operations, so the previous example is rare. More commonly, an Applicant estimates project survival for multiple diadromous species and life stages through many routes of passage with highly variable survival rates based on operations. To elucidate the project survival evaluation, we developed a complex hypothetical example involving a fish bypass system, two different turbine types, an uncontrolled spillway, and a controlled spillway with a crest gate. Turbine 1 is a Kaplan unit with a hydraulic range of 150 to 500 cfs and turbine 2 is a Francis unit with a hydraulic range of 250 to 625 cfs. The Applicant operates the project under five distinct hydrologic regimes (**Table 3**). Therefore, the Applicant needs to estimate the project survival under each operating regime for each target species and life stage. For this example, we partially go through the evaluation process for just one target species at two life stages. The species is an iteroparous, pelagic species with the adults migrating during the spring and the juveniles migrating during the fall.

Table 3. Operating regimes of a hypothetical hydroelectric facility with a complex downstream passage evaluation.

Operating Regime No.	River Flow (cfs)	Fish Bypass System	Kaplan	Francis	Uncontrolled Spill	Gated Spill
1	0-250	Open	Off	Off	Open	Closed
2	250-550	Open	On	Off	Open	Intermittent
3	550-1,225	Open	On	On	Open	Intermittent
4	1,225-2,000	Open	On	On	Open	Intermittent
5	>2,000	Open	On	On	Open	Open

Under the first operating regime, the fish bypass system conveys 100 cfs and the remainder of the river flow spills. During the field studies, the Applicant collected no field data under this regime for adult life stages. However, under other operating regimes the fish bypass system has a consistent survival estimate of 97% and the depth of flow over the uncontrolled spillway likely precluded passage of adult target species. During the field studies, the Applicant collected information for the juvenile target species. The survival estimate for juveniles using the bypass facility and the spillway is 98% and 23%, respectively. Observations during the field studies suggest that birds preyed upon the juvenile emigrants using the uncontrolled spillway, particularly at low spill levels. The field studies estimate bypass facility and spillway route probabilities for juveniles of 80% and 20%, respectively. The resulting project survival under the first operating regime for adults and juveniles is 97% and 83%, respectively.

$$S_{Adult}^{1} = (Bypass_P * Bypass_S)$$

$$(1 * 0.97) = 97\%$$

$$S_{Juvenile}^{1} = (Bypass_P * Bypass_S) + (Spill_P * Spill_S)$$

$$(0.8 * 0.98) + (0.2 * 0.23) = 83\%$$

The second operating regime involves running the Kaplan turbine up to maximum hydraulic capacity and the fish bypass system with no spill. The bypass FGE during these conditions is 62% for juveniles and 83% for adults. Survival through the Kaplan turbine is 92% for juveniles and 73% for adults. The route-specific survival estimate for the fish bypass system remained the same. The resulting project survival under the second operating regime for adults and juveniles is 92.9% and 95.7%, respectively.

$$S_{Adult}^{2} = (Bypass_P * Bypass_S) + (Kaplan_P * Kaplan_S)$$

$$(0.83 * 0.97) + (0.17 * 0.73) = 92.9\%$$

$$S_{Juvenile}^{2} = (Bypass_P * Bypass_S) + (Kaplan_P * Kaplan_S)$$

$$(0.62 * 0.98) + (0.38 * 0.92) = 95.7\%$$

The third operating regime includes running both turbines and the fish bypass system up to the hydraulic capacity of the powerhouse. The bypass FGE during these conditions decreases to 53% for juveniles and 81% for adults. The route probability between the turbines reflected the flow into each unit (i.e., the fish were entrained proportional to the flow), however the Applicant typically balances generation between the two turbines. Survival through the Kaplan turbine is the same as the second operating regime. The survival estimate through the Francis unit is 84% for juveniles and 62% for adults remaining consistent throughout the operational range of the turbine. The route-specific survival estimate for the fish bypass system remains the same. The resulting project survival for adults and juveniles under the third operating regime is 91.4% and 93.3%, respectively.

$$S_{Adult}^{3} = (Bypass_P * Bypass_S) + (Kaplan_P * Kaplan_S) + (Francis_P * Francis_S)$$

$$(0.81 * 0.97) + (0.095 * 0.73) + (0.095 * 0.62) = 91.4\%$$

$$S_{Juvenile}^{3} = (Bypass_P * Bypass_S) + (Kaplan_P * Kaplan_S) + (Francis_P * Francis_S)$$

$$(0.53 * 0.98) + (0.235 * 0.92) + (0.235 * 0.84) = 93.3\%$$

The fourth regime includes running both turbines, operating the fish bypass system, and allowing uncontrolled spill to occur until a set headpond elevation. The FGE and the turbine entrainment rates remain the same as the third operating regime. Route probabilities for the uncontrolled spillway are variable for both juveniles and adults. Adults do not use the spillway as a route of egress until a spill threshold of 300 cfs at which point the route probability is 15%. Spillway survival for adults is 96%. The spillway route probability for juveniles is proportional to the amount of flow. Spillway survival for juveniles ranges from 23% to 98%. The presence of predators and debris at the spillway increases the risk of injury and mortality based on observations during the field study. The resulting project survival under the fourth operating regime for adults remains 91.4% until the spill threshold when the estimate increases to 92.1%. For juveniles, the project survival initially decreases from 93.3% before increasing to 95.1% at a river flow of 2,000 cfs. In order to calculate the adult and juvenile project survival estimates for this operating regime, the Applicant needs to determine the incremental exceedance values of the river flow from 1,225 cfs to 2,000 cfs (see Section 6.2.3).

$$S_A^4 = [(Byp_P * Byp_S) + (Kap_P * Kap_S) + (Fra_P * Fra_S)] * (1 - Spill_P) + (Spill_P * Spill_S)$$

$$[(0.81 * 0.97) + (0.095 * 0.73) + (0.095 * 0.62)] * 0.85 + (0.15 * 0.96) \leq 92.1\%$$

$$S_J^4 = [(Byp_P * Byp_S) + (Kap_P * Kap_S) + (Fra_P * Fra_S)] * (1 - Spill_P) + (Spill_P * Spill_S)$$

$$[(0.53 * 0.98) + (0.235 * 0.92) + (0.235 * 0.84)] * 0.6125 + (0.3875 * 0.98) \leq 95.1\%$$

Finally, under the fifth regime, the gated spillway becomes a viable route of egress for migrating fish, as it remains open to maintain headpond levels during higher river flows. When the river flow is 2,000 cfs to 2,500 cfs, the survival is 85% and 72% for adults and juveniles, respectively. Once the gated spillway conveys more than 500 cfs, the survival increases to 96% and 93% for adults and juveniles, respectively. Like the previous operating regime, the routing becomes dynamic under these conditions with fish using all viable routes of passage with different probabilities based on operations (**Table 4**). Each of these changes in operation results in altered migratory behavior and survival, so the Applicant calculates four project survival estimates within this operating regime to evaluate the project effects. These four estimates require determining the incremental flow exceedance values of the river from 2,000 to over 3,000 cfs (see Section 6.2.3).

Table 4. Estimated route probabilities during the fifth operating regime for juvenile (Juv.) and adult emigrating fish. The possible routes are the fish bypass system (Byp.), the Kaplan unit (Kap.), the Francis unit (Fra.), the spillway (spill), and the gate.

River Flow (cfs)	Byp. Juv.	Kap. Juv.	Fra. Juv.	Spill Juv.	Gate Juv.	Byp. Adult	Kap. Adult	Fra. Adult	Spill Adult	Gate Adult
2,000-2,100	0.3	0.1	0.1	0.3	0.2	0.69	0.08	0.08	0.15	0
2,100-2,500	0.25	0.075	0.075	0.3	0.3	0.5	0.05	0.05	0.2	0.2
2,500-3,000	0.2	0.05	0.05	0.3	0.4	0.25	0.025	0.025	0.3	0.4
>3,000	0.05	0.025	0.025	0.4	0.5	0.1	0	0	0.4	0.5

6.2.3 Total Project Survival Estimate

In the preceding sections, we estimate project survival for multiple operating conditions at a simple and complex hydroelectric facility. Each of these survival estimates has value for understanding effects to downstream migrating fish (see Section 6.3). However, the Applicant may need to determine a total project survival estimate for each diadromous species and life stage requiring development of flow, and thus operation, exceedance values based on historical flow data at the hydroelectric facility. The estimation of flow exceedance values requires constructing a FDC for the species and life stage migratory periods at the site (**Figure 7**). A FDC estimates the percentage of time a given streamflow was equaled or exceeded over a historical period and has a variety of applications (Vogel and Fennessey 1995).

In our complex hypothetical example (see Section 6.2.2), the first operating regime includes river flows less than or equal to 250 cfs. As shown in Figure 7, this river flow has no record of occurring in the last 20 years for the adult migratory period, therefore the project survival estimate of 97% for adults during that operating regime is not included in the total project survival calculation. However, for juveniles, the river flow of 250 cfs is equaled or exceeded nearly 57% of the time during their migration meaning the first operating regime occurs approximately 43% of the migratory period. The project survival for juveniles under this operating regime was 83%. When calculating the total project survival for juveniles at the hydroelectric facility, the Applicant should weigh that operating regime survival estimate accordingly (i.e., a survival of 83% occurs 43% of the time during the migratory season).

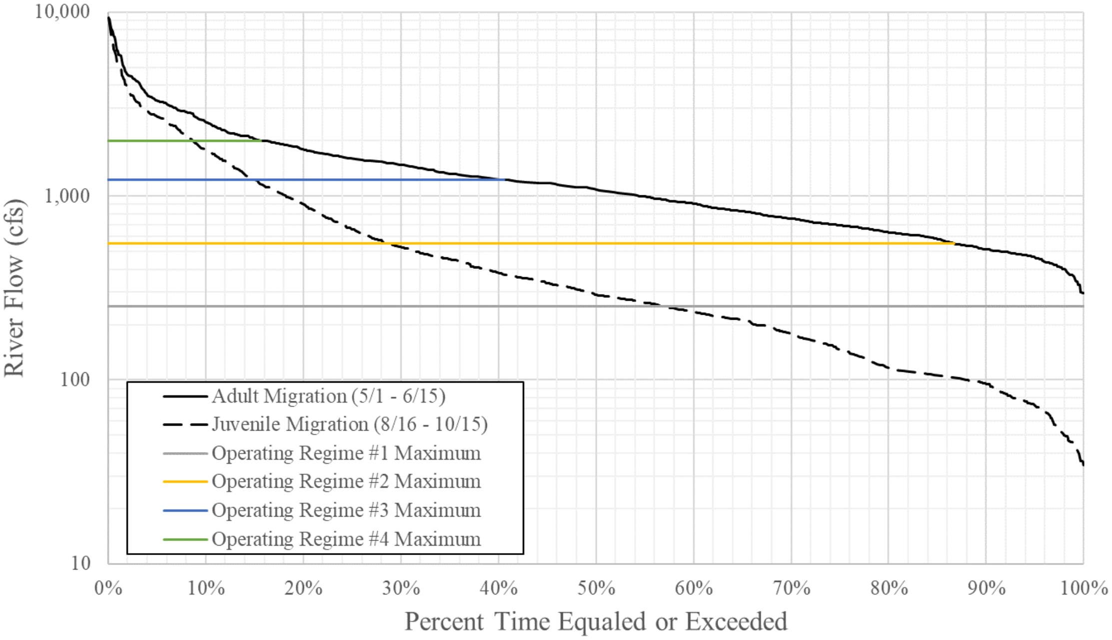

Figure 7. Flow duration curve for the adult and juvenile life stages at a hypothetical hydroelectric facility described in Section 6.2.2. The flow duration curve was constructed using the last 20 years of daily average flow data from May 1st to June 15th to represent adult migration and August 16th to October 15th to represent juvenile migration. The gray, yellow, blue, and green lines represent the river flows at which the hydroelectric facility switches to a new operating regime.

Likewise, the Applicant should weigh the remaining operating regime project survival estimates by the difference in exceedance values at the beginning and the end of the operating regime. For example, the second operating regime occurs approximately 28% of the time during juvenile migration (57% exceedance at 250 cfs minus 29% exceedance at 550 cfs). For operating regimes with multiple survival estimates (e.g., operating regime number four and five), each distinct survival estimate should be weighed by the appropriate difference in exceedance values. At the end of this accounting exercise, the weighting applied to each of the survival estimates should sum to one in the total project survival calculation.

Now that the Applicant has estimated survival during all of the operational situations, they can estimate a total project survival by weighting each unique operational project survival estimate by the percent time that condition is likely to occur during the migratory season. This method using a FDC requires that the daily average flow data set has an adequate number of observations to characterize the flow intervals that determine the operational, and thus, project survival conditions. Typically, many hundreds, if not thousands, of observations are necessary, but the historical record should not extend beyond 30 years to best reflect current climate conditions. If observations are limited, alternative non-parametric or parametric statistical methods (Amaral et al. 2012) may be required. These situations will be reviewed on a case by case basis by NMFS. Total project survival estimate will change over time with modified facility operations and climate conditions. For this reason, we recommend using the last 10 to 30 years of daily average flow data when evaluating flow conditions at a hydroelectric facility instead of the entire hydrologic record. In addition, if the Applicant modifies the facility operations, then they will need to recalculate the overall project survival estimate. Within the timespan of a 30 to 50 year license, we recommend reviewing the representativeness of the project survival estimate as conditions change at the hydroelectric facility.

6.2.4 Survival Estimate Uncertainty

The objective of a project survival estimate is to quantify the effects on downstream migrating fish during licensing and to compare the survival estimate to a performance standard. Uncertainty deriving from sampling error, model error, and natural variability is inherent in estimates of project survival. The deterministic project survival methodology we recommend in this technical memorandum provides a point estimate, but does not incorporate uncertainty. Typically, there is not enough time allocated in the licensing and compliance regulatory process to obtain estimates of uncertainty for all inputs to the project survival calculation. This limitation will hopefully be addressed over time as more data at each facility is acquired through field studies and modeling exercises. For hydroelectric facilities where non-listed species are involved, we will use professional opinion, existing information, and field study data during the regulatory process to evaluate the accuracy of the project survival point estimate. However, at facilities where protected species are involved, characterizing the uncertainty in point estimates may be necessary, thus requiring multiple years of extensive study to build confidence that the facility is accurately quantifying effects and meeting performance standards during authorization and compliance. An example of the evolution in deterministic downstream survival estimation is the Federal Columbia River Power System (FCRPS) where initially system-wide downstream survival was estimated by the SIMPAS model (NMFS 2002) that eventually morphed into the COMPASS model (NMFS 2019). After decades of survival studies, the complex and computationally burdensome COMPASS model only accounts for reservoir uncertainty highlighting the difficulty in fully accounting for all major sources of uncertainty with deterministic models.

6.3 Mitigation Strategies

NMFS strives to make informed decisions about potential mitigation measures at hydroelectric projects for the conservation benefit of diadromous species and the value they have for the American public. Therefore, the Applicant must identify the risks to diadromous species at the hydroelectric facility and, to the extent possible, quantify the magnitude of those effects. Using this information, we can develop informed strategies to minimize harm to the species while considering the burden on the Applicant and the potential effects to other public benefits (e.g., loss of renewable energy production). Informed decision-making is contingent on the quality and accuracy of the data. We cannot optimize public and private benefits without representative, high-quality data (Song et al. 2021).

Mitigation measures typically involve modified operations, improvements to project structures, installation of new project structures, or some combination of both structural and operational alterations. We describe some general approaches to mitigation using the hypothetical examples (Sections 6.2.1 and 6.2.2) in the following sections.

6.3.1 Modified Operations

An Applicant may modify project operations temporally to minimize exposure of the species to injury and mortality risks. These mitigative opportunities only occur when species interact with the project during limited times (diurnally, seasonally, or both). For example, a migratory species may only interact with the project a few months of the year. During these migrational windows, an Applicant may increase safe spill or another measure that improves passage effectiveness and survival. Similarly, the Applicant likely does not need to operate dedicated fish passage structures during months when no target species are present. If sufficient behavioral knowledge is available, the Applicant may also employ this strategy on a diurnal time scale. For example, if a species shows a strong preference for passing at night, the operator may implement fish passage operations after dark. Where possible, tailoring operations to maximize benefit to the species while minimizing burden on the Applicant represents successful mitigation.

6.3.2 Improvements to Project Structures

Successful mitigation of the effects on downstream migrating diadromous fish may be as simple as improving the performance of the facility structures already in place. In our simple hypothetical example (Section 6.2.1), the Applicant needs to improve project survival for the adult species as both the spill and non-spill conditions are below a hypothetical performance standard of 95% survival. Because the existing downstream fish bypass has a survival estimate that meets the standard, the Applicant just needs to improve the FGE (i.e., increase the percentage of adult fish using the downstream fish bypass). The FGE may improve by modifying the entrance to the downstream bypass (e.g., increasing the entrance size and flow, adding another entrance, installing behavior deterrents/guidance) to boost attraction to that safe route or screening the turbine intake (e.g., narrower open space on the trash rack, seasonal or permanent trashrack overlays) to decrease entrainment.

In our complex hypothetical example (see Section 6.2.2), the first operating regime results in high mortality of juveniles at the spillway due to avian predation. The juveniles tend to migrate at low flow periods of the year, so the Applicant may propose to implement mitigative measures during this operating regime. An example mitigative measure may include installing anti-predatory devices (e.g., a behavior deterrent that prevents birds from perching at the uncontrolled spillway) during low flow periods of the year.

6.3.3 New Project Structures

In our simple hypothetical example (Section 6.2.1), the Applicant needs to improve the FGE of the existing downstream bypass system and modifications to the entrance are not feasible; thus requiring an intake screen. A narrow-spaced trash rack replacement or overlay results in velocities in front of the intake that cause impingement of fish. In this case, the Applicant may design a new screen structure that does not result in impingement. This typically involves an angled or inclined screen (or trash rack) design that minimizes the velocities in front of the intake, and thus, impingement. Alternatively, the Applicant may consider replacement of their turbine infrastructure with a fish friendlier design that meets passage requirements.

In our complex hypothetical example (Section 6.2.2), the gated spillway has low survival at flows up to 500 cfs because the receiving waters are unsafe with multiple mechanical injury risks (e.g., accumulated debris, shallow depth, rough surfaces). To improve survival through this route, the Applicant could install a plunge pool at the toe of the gated spillway that provides safe receiving water conditions that rapidly and safely convey migrating fish.

6.3.4 Combination of Measures

As highlighted in our complex hypothetical example (see Section 6.2.2), downstream passage mitigation will likely be a combination of operational measures, modified infrastructure, and new infrastructure. For example, if the performance standard for the hypothetical facility is 95% passage survival for both adults and juveniles, then the Applicant needs to improve passage survival for each operational regime. Even if the Applicant installed the safest turbine available, there are still operating regimes in the example where spill survival is too low requiring additional operational or infrastructure measures to ensure the hydroelectric facility meets performance standards for the full suite of diadromous species and life stages. Without site-specific data, making an informed decision about which measure is appropriate for an operational regime, and thus the total project survival, is challenging.

7 Conclusion

The management of our Nation's depleted diadromous fishery resources requires an evidence-based approach that combines the need for immediate action with planned learning – also known as adaptive management. NMFS defines adaptive management as an on-going process of evaluating if management objectives have been met and adjusting management strategies in response. This process includes periodic re-evaluation and updating of the management goals and objectives to ensure relevancy to current conditions and needs. Adaptive management is contingent on the continual collection of high quality data.

If Applicants rely on old data and information, we would be unable to advance our understanding of the downstream passage threats and effects from hydroelectric facilities—which is antithetical to an adaptive management framework. This Technical Memorandum describes the latest science with regards to downstream passage of diadromous fish at hydroelectric facilities, most of which has been published within the last 30 years. We hope it highlights the importance of collecting new data and performing additional analyses as opportunities arise during the licensing and compliance process.

Safe, timely, and effective downstream passage at hydroelectric facilities is essential for sustainable hydropower in the U.S. During the permitting and authorization process, an Applicant is required to provide FERC with sufficient information to process the application and complete their NEPA review. Likewise, during the administrative and compliance process of a license, an Applicant is required to provide FERC with sufficient information to oversee compliance with terms and conditions. In this Technical Memorandum, we promote a four-step process to estimate downstream survival of diadromous fishes at hydroelectric facilities consisting of site characterization, field studies, data analyses, and effects determination and mitigation.

If an Applicant follows the protocol in this Technical Memorandum during their assessment processes, they will be able to understand the effects of their facility on diadromous species and select appropriate protection, mitigation, and enhancement measures that foster the greatest likelihood of successful downstream passage. Consistent evaluation of downstream passage across the U.S. fleet, where each facility is unique, will lead to better outcomes for our trust species and a more sustainable hydropower industry.

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