Determining the Best Methods for Reducing Fish Mortality

Glenn F. Cada, *Oak Ridge National Laboratory* and Stephen Amaral, Alden Research Laboratory

Introduction

Fish pass hydroelectric facilities by many methods, with many traveling through the turbines. Research performed in the USA to improve survival of fish passing through turbines can be applied to facilities in South America and other regions of the world.

Survival of migratory fish during their passage both upstream and downstream past a hydroelectric facility is a significant concern worldwide. Of particular interest currently is the Amazon Basin, where more than 100 hydro projects are planned or under construction. Unless proper attention is paid to the location and mitigation measures, these new projects could have potentially negative environmental impacts.

To aid fish survival, owners of hydro facilities in South America and other parts of the world can take advantage of research performed in the USA over the past two decades by the U.S. Department of Energy (DOE), Electric Power Research Institute (EPRI), Alden Research Laboratory Inc. and other organizations.

Much of this research was funded by the government of the USA and EPRI to address fish passage issues at projects in the USA, which means most of the studies were conducted using North American migratory fish species (such as chinook salmon, rainbow trout and American eel). However, the lessons learned from this research can be adapted for use with other fish species. For any dam, passage assessments would need to be conducted on the actual species traveling past that location to accurately determine their behavior and survival rates.

Hydro in South America

While hydropower generation in Europe and North America has grown slowly over the past few decades, in Central America and South America hydro generation more than tripled between 1980 and 2006, according to the U.S. Energy Information Administration (EIA). Growing from 201 TWh in 1980 to 640 TWh in 2006, hydro accounts for more than two-thirds of the region's total electrical energy production. In its International Energy Outlook 2010, EIA predicts that by 2030, electrical generation in the region will grow to 1,061 TWh as countries, led by Brazil, seek to harness the up to 300,000 m^3/sec of water flowing down the Amazon River.

Brazil has long been a leader in using alternative energy sources. For example, the country's automotive ethanol program dates back more than 30 years, and it is rapidly expanding its use of hydropower. In 2007, 85% of the country's installed electricity generating capacity was hydro, according to EIA. Two dozen hydroelectric facilities are operating in Brazil, with at least another 30 expected over the next decade. Among those projects is 11,000 MW Belo Monte on the Xingu River, which will be the world's third largest hydro facility in terms of generating capacity when it comes on line in 2015.

But this hydropower growth has not been without controversy. In July 2010, 300 protesters took over the 256 MW Dardanelos plant being built in Mato Grosso State.[1] That protest revolved around demands for $5.6 million in compensation for loss of lands. Local and worldwide attention also is focusing on potential for loss of biodiversity in riverine fish communities as a result of hydroelectric development. Other countries in South America may be facing similar issues as the demand for renewable energy, particularly hydropower, increases.

Wide range of options

South America is home to more than 4,500 named fish species, about one-fifth of which are migratory. To ensure that South America has the power it needs to provide a better life for its residents without eliminating hundreds of unique fish species in the process, dams and turbines must be designed to allow the passage of migratory species and minimize injury as these fish pass through the turbines. There are three main options for getting fish downstream past a dam — spills, collection and transport (e.g., via intake screens and bypasses), and turbine passage — as well as several alternative approaches. Each of these options has its advantages and disadvantages.

Spills

Spilling water over a dam is often considered the safest means of getting juvenile fish downstream, with mortality rates as low as 1-2%. Controlled spilling works well with fish species that tend to congregate near the water's surface. For species that typically travel in deeper water, structural measures can be incorporated to promote spills from other elevations of the dam.

However, safe passage for fish only occurs when the spill is properly designed, with the water pouring into a sufficiently deep basin or plunge pool that offers hydraulic conditions that minimize the potential for injury. Because of the high pressure and strong erosive power of water discharged over a dam, typically a concrete apron, energy dissipators and/or a barrier of rocks is included in the design to break the force of the spill. But this can increase fish mortality due to abrasion and collisions with solid objects at high speeds.

In addition, when there is a deep plunge pool, the spilled water drags air bubbles to great depths, and the nitrogen in the water becomes absorbed into solution at the bottom of the pool, creating what is called "nitrogen supersaturation." When fish in deep plunge pools become equilibrated with the supersaturated water and then move into shallower waters, the nitrogen can form small bubbles in the fish's tissues, causing damage or death. This is similar to what divers refer to as "the bends." When spills into deep plunge pools are used, nitrogen gas levels in the water may need to be monitored.

Collection and transport

Screens often are used at the powerhouse intakes to prevent fish from entering the turbines and instead direct them to a bypass — a small conduit or pipe that leads to the tailwaters of the dam. From an engineering viewpoint, these screens are not ideal because they reduce turbine efficiency and do occasionally collapse or break free, sending steel through the turbines. In addition, screens require regular maintenance associated with debris removal.

Screens can also create problems for fish. Fish that are not strong swimmers (particularly younger and smaller fish) can perish by being pressed up against the screen by the pressure of the water. Even strong swimmers may become impinged after repeated screen contacts or after becoming tired.

In addition, predatory fish and birds often learn where the bypass releases fish downstream and feast on the steady supply of food. There are a couple of strategies for minimizing this loss at the bypass outlet. One is to install several bypasses and use valves to switch between them, so that the fish are released at different locations at different times. Another is to put the bypass release in an area of fast-moving water so predatory fish cannot stay in the area and the fish passing downstream move swiftly away.

Transporting fish is a useful approach for rivers with multiple dams, each of which can be a barrier to passage. Fish are captured at a ladder, spillway or bypass at the first dam on the way upstream or downstream, loaded onto a barge or truck, transported past the final dam on the route and then released. This practice gets the fish past all the dams, reduces losses to predators and minimizes migration delays that can reduce fitness.

Turbine passage

An alternative to getting fish to bypass the dams is to allow them to pass through the turbines. However, this can result in severe stresses to the fish (see sidebar on page 46). The exact mortality figures vary depending on the size and species of fish involved, as well as site-specific design factors. The problem is exacerbated when the fish have to pass multiple dams along their migration path.

In the 1990s, the DOE began a research program designed to improve fish survival during passage through turbines. Called the Advanced Hydropower Turbine Systems (AHTS) Program, it supported the development of two "fish-friendly" turbine designs.

One approach, developed by a team that included turbine manufacturer Voith Hydro, was to modify Kaplan turbines. The resulting minimum gap runner (MGR) design greatly reduced the gaps between the runner blades and hub and the outer discharge ring so fish do not get caught and crushed (grinding). The severity of other stress mechanisms (strike, pressure changes) was also reduced in the design of the MGR.

The MGR received its first real-world test when the U.S. Army Corps of Engineers installed MGRs on Units 4 and 6 at the 518 MW Bonneville Powerhouse 1 in Oregon State in 1999. Tests conducted using 7,200 balloon-tagged juvenile Chinook salmon showed the Unit 6 MGR had an overall injury rate of 1.5%, compared to the adjacent Unit 5's 2.5% injury rate.[2]

Further data on this technology were gathered in 2005 when Grant County Public Utility District No. 2 replaced one of the 10 Kaplan turbines at its 1,038 MW Wanapum Dam on the Columbia River in Washington State with an MGR turbine. Nearly 9,000 juvenile chinook salmon were tagged and used to identify the differences in direct and indirect mortality between the MGR and a conventional hydroelectric turbine. Because the survival rate through these conventional turbines was already high (>95%), not much improvement could be expected.

The survival rate for salmon was found to be similar for both turbine designs. However, the MGR provided about a 10% increase in power production over the existing units. Because of the combination of high salmon survival and increased power production, the utility decided to replace the remaining Kaplan turbines with MGRs. The replacement process in ongoing, at a rate of about one turbine every nine months. The final unit is scheduled for installation in 2012.

The second part of the DOE AHTS program funded development of a completely new turbine design. DOE contracted Alden, a flow modeling firm, to provide experts in biology, computer modeling and engineering to develop a turbine design that considers criteria for safe fish passage, and has facilities to test how fish react to structures or methods designed to encourage or block their passage. These facilities include two primary flumes, the larger of which is 36.5 meters long, 6 meters wide and 3 meters deep, with a flow rate of up to 14 m^3/sec provided by axial pumps. Flow velocity can be adjusted by manipulating flume width and pump speed.

More than 40 freshwater and saltwater species have been tested at the Alden facility, which includes environmental controls to ensure that fish are not stressed by typical factors that cause problems in experimental facilities, such as temperature, dissolved oxygen and ammonia.

The prototype of this new turbine was designed to operate at a flow of 28 m^3/sec, with a 24.4 meter head and at 120 rpm, and to meet seven criteria for reducing the potential for fish injury and mortality:[3]

— Limit the relative velocity of the inflow to the blades;

— Have a high minimum pressure;

— Limit negative pressure change rates;

— Limit the maximum flow shear;

— Minimize the number of leading blade edges;

— Maximize the distance between the runner inlet and wicket gates trailing edges and minimize clearances (i.e., gaps) between other components; and

— Maximize the size of flow passages.

The Alden turbine design uses an integrated concept to eliminate or reduce conditions that can lead to fish mortality during turbine passage (see Figure 1). The three runner blades are attached to a rotating shroud, eliminating the low-pressure vortices that typically occur near the blade tips and thus the chance of fish being caught between the blades and outer discharge ring. The blades, which have nearly 180 degrees of wrap around the hub, are longer in the flow direction than conventional blades, to extract power at a high efficiency.

The runner rotates relatively slowly (about 120 rpm, depending on head and flow) to reduce the chance of blade strike. The turbine is designed to operate over a wide range of heads (6 to 40 meters) and, therefore, could be used at projects where Kaplan or Francis turbines may be considered.

Biological Factors that Affect Turbine Passage Mortality

Injury and mortality of fish that pass through hydro turbines results from several factors, and the relative effects of those factors vary with the turbine design and fish species and size. Therefore, it is necessary to know the species that needs protection, especially its physical and behavioral characteristics, before selecting the optimum turbine design. As fish pass through a hydroelectric turbine, they are subject to a variety of physical stresses, including:

Rapid and extreme pressure changes. In seconds, water pressures in the turbine can increase to several times atmospheric pressure and then drop to subatmospheric pressure within and just downstream from the runner. Many fish species have a swim bladder, a balloon-like organ the fish can inflate or deflate to maintain neutral buoyancy in the water column. Some fish have a duct that allows them to rapidly vent the gas in the swim bladder; such fish can often better survive the pressure drops they experience while passing through turbines. Others lack this duct, and it takes hours for them to adjust the volume of gas in the swim bladder to pressure changes. As a result, when those fish pass through the low-pressure area of the turbine, their swim bladders can rapidly expand and burst.

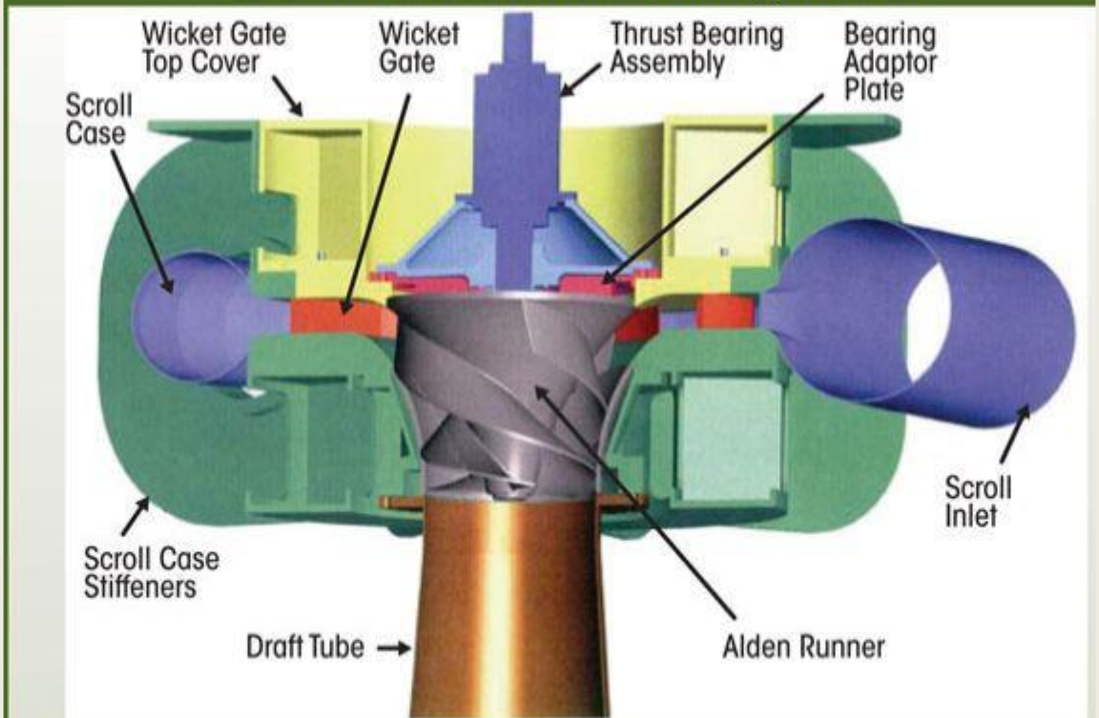
Cavitation. Extremely low water pressures within and just downstream from the runner may cause the formation of vapor bubbles that subsequently collapse violently. The resulting pressure spikes can injure nearby fish.

Shear stress. Different portions of adjacent water flow moving at different velocities can generate shear forces applied parallel to the fish's body. In addition to bruising or tearing of tissue, these shear forces can strip the scales from fish with loose scales, such as shad and herring. Hours or days later, the fish can die from osmotic stress or diseases that develop in the stripped areas.

Turbulence. Turbulent (irregular) motions and eddies within the mean flow can, depending on their intensity and scale, cause localized injuries or disorientation. Among other problems, the disorientation can make the fish easier targets for predators.

Strike. Collision may occur with structures, including stay vanes, wicket gates, runner blades and draft tube piers. Larger fish are more likely to suffer strikes by the runner blades.

FIGURE 1 Alden Turbine Configuration



The Alden turbine is designed to minimize injury to fish by reducing or eliminating structures and/or locations that cause these injuries.

Figure 1 shows the locations within a hydroelectric turbine where these injury mechanisms tend to be most pronounced. Each of these mechanisms on its own can be severe enough to be fatal, or it can be a combination of these that immediately kills a fish or causes it to succumb later to disease.

Two- and three-dimensional modeling was used to design the helical blades attached at one end to the hub and at the other end to the rotating shroud. Water reaches the runner through a scroll case and flow distributor. Fewer wicket gates are used than is typical for Kaplan turbines to increase the clearance between gates, but consequently these gates are almost twice as long as is typical.

Once the conceptual design was complete, tests were conducted on a 1:3.25 scale turbine, with a runner diameter of 1.2 meters, at flows from 1.4-2.7 m^3/sec with heads of 10.7-26 meters. Speeds of 200-375 rpm were tested to determine the best efficiency point (BEP) at a variety of wicket gate positions.

Biological testing was then conducted using several fish species. Preliminary tests were conducted without wicket gates to assess injury and mortality mechanisms associated with just the runner, and using two sizes of rainbow trout (94 mm and 174 mm) under two BEP operating conditions — 11.6 meters of head at 240 rpm and 24.4 meters of head at 345 rpm. Tests were then conducted at the same head and flow conditions with the wicket gates at the BEP position of 18.2 degrees, using trout (38 mm, 85 mm and 175 mm), smallmouth bass (69 mm and 155 mm), American eels (249 mm and 431 mm), alewife (87mm), white sturgeon (103 mm) and coho salmon (102 mm).

Results indicated that fish survival through a full-scale turbine (with increased leading edge blade thickness) designed for a reference site with a head of 28 meters would exceed 98% for fish up to 200 mm in length (most juvenile migratory fish are smaller than this). Due to better survival observed in the pilot scale tests, eel and sturgeon survival rates could be as high as 99-100%

These early engineering tests on the pilot scale indicated the full-sized turbine would achieve a maximum efficiency of 90.5%, with or without wicket gates. However, because there was considerable swirl at the exit of the draft tube, this efficiency could be improved by redesigning the blades. Also, a major increase in turbine power might be achieved by doubling the height of the flow distributor and accommodating about twice the flow through a redesigned runner, scroll and draft tube.

In 2009, Voith Hydro was contracted to complete the engineering design and operational model testing of the Alden turbine, with funding from EPRI and DOE. Design refinements and performance testing on a 1:8.7 scale model indicated the maximum full scale efficiency of the turbine would be about 94%. Computational fluid dynamic (CFD) simulations and minimum pressure (cavitation) observations in the model (at depressed tailwater) indicated that biological criteria for flow shear, pressure change rate and absolute minimum pressure were met.

In addition to a tentatively planned installation and evaluation of a full-scale unit at Brookfield Renewable Power's 38 MW School Street Project in New York State, EPRI conducted a site selection process and chose Electricite de France's 8 MW Pebernat project as a second possible demonstration project.

Need for a site-specific approach

There is no single approach to fish passage that will work at all hydroelectric facilities. Installation of a dam causes changes to the ecosystem, and a decision must be made as to which changes are acceptable and which must be minimized or mitigated. For example, a dam may act as a barrier to migratory riverine species, but the reservoir could provide a new home for lake species that thrive in low-velocity habitats. This poses questions. Can a specific species survive with its spawning ground below the dam? Will it survive passage through a fish-friendly turbine?

The fish-friendly turbine testing that has been completed by DOE and Alden in the USA might be used to estimate the survival of South American fish. Until turbine passage tests are carried out with the species of interest, the value of advanced, fish-friendly turbines for fish species in South America or elsewhere in the world remains uncertain. But the initial tests of these designs, based on a limited number of fish species, have been promising. Similarly, research and experience with regard to migratory fish on other river systems can be used to predict how non-tested species will react to spills, screens or other passage solutions.

As research continues with more species and the knowledge base on downstream passage effects expands, it will become easier to design hydro facilities to reduce their impact on fish populations and the people who rely on them for their survival and livelihood.

Notes

[1]http://www.hydroworld.com/index/display/article-display/6715484412/articles/hrhrw/News-2/2010/07/amazon-indians_seize.html

[2]Cada, Glenn F., "The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival," *Fisheries*, Volume 26, No. 9, September 2001, pages 14-23.

[3]*Final Report – Pilot Scale Tests Alden/Concepts NREC Turbine*, U.S. Department of Energy, Washington, D.C., USA, 2003.

Survival of migratory fish during their passage both upstream and downstream past a hydroelectric facility is a significant concern worldwide.

Glenn Cada, PhD, is a zoologist in the environmental sciences division at Oak Ridge National Laboratory, studying the effects of hydraulic forces on fish. He has served as an advisor to Brazilian research organizations on fish passage issues at hydro plants. Steve Amaral, a senior fisheries biologist with Alden Research Laboratory, served as the project manager for the biological evaluation of the fish-friendly Alden turbine and blade strike studies.