Efforts to Reduce the Impacts of Hydroelectric Power Production on Reservoir Fisheries in the United States

key words: upstream fish passage, turbine passage, fish screen, instream flow releases, hydroelectric

Abstract

Research into the environmental effects of hydroelectric power production in the United States has focused increasingly on resident and migratory fish populations. Hydropower dams and reservoirs can block fish movements in both upstream and downstream directions. These movements are essential for important stocks of anadromous and catadromous fish. In addition, some strictly freshwater fish may move long distances within a river during their life cycle. A dam can pose an impassable barrier for fish trying to move upstream unless mitigation measures in the form of ladders or lifts are provided. Fish moving downstream to the sea may become disoriented when they encounter static water within a reservoir. Both resident and migratory fish may be injured or killed by passing through the turbine or over the spillway. In the United States, a variety of organizations conduct applied research and development of measures to (1) enhance fish passage, (2) reduce the numbers of fish that are drawn into the turbine intakes, and (3) reduce the injury and mortality rates of fish that pass through the turbines. Examples of these efforts from a variety of river systems and hydroelectric power plants are described.

1. Introduction

Hydroelectric power is an important contributor to electrical generating capacity in the United States. Hydropower plants currently provide 11 percent of the electricity generated in the U.S., and nearly 98 percent of the electricity generated by renewable resources (hydropower, biomass, geothermal, wind, and solar energy). In an era in which nuclear power is viewed with concern because of unresolved safety and waste storage issues, and many governments are attempting to reduce carbon emissions from fossil-fueled power plants, it is important to maintain or even increase environmentally sound hydroelectric generating capacity.
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However, the contribution of hydropower to total generating capacity in the U.S. has declined in recent years, from 30 percent in 1950 to approximately 11 percent today. This is due, in part, to concern about the adverse environmental effects of hydroelectric dams and reservoirs. It is well known that reservoirs can inundate large amounts of terrestrial habitat, alter water quality and hydrology, and transform biotic communities (ACKERMANN et al., 1973; PETTS, 1984; MATTICE, 1991; ROSENBERG et al., 1997). A recent survey of hydropower industry and its regulators found that the two biggest environmental issues facing hydropower plants in the U.S. is obstruction of fish passage and water quality degradation. This paper will focus on the former issue, fish passage. Our understanding of these impacts to riverine and reservoir fish populations, and the research being carried out to mitigate the impacts, will be outlined.

2. Impacts to Riverine and Reservoir Fish Populations

Hydroelectric power plants can interfere with the movements of riverine fish in three general ways: (1) water velocities within the reservoir or flows released from the dam may be too low to allow migration; (2) the dam may create a barrier to upstream movements; and (3) resident or downstream-migrating fish may be drawn into the intake flows (entrainment) and suffer injury or mortality on passing through the turbine. These impacts can be especially serious for anadromous fish (salmon, American shad, striped bass) and catadromous fish (eels) that spend part of their lives in rivers and part in the oceans. In addition, some strictly freshwater fish may need to move long distances within a river during their life cycle. The reduction in fish populations caused in part by migration barriers has caused some fish stocks to be declared in danger of extinction. As a result, a number of government agencies, electrical utilities, and research organizations are studying these problems and attempting to mitigate them.

2.1 Insufficient Flows Within or Below the Reservoir

Downstream-migrating fish are often adapted to moving from freshwater to the sea during flood flows in spring and early summer. Large storage reservoirs can alter the natural hydrograph by holding back flood flows and releasing the water through the turbines in other months, when electrical power is needed. Consequently, downstream migrants now encounter large reservoirs with slow or no flows, and, compared to pre-impoundment conditions, may experience disorientation, increased travel times from their natal streams to the sea, increased predation within the reservoir, and altered water quality. All of these factors can reduce the number of fish migrating to the sea. Although many feel that inadequate flows within large storage reservoirs has been a major factor in the decline of salmon populations in the Columbia River basin
(Northwest U.S.), this issue has not been rigorously studied. ČADA et al., (1997a) reviewed literature relating to the influence of water velocity on the survival of juvenile salmon and steelhead. Most of the studies they reviewed found a positive relationship between outmigration flows and survival of juvenile salmonids, but there is considerable uncertainty about the reliability of the early data. The relationship is complicated by other factors that vary from year to year and were not controlled or fully accounted for, for example, predation, water quality, and physiological state of the fish. Despite limitations of the existing data, ČADA et al., (1997a) concluded that a positive relationship between increasing flows in the Columbia River Basin and increasing survival of downstream-migrating salmonids was reasonable.

The influence of flow releases from the reservoir on downstream (riverine) fish habitat has been better studied. Streamflows may be stopped entirely below storage reservoirs or within the bypassed reach of diversion projects, resulting in dewatered river reaches that can extend for great distances. The loss of habitat for fish and benthic organisms is obvious in extreme cases (e.g., no flow releases), but there is considerable controversy over the appropriate flow releases that both protect downstream aquatic habitat and allow the generation of needed electricity. Mathematical models that relate flow releases to the amount of physical habitat in the river below the reservoir (expressed as depth, velocity and substrate type) have been employed for nearly two decades (STALNAKER, 1993). However, physical habitat may not be the limiting factor in all streams. Individual-based instream flow models, which allow the incorporation of other limiting factors (e.g., temperatures, feeding, interspecies competition) are now being developed to refine or replace the physical habitat-based models (VAN WINKLE et al., 1997).

2.2 Upstream Fish Passage Barriers

Maintenance of fish populations whose life cycles include upstream migrations may require the construction of facilities to allow for upstream fish passage (fishways). ČADA and SALE (1993) surveyed upstream fish passage measures at the approximately 1825 non-federal hydroelectric projects in the U.S. They found that an estimated 12 percent of the hydropower projects had upstream fish passage facilities. Fish ladders accounted for over 70 percent of the upstream devices. Fish elevators and trapping and hauling (via truck or barge) were also used to transport fish upstream from hydropower dams. Performance monitoring and detailed, quantitative performance criteria for these fishways were frequently lacking, so in most cases it was difficult to establish their effectiveness. In a subsequent, detailed examination of 12 case studies of upstream passage measures, FRANCFORT et al., (1994) concluded that if ladders and lifts are properly sized and configured for the species of concern they can be extremely effective in moving fish upstream of a hydropower project.

OTA (1995) examined a variety of fishways employed in the U.S. to promote upstream fish passage, ranging from simple culverts under a road to ladders, lifts, and
locks having a complex system of attraction features, entrances, exits, and collection and transport channels. They noted that effective fishways must take into account both site-specific environmental conditions and knowledge of the often unique biology and behavior of the fish species. For a fishway to be effective, the entrance must be located where fish can find it, must provide sufficient attraction flows, and must be accessible under a wide range of streamflows. Location of the fishway entrance near a shoreline or a consistent downstream current should minimize disorientation. Exits from the fishways should not be located near spillways or turbine intakes. Water depths and velocities in the fishway should be designed to accommodate the weakest-swimming individuals of the fish population of interest. Fishways must be properly maintained and flow passages must be kept free of debris.

2.3 Turbine Passage

It is important to protect both downstream-migrating fish and fish residing in the reservoir from entrainment in the turbine intake flows. At best, resident fish that pass through the turbine are lost to the population in the reservoir. At worst, the physical stresses associated with turbine passage (pressure changes, shear and turbulence, striking the turbine blade or other mechanical structures) can cause injury or mortality (Figure 1). ČADA and SALE (1993) estimated that 30 percent of the nonfederal hydropower projects in the U.S. had downstream fish passage facilities (for migratory fish) and/or fish protection facilities (e.g., screens for migratory and resident fish). A wide variety of downstream passage and protection measures had been employed to prevent fish from becoming entrained, ranging from spill flows to pass fish over the dam to complicated physical screening and light- or sound-based guidance measures. The most common methods for preventing turbine entrainment were fixed screens with closely spaced bars. As with upstream passage measures, downstream passage and protection measures were often poorly monitored and lacked quantified performance objectives.

The detailed examination of 14 downstream passage/protection case studies by FRANCFORT et al., (1994) revealed fewer successes than found in the upstream passage case studies. In some instances, this was because the downstream measures had been installed only recently and were not yet tested adequately. In other cases, the monitoring studies were complete but were too narrow in scope or duration to draw general conclusions. Some of the screening and bypass systems operated satisfactorily by reducing, with low bypass mortality, the numbers of entrained fish. In two of the case studies, however, initial monitoring indicated that mortalities associated with the screening and bypass systems were higher than mortalities associated with turbine passage.

No downstream passage/protection system has yet been demonstrated to be biologically effective, practical to install and operate, and acceptable to regulatory agencies under a wide range of site conditions. Even well-designed screening and
Figure 1. Locations within a hydroelectric turbine at which particular injury mechanisms to entrained fish tend to be most severe.

1. Increasing Pressure
2. Rapidly Decreasing Pressure
3. Cavitation
4. Strike
5. Grinding
6. Shear
7. Turbulence
bypass systems may protect only a portion of the fish susceptible to entrainment; the remainder will pass around the screens and through the turbines. Consequently, it is also desirable to maximize the survival of turbine-passed fish. Recognizing the need for multiple solutions to the downstream fish passage problem, the U.S. Army Corps of Engineers conducts research aimed at reducing mortality of fish (especially salmon) caused by passage through Kaplan turbines at their hydropower plants (USACE, 1995). On a wider scale, the U.S. Department of Energy, through its Advanced Hydropower Turbine System (AHTS) program, supports the development of "environmentally friendly" turbines, i.e., turbine systems in which environmental attributes such as entrainment survival are emphasized (BROOKSHIER et al., 1995). Advanced turbines would be suitable for installation at new hydropower facilities and to replace aging turbines at existing plants. It is expected that these turbines could permit the efficient generation of electricity while minimizing the damage to fish and their habitats. The first phase of the AHTS program has been completed with the delivery of preliminary designs for two new turbines. One of the turbines developed in the first phase is the product of several improvements to existing Kaplan (propeller-type) turbines, whereas the other turbine is a completely new design. Subsequent phases of the AHTS program will construct and test scale models and eventually full-scale prototypes of advanced turbines.

Continued development of environmentally friendly hydroelectric turbines requires knowledge of the physical stresses (injury mechanisms) that impact entrained fish and the fish's tolerance to these stresses. Possible causes for entrainment injury, mortality, sublethal physiological stress, and disorientation are many and varied; a recent workshop (USACE, 1995) concluded that entrainment injuries could result from rapid and extreme water pressure changes, cavitation, shear, turbulence, and/or mechanical injuries (strike, grinding, and abrasion). Instrumentation of turbines and the increasing use of Computational Fluid Dynamics (CFD) modeling can provide information about the levels of each of these potential injury mechanisms that can be expected within the turbine. Frequently missing, however, are data on the responses of fish to these levels of stress. For example, the sensitivity of fish to the levels of shear or turbulence that are predicted to occur in a turbine is not well understood, and as a result we do not know what effect altering the amount of shear in a new turbine design will have on survival. In order to continue their work, the turbine designers need numbers (biological criteria) that define a safety zone for fish within which pressures, shear forces, turbulence, cavitation, and the chance of mechanical strike are all at acceptable levels for survival.

To address these uncertainties, ČADA et al., (1997b) reviewed published laboratory bioassays and similar studies of the responses of fish to the component stresses of turbine passage. Provisional biological criteria were developed for maximum and minimum pressures, maximum rate of pressure change, probability of blade strike, and cavitation. Although fish are exposed to fluid stresses (shear and turbulence) throughout the turbine passage, very little is known about their sensitivity to these phenomena. As a result of this review and the identification of critical data gaps, the
Department of Energy is now supporting laboratory studies of shear and turbulence. It is hoped that, ultimately, the most significant injury mechanisms that affect entrained fish can be "designed out" of the next generation of turbines.

3. Summary

Hydropower is the source of 11 percent of the electricity generated in the U.S. and nearly all of the electricity produced by renewable energy sources. Despite its advantages over most other sources of electrical power, hydropower has a number of significant environmental problems that must be overcome. In order to realize the benefits of hydropower, protection of resident fish and passage of migratory fish must be assured. A number of U.S. government agencies, electrical utilities, and research organizations are engaged in research to reduce or mitigate hydropower impacts to reservoir fisheries and migratory fish stocks. They have had considerable success in designing and operating fishways for upstream passage, but the results for downstream passage and protection measures have been mixed. Consequently, many recent research and development efforts are now focused on either preventing turbine passage or reducing turbine-passage mortality. Whatever mitigation measure is chosen for a particular site, its effectiveness must be demonstrated by quantitative performance objectives and operational monitoring.

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5. References


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