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Fish Passage Mitigation of Impacts from Hydroelectric Power Projects in the United States

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Introduction

Obstruction of fish movements by dams continues to be the major environmental issue facing the hydropower industry in the United States. Dams block upstream migrations, which can cut off adult fish from their historical spawning grounds and severely curtail reproduction. Conversely, downstream-migrating fish may be entrained into the turbine intake flow and suffer turbine-passage injury or mortality. Hydroelectric projects can interfere with the migrations of a wide variety of anadromous fish [e.g., salmon (*Oncorhynchus* spp.), American shad (*Alosa sapidissima*), blueback herring (*A. aestivalis*), striped bass (*Morone saxatilis*)], catadromous fish [e.g., eels (*Anguilla anguilla*)], and some resident fish [e.g., trout (*Oncorhynchus* spp., *Salvelinus* spp., *Salmo trutta*), white bass (*M. chrysops*), sauger (*Stizostedion canadense*)]. Many of these species support important commercial or recreational fisheries. Maintenance, restoration or enhancement of populations of these species may require the construction of facilities to allow for upstream and downstream fish passage (Mattice 1990).

Francfort et al. (1994) reported about 2,350 operating conventional hydroelectric power projects in the United States. Of these, about 1,825 (78%) are non-federal projects, i.e., they are operated by private citizens, corporations, cities, or states. These non-federal developments are licensed by the Federal Energy Regulatory Commission (FERC). By law, FERC must give fish and wildlife resources equal consideration with power production in its licensing decisions, must be satisfied that a project is consistent with comprehensive plans for a waterway (including fisheries management plans), and must consider all federal and state resource agency terms and conditions for the protection of fish and wildlife. As a consequence, FERC often requires fish passage mitigation measures as a condition of the hydropower license when such measures are deemed necessary for the protection of fish. Although not licensed by FERC, hydroelectric projects operated by the federal government must also comply with environmental laws that may lead to the installation of fish passage facilities.

Much of the recent research and development efforts of the U.S. Department of Energy's Hydropower Program have focused on the mitigation of impacts to upstream and downstream fish passage. This paper describes three components of that effort: (1) a survey of environmental mitigation measures at hydropower sites across the country; (2) a critical review of the effectiveness of fish passage mitigation measures at 16 case study sites; and (3) ongoing efforts to develop new turbine designs that minimize turbine-passage mortality.

Frequency of Fish Passage Mitigation in the United States

We surveyed mitigation measures related to three most common environmental issues in the United States: fish passage, instream flow releases, and dissolved oxygen concentrations in reservoir releases (Sale et al. 1991). The information that was collected on upstream and downstream fish passage measures is summarized here and provided in greater detail in Čada and Sale (1993). As a first step, FERC's computerized licensing records were used to identify non-federal hydroelectric projects that have been required to mitigate environmental impacts related to either upstream or downstream fish passage. The data contained in these records were verified by contacting hydropower developers, and additional information was obtained directly from both developers and state and federal resource agencies responsible for overseeing hydropower development. In addition, an effort was made to acquire new information directly from the developers of projects at which fish passage mitigative measures were required. Developers were contacted via mailings and were asked to describe the specific mitigation measures required by their FERC licenses, the extent to which the requirements had been implemented, and the extent of monitoring to determine if mitigation was successful.

Analysis of the FERC databases indicated that 707 projects had some type of environmental mitigation requirement, e.g., for fish passage, instream flow releases and/or maintenance of dissolved oxygen concentrations. We asked the developers of all 707 projects about fish passage facilities, even though only a fraction were known to have relevant license requirements. Developers of 280 of the 707 projects (40%) responded to the information request, including 34 projects with upstream fish passage facilities and 85 projects with downstream fish protection measures.

Fish passage requirements are most common in states in the Northeast U.S., along the Pacific coast, and in the Rocky Mountains. Coastal states support the most important anadromous fisheries (salmon, steelhead, and shad), whereas the Rocky Mountain states have valuable recreational fisheries for resident trout and char. Around 11 % of the hydropower licenses issued in the 1980s had upstream fish passage requirements (Sale et al. 1991). Downstream fish passage requirements became more common during this same decade; the percentage of new licenses that have downstream fish passage requirements increased from 22% in 1980-83 to 35% in the period 1984-90.

Upstream Fish Passage - Most upstream passage measures that have been installed can be placed into three general categories: trapping and hauling, fishways (fish ladders), and fish lifts or elevators. Descriptions of the basic types of upstream fish passage measures are provided in earlier reviews (Clay 1961; Hildebrand 1980; Orsborn 1987). Of 34 projects with upstream fish passage requirements, 31 were either in operation or recently completed. Fish ladders were the most common mitigative measure, accounting for 24 of the 34 upstream passage devices reported (Figure 1). Fish ladders are employed throughout the United States, and some are quite old, dating back to the turn of the century. Fish elevators are a less common (4 out of 34) mitigative measure. The trapping and hauling (by trucks) of fish to upstream spawning locations is used at some older dams or in conjunction with fish lifts, but in two of the projects, fish ladders or elevators are being constructed to replace this labor-intensive mitigative measure. Some upstream passage measures that were reported at a few sites fit none of the three categories; these include berms (to keep upstream migrating fish away from the powerhouse discharge area or to guide fish toward ladders) and the use of navigation locks. Fish elevators were used mainly at taller dams, but ladders had been constructed at both short and tall dams.

Among the 29 respondents that have operating upstream fish passage facilities, 12 reported that the facilities are in operation at all times. Another 10 of the 29 projects reported that the passage facilities are operated only during specified seasons, whereas 4 are required to operate only during certain hours (e.g., nighttime) during specified seasons. Three of the developers didn't respond to this question.

Twenty-three of the 34 projects with upstream fish passage requirements reported that the mitigation measure was designed for anadromous fish. On the other hand, some hydroelectric projects are required to maintain upstream movements of resident (non-anadromous) fish as well. Thirteen of the projects reported both anadromous and resident fish passage requirements, and 4 reported only resident fish passage requirements. Some ladders were installed at dams without significant fish populations; the requirements were based on the expectation that planned fish restoration efforts would result in upstream migrants encountering the dam in the future.

Monitoring the operational performance of fish passage facilities is important. Without performance monitoring, the effectiveness of site-specific mitigation cannot be determined, nor can knowledge gained at that site be transferred to other sites. We found only limited performance monitoring at the non-federal hydroelectric projects examined in this study. Performance monitoring of the upstream fish passage measures was not being conducted at 17 operating projects that provided information. Twelve of the operating facilities monitor fish passage rates; these are generally fishway counts, i.e., simple tallies of the number of fish that used the passage measure. Although such studies determine the number of fish that passed through the facility, they rarely provide information about the numbers of fish that were unable to successfully negotiate the facility. Simple fishway counts are not useful for comparing effectiveness of different devices or of the same device at different sites. Seven of the operating projects monitored the specific fish populations protected by the mitigation measure. Population monitoring studies provide a longer-term view of the success of a mitigative measure because they can estimate whether fish populations have been maintained or enhanced during the facility's operation. Because other factors may influence fish numbers or standing crops, however, fish population monitoring by itself may not yield widely transferable information about the effectiveness of a device.

Downstream Fish Passage - A variety of downstream fish passage screening devices have been employed to prevent fish from becoming entrained in turbine intake flows. The simplest measure, spill flows, can transport fish over the hydropower dam rather than through the turbines. At the other end of the scale, sophisticated physical screening and light- or sound-based guidance measures are being studied. Spilling water can be an effective means for passing surface-oriented downstream migrants, but spilled water cannot be used for electrical power generation. Physical and behavioral screening make it possible to bypass downstream migrating fish with a minimal loss of water. Extensive reviews of downstream fish passage mitigation measures are available (Taft 1986; EPRI 1988; Bell 1991). No single fish protection system or device has yet been demonstrated to be biologically effective, practical to install and operate, and acceptable to regulatory agencies under a wide variety of site conditions.

Information was obtained from 85 hydroelectric projects that have downstream fish passage requirements. The measures are in operation at 58 of the 85 projects. Figure 2 lists the most common measures that are employed to reduce turbine entrainment of fish. The single most frequently required downstream fish passage device is the angled bar rack. This mitigative measure, in which a trash rack that has closely spaced bars (ca 2 cm) is set at an angle to the intake flow, has been commonly required in the northeastern U.S. Angled bar racks are used by 32 of the 85 projects that responded to the information request. Other types of fixed fish screens range from variations of conventional trash racks oriented perpendicular to flow to more novel designs employing cylindrical, wedge-wire intake screens. Traveling screens are used at three of the projects; these screens are installed in the gatewells of large hydroelectric projects. Some of these measures are used in combination, e.g., fixed screens with velocity limits. Angled screens tended to be used at the smaller hydro facilities. On the other hand, traveling screens, which are often large and mechanically complicated, tended to be used at the larger hydroelectric plants.

Intake screens of all kinds may have a maximum approach velocity requirement and a sluiceway or some other type of bypass to transport the fish below the dam. In some cases a properly designed trash sluiceway may serve to transport screened fish downstream. Twenty of the 85 projects have a maximum velocity limit on the intake flows (ranging from 0.1 to 1.2 m/s), and 22% have a sluiceway or some other form of bypass. Three of the projects reported that a maximum approach velocity requirement was the sole measure to reduce turbine entrainment. Eight of the projects have a sluiceway or bypass as the only mitigative measure to enhance downstream fish passage.

The other types of downstream fish passage measures reported (Figure 2) were barrier nets, blockage of the top portion of the trash rack to guide surface-oriented fish to a sluiceway, modification of the sequence of operation of multiple-unit projects, and experimental use of strobe lights or underwater sound to drive fish away from the turbine intake area.

As with upstream fish passage facilities, a large percentage (57%) of the downstream fish passage measures are in operation at all times. Eighteen of the 85 projects operate the mitigative measure only during specified seasons, whereas 3 are operated only during certain hours of specified seasons. Seventeen percent of projects did not report when the downstream fish passage measures are used, perhaps because many are still under construction and specific operational requirements have not been specified.

Downstream fish passage facilities were most frequently designed to protect adult resident fish (55% of projects with such facilities). Juvenile resident fish (41%) and juvenile anadromous fish (25%) were also important targets for these mitigative measures. Downstream fish passage facilities are intended to protect fish eggs and larvae at only 8% of the projects.

We found a relatively low level of performance monitoring for operating downstream fish passage facilities at the non-federal projects. No performance monitoring was reported at 79 percent of the projects that have operating downstream fish passage measures. Among the projects where operational monitoring was conducted, 11 monitored passage rates, 10 estimated mortality rates of either entrained or bypassed fish, and one monitored fish populations.

Despite increasing efforts in recent years to install a variety of fish passage and protection measures at hydroelectric power plants, few comprehensive field studies have been carried out either to assess the site-specific effectiveness of these mitigative measures or to evaluate their usefulness in other settings (Čada and Sale 1993). The lack of information about effectiveness is a particular problem for downstream fish passage measures, where designs are newer and more varied and where practical operating experience is less than, for example, at fish ladders. Construction and operation of often costly fish passage measures may be required at sites where need is uncertain (e.g., at sites without clearly migratory fish species) or where the subsequent biological benefits remain unknown.

Effectiveness of Fish Passage Mitigation

Francfort et al. (1994) recently completed a detailed study of the benefits and costs of measures used to enhance upstream and downstream fish passage at dams, using operational monitoring data from 16 case study projects across the U.S. (Table 1). The 16 case study projects encompass a wide range of plant sizes, although most are relatively small. Generating capacity among the case study projects ranges from 0.4 to 840 MW; median generating capacity is 15 MW. Heights of the diversion dams range from 1.1 to 56 m, but 13 of the 16 case study projects have diversion dams less than 20 m high. While the 16 case studies do not include all the fish passage technologies, they represent the measures most commonly used in the U.S.

Based on operational monitoring to date, at least six of the case study projects have successfully increased the upstream passage rates or downstream passage survivals of anadromous fish (Čada and Francfort 1995). For example, fish lifts were installed at the Conowingo Dam in 1972 and 1991 to assist the upstream migration of American shad (*Alosa sapidissima*) in the Susquehanna River. Although this stock had formerly supported important commercial and recreational fisheries in the river, Chesapeake Bay, and the Atlantic Ocean, construction of mainstem dams in the lower river beginning in the 1920s had prevented the adults from reaching nearly all of the historical spawning and nursery grounds. The annual catch of adult American shad at the Conowingo fish lift had declined to an average of 110 fish from 1972 to 1980 (Foote et al. 1993). The two fish lifts at the Conowingo Hydroelectric Project were operated as a part of an overall American shad restoration program which included releases of hatchery-reared fry and fingerlings, distribution of pre-spawning adults from other rivers in the eastern U.S. to upstream tributaries of the Susquehanna River, and, as the stock rebuilt in the 1980s, natural reproduction of adult shad collected at the Conowingo Dam fish lifts and transported upstream to spawn. The two lifts operate like elevators, raising American shad and other fish species from the base of the 32-m-high dam into either a sorting tank or the impoundment. Between 4.7 and 35.1 percent (mean: 23.7 percent) of adult shad in the Conowingo tailrace were transported by the lifts between 1984 and 1992. After sorting, adult shad are transported in trucks to spawning grounds upriver. Effectiveness of the Susquehanna River American shad restoration program, of which the Conowingo Dam fish lifts are an essential part, is seen in the increasing numbers of adult shad that return to the Conowingo Dam. Adult American shad numbers below the Conowingo Dam increased from about 4,000 to over 80,000 between 1984 and 1992 (Foote et al. 1993).

The Buchanan project is a run-of-river facility on the St. Joseph River in Michigan. A 5-

m-high vertical slot fish ladder was completed in 1990 to allow the upstream migrations primarily of chinook salmon (*O. tshawytscha*), steelhead trout (*O. mykiss*) and, incidentally, coho salmon (*O. kisutch*) and brown trout (*S. trutta*) from Lake Michigan. The resource agencies' objectives for the Buchanan fish ladder were to allow the upstream passage of chinook and steelhead above the former barrier and to distribute the fish (and sport fishery) throughout the lower 100 km of the St. Joseph River. Monitoring in the summer and fall of 1992 indicated that 92 percent of the chinook and 69 percent of the steelhead that reached the Buchanan Dam successfully passed upstream through the fish ladder (Francfort et al. 1994). The Buchanan fish ladder is expected to increase recreational fishing by 125,000 angler days per year.

A penstock (Eicher) screen, composed of fine-mesh wedge wire, was installed in one of the 13 turbine units at the T.W. Sullivan Plant on the Willamette River in Oregon. The penstock screen diverts fish from the intake flow and directs them to a bypass for release below the dam. Between 77 and 95 percent of hatchery spring chinook smolts experimentally introduced into the forebay were bypassed away from the turbines. Bypassed chinook, coho, and steelhead smolts showed low levels of injury, with an average descaling rate of 3.3 percent (Clark and Cramer 1993). Further, a limited series of tests indicated that delayed mortalities among bypassed fish were low. Mortality resulting from passage of downstream-migrating salmonids through the Sullivan bypass system could be expected to average less than 1 percent, compared to estimated turbine-passage mortalities of 10-15 percent (Francfort et al. 1994).

The Leaburg Hydroelectric Project is a 15 MW, run-of-river development on the McKenzie River in Oregon. The 6-m-high diversion dam has a single pool-and-weir ladder for upstream fish passage and three profile-wire (wedge-wire) fixed screen arrays to remove entrained fish from the power canal. Monitoring of angler harvest, escapement, and redd counts, and observation of migrants by video cameras at the ladder, indicated that an average of over 2,800 spring chinook salmon used the ladder each year. Although the average annual return of spring chinook salmon to the McKenzie River has been below the agency goal of 18,000, numbers have increased in recent years and averaged over 11,000 in the last 4 years of record. The wedge-wire screens at Leaburg have reduced mortality among downstream-migrating fish. Mortality of screened and bypassed smolts was less than 5 percent, compared to turbine-passage mortality of 28 percent. Owing to recent modifications of the screens, screening mortality among the smaller salmon fry has also been reduced from more than 80 percent to less than 5 percent (Francfort et al. 1994).

In addition to these examples, other case study projects appeared to have effective fish passage measures based on early monitoring, but environmental conditions or changing fisheries management goals have prevented a fuller assessment of the benefits.

Although all of the projects had conducted some degree of performance monitoring of their fish passage mitigation measures, there were substantial differences in the extent and rigor of the studies. As might be expected, the extent of monitoring was directly related to the size of the hydroelectric project and the importance of the fish resource. Some projects supported quantitative, multi-year studies of the effectiveness of the mitigative measures, whereas for others the monitoring was limited to studies conducted during a single season or based only on visual observations. For most case study projects, benefits could be expressed only in terms of increased numbers of fish that were transported around that dam or protected from turbine entrainment.

The influence of these increased numbers on the subsequent size of the fish populations or on recreational/commercial fisheries were rarely known.

Most of the monitoring studies of fish passage mitigation measures have dealt with anadromous salmonids or clupeids because of their commercial or recreational values. Much less is known about the effectiveness of fish passage/protection measures for resident fish, especially those with only non-use value. Existing ladders and lifts also allow the upstream passage of non-target fish species, although they may be less effective because they have been designed with the behavior and swimming ability of only trout and salmon in mind. Given the growing emphasis in the U.S. on managing natural resources to maintain biodiversity, hydropower facilities may eventually need to operate upstream passage measures to promote free passage of a wide variety of fish species and sizes. Alternatively, protecting biodiversity may lead to the closing of fishways in streams where the native fish populations above the dam may be adversely affected by upstream movements of planted hatchery fish, or where extending the range of native or introduced fish is considered undesirable.

Case studies of upstream fish passage have shown that both fish ladders and fish lifts can successfully transport large numbers of spawners. The downstream passage case studies revealed fewer successes than the upstream case studies. In some instances this was because the downstream measures were only recently installed and not yet adequately monitored. However, mitigation of turbine entrainment impacts may be a more difficult problem to resolve than upstream passage.

Ongoing and Future Studies

Uncertainty about the effectiveness of screening for downstream fish passage has led to research into new turbine designs to maximize the survival of turbine-passed fish. Even effective, well-designed screening and bypass systems may protect only a portion of the fish entrained in the intake flows; the remainder will pass through the turbines. Hence, it is desirable to maximize the survival of turbine-passed fish. Further, bypassed fish may suffer mortality due to screen abrasion or exposure to predators at the bypass outfall. Mortality caused by the bypass system may equal or exceed that of turbine passage (Ferguson 1991).

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 (mainly salmon) associated with passage through Kaplan turbines at their hydropower plants (Wittinger et al. 1995). On a wider scale, the U.S. Department of Energy is supporting the development of "environmentally-friendly turbines," i.e., turbine systems in which environmental attributes such as entrainment survival, instream flow needs, and/or water quality enhancement are emphasized (Brookshier et al. 1995). As presently envisioned, this multi-year effort will be carried out in three phases: Phase I - development of conceptual designs for new turbines; Phase II - construction and testing of scale models; and Phase III - construction and testing of full-sized prototype turbines. If successful, such turbine systems could allow the efficient generation of electricity while minimizing the damage to fish and their habitats.

Whether the focus of research and development is improvement of upstream fish passage, intake screening and bypassing of downstream migrants, or decreasing the mortality of turbine-passed fish, there remains a considerable need to examine rigorously the effectiveness of mitigation measures. Needed areas of research include estimation of population-level effects of mitigative measures, examination of effectiveness for non-target species (i.e., fish species with no recreational or commercial value), and quantification of the economic benefits of the mitigative measure for comparison to construction, operation, and maintenance costs (Francfort et al. 1994).

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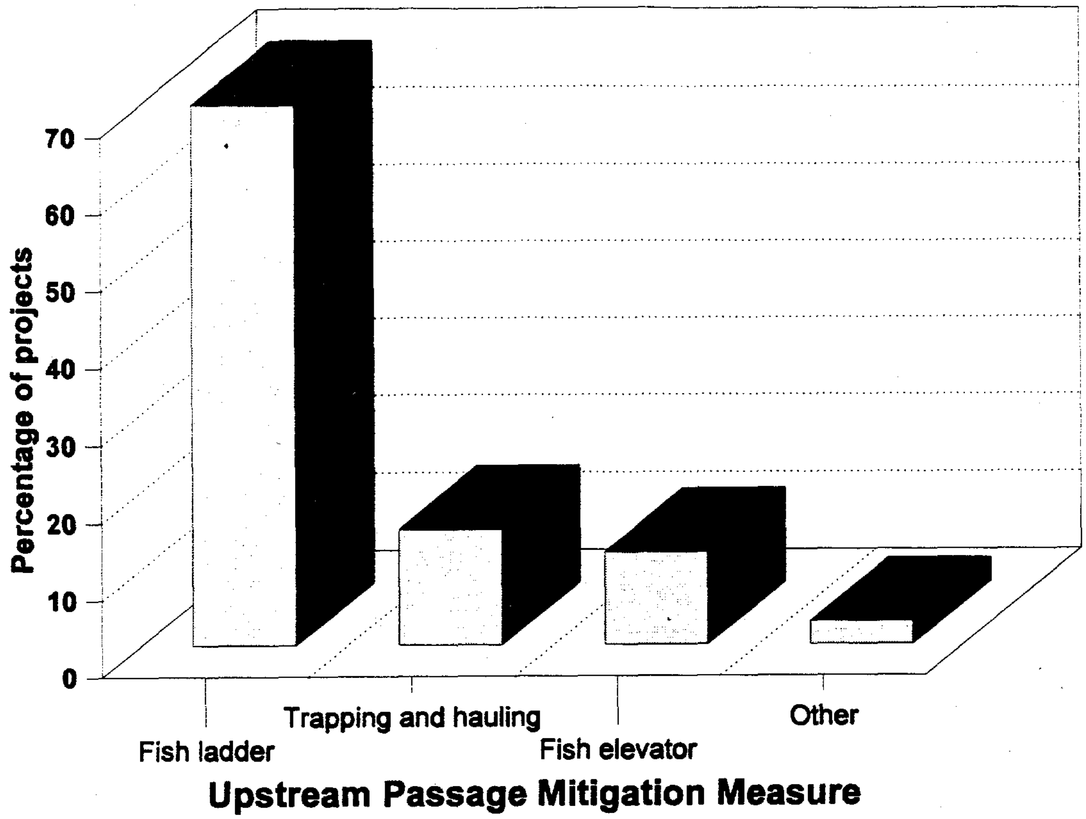

Figure 1. Types and frequencies of mitigation measures used to assist upstream fish passage at hydroelectric power plants in the United States.

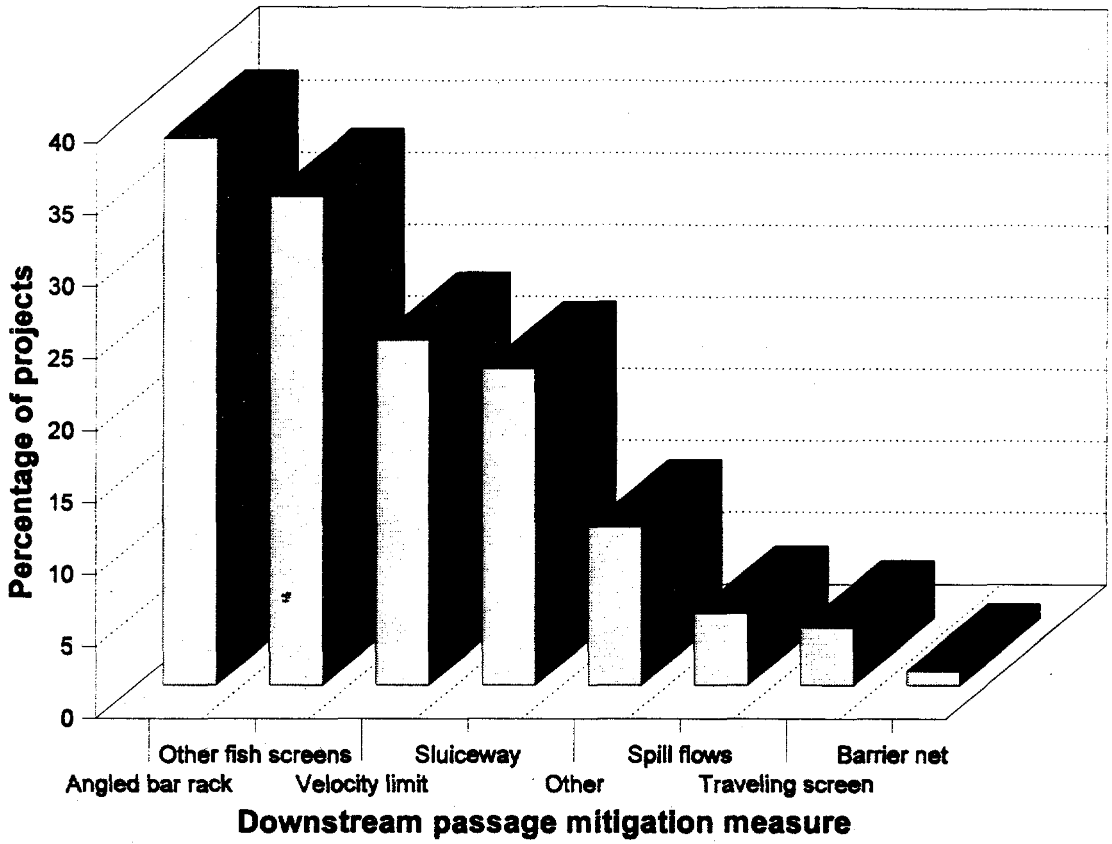

Figure 2. Types and frequencies of mitigation measures used to assist downstream fish passage at hydroelectric power plants in the United States.

Table 1. Case study hydroelectric projects used to examine effectiveness of fish passage and protection mitigative measures. From: Francfort et al. (1994).

Project	Fish species	Effectiveness of mitigative measures
Brunswick	American shad Alewife	76,000 alewives move through vertical slot fish ladder per year, but only small numbers of American shad
West Enfield	Atlantic salmon	Vertical slot ladder is effective, but downstream fishway may result in greater mortality than turbine passage
Lowell	American shad	Average of 2,200 American shad/year use vertical slot ladder and mechanical lift
Little Falls	Blueback herring	Entrainment of blueback herring reduced to < 1 percent by fixed wire mesh intake screens and bypass
Wadhams	Atlantic salmon	Significant reduction in entrainment by angled bar rack
Conowingo	American shad	Mechanical fish lifts pass increasing numbers of American shad upstream
Buchanan	Steelhead trout Chinook salmon	Vertical slot fish ladder passed an estimated 92 percent of chinook salmon and 69 percent of steelhead trout
Kern River No. 3	Rainbow trout	No monitoring program for old fish ladder, but changing management goals may result in its closure
Potter Valley	Steelhead trout Chinook salmon	Observed passage of chinook salmon and steelhead through pool-and-weir ladder, but low streamflows constrained monitoring
Arbuckle Mountain	Steelhead trout Chinook salmon	Denil ladder and cylindrical wedge-wire screens; monitoring and restoration of anadromous fish hindered by low streamflows, but no obstruction of resident trout observed.
T.W. Sullivan	Chinook salmon	Penstock screen on one unit bypassed 77-95 percent of smolts with little injury
Jim Boyd	Steelhead trout Chinook salmon	Visual observations indicate that agency goals for V-notch weir and perforated steel screen are being met
Leaburg	Chinook salmon Steelhead trout	Pool-and-weir ladder and wedgewire screens achieve agency performance standards
Wells	Steelhead trout Chinook salmon Sockeye salmon	Pool-and-weir ladders pass an average of 48,000 salmonids per year. Efficiency of hydrocombine bypass for smolts exceeds agency standards
Twin Falls	Rainbow trout Cutthroat trout Brook trout	Inclined wedge-wire screens meet agency criteria for approach and sweeping velocity limitations
Lower Monumental	Steelhead trout Chinook salmon	Overflow weir ladders pass 82-100 percent of spring and summer chinook salmon. Submerged traveling screens not yet monitored.