Fish Passage Technologies: Protection at Hydropower Facilities

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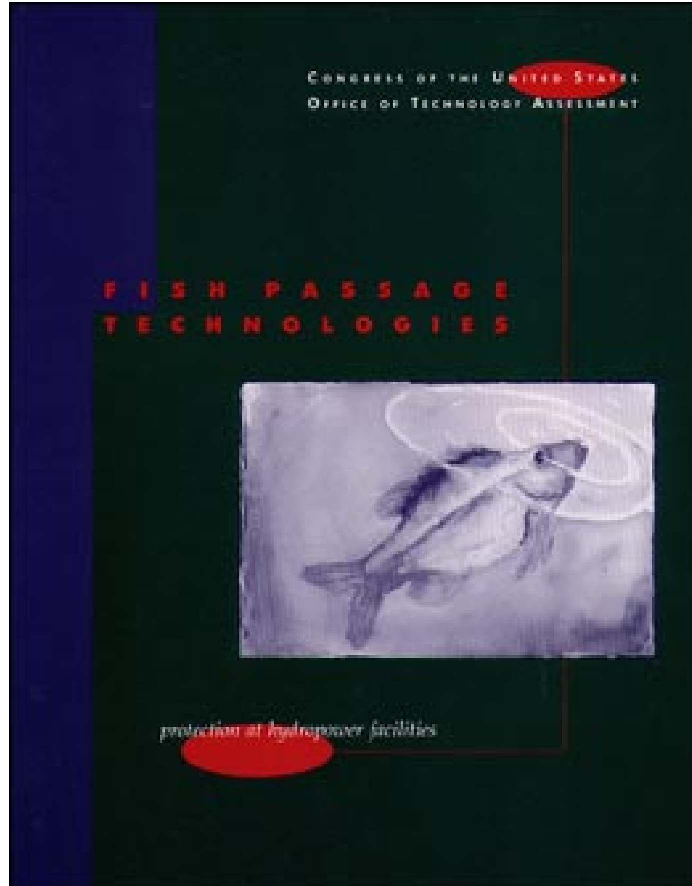

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Foreword

The House Committee on Merchant Marine and Fisheries requested that the Office of Technology Assessment (OTA) examine the role of fish passage and protection technologies in addressing the adverse effects of hydropower development on North American fish populations. After the elimination of the requesting committee, the report was continued on behalf of the House Resources Committee, Subcommittee on Fisheries, Wildlife, and Oceans.

Hydropower development may adversely affect fish by blocking or impeding biologically significant movements, and altering the quantity, quality, and accessibility of necessary habitat. Fish moving downstream that pass through hydropower turbines can be injured or killed, and the inability of fish to pass upstream of hydropower projects prohibits them from reaching spawning grounds. Hydropower licenses issued by the Federal Energy Regulatory Commission (FERC) may include requirements for owners/operators to implement fish passage technologies or other measures to protect, enhance, or mitigate damages to fish and wildlife, as identified by the federal resource agencies. Although FERC is directed to balance developmental and nondevelopmental values in licensing decisions, many contend that balancing has been inadequate. Thus, fish passage and protection has become a major controversy between the hydropower industry and resource agencies.

This report describes technologies for fish passage, and those for protection against turbine entrainment and mortality, with an emphasis on FERC-licensed hydropower projects. OTA identifies three areas for policy improvements. First, to establish and maintain sustainable fisheries, goals for protection and restoration of fish resources need to be clarified and strengthened through policy shifts and additional research. Secondly, increased coordination is needed among fishway design engineers, fisheries biologists, and hydropower operators, especially during the design and construction phases of fish passage and protection technologies, to improve efficiency. Finally, new initiatives with strong science and evaluation components are needed to advance fish passage technologies, especially for safe downstream passage.

OTA sincerely appreciates the contributions of the advisory panel, workshop participants, contractors, and reviewers. We are especially grateful for the time and effort donated by the federal and state resource agencies and the Federal Energy Regulatory Commission. The information and assistance provided by all of these individuals was invaluable.

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Executive Summary and Policy Directions 1

The focus of this report is technologies for fish passage around hydropower generation facilities and protection against entrainment and turbine mortality. Emphasis is given to Federal Energy Regulatory Commission (FERC)-licensed hydropower projects where fish protection is a subject of controversy and congressional interest due to the Federal Power Act (FPA) and the Electric Consumers Protection Act (ECPA). Thus institutional issues related to FERC-relicensing are also discussed. (Major points of controversy are highlighted in box 1-1.) Federal hydropower projects, especially in the Columbia River Basin, and irrigation water diversions in the Pacific Northwest and California are included to the extent that they provide information on fish passage technologies (see table 1-1). Many of the technologies discussed are applicable to other types of dams and water diversions. In fact, there are many more obstructions to fish passage that are not covered by FERC-licensing requirements, than are (approximately 76,000 dams versus 1,825 FERC-licensed facilities) (70).

Fish passage is considered necessary where a dam separates a target species from needed habitat. Fish are generally unable to pass upstream of a hydropower dam unless some fish passage facility is present. Downstream passage facilities may not always be necessary if the fish can safely pass through turbines, spillways, or sluiceways, though there is significant debate about the adequacy of these latter two passage methods. [1]

Decisions about the need for fish protection measures at dams are often based on the perceived or measured impacts on one or more species at the site (242). Fish populations may be adversely affected by hydropower facilities and many other activities and facilities (e.g., multiple use, flood control, and water supply dams; land use practices like grazing and forestry; and facilities like coal-fired power plants that cause acid rain). Migrations and other important fish movements can be blocked or delayed. The quantity, quality, and accessibility of up- and downstream fish habitat, which can play an important role in population sustainability, can be affected. Fish that pass through power generating turbines can be injured or killed. Increased predation on migratory fishes has also been indirectly linked to hydropower dams (e.g., due to migration delays, fish being concentrated in one place, or increased habitat for predatory species). Habitat

[1] Spillways are used to pass water over a dam. Sluiceways are used to pass debris, ice, logs, etc.

BOX 1-1: Fish Passage At FERC-Licensed Hydropower Facilities: Controversial Issues

This study was initiated because of significant controversy about technical issues related to fish passage and the relicensing of a large number of hydropower facilities, beginning in 1993 and continuing through 2010. Major controversial issues that are discussed in this study are listed below:

Discussed in Chapters 1–4:

- Do riverine fish need passage? (chapter 2)
- Do riverine fish need protection from entrainment? (chapter 2)
- Is experimentation with alternative behavioral technologies warranted? (chapters 1 and 4)

Discussed in Chapter 5:

- Is FERC's balancing of developmental and nondevelopmental values adequate?
- How should the baseline goal for mitigation be defined?
- How timely is the licensing process?
- How well are license reopeners implemented?
- Should dams be decommissioned and/or removed?

SOURCE: Office of Technology Assessment, 1995.

TABLE 1-1. Columbia River Basin: Downstream Fish Passage Methods And Research

Downstream passage technique	Status	Stakeholder views		Effectiveness
		Resource agencies	Hydro industry	
TRANSPORTATION				
Barging	Conventional	Mixed	Accepted	Good
Trucking	Conventional	Mixed	Accepted	Good
SCREENS (low-velocity)				
STS	Conventional	Mixed	Contentious	Good
Vertical traveling	Conventional	Accepted	Accepted	Good
Rotating drum	Conventional	Accepted	Accepted	Good
SCREENS (high-velocity)				
Eicher screen	Experimental	Mixed	Mixed	Very Good
MIS	Experimental	Mixed	Mixed	Very Good
ALTERNATIVE BEHAVIORAL DEVICES				
Acoustics (sound)	Experimental	Hopeful	Hopeful	Unknown
Surface collector	Experimental	Hopeful	Hopeful	Unknown
OTHER METHODS				
Turbine passage	Conventional	Contentious	Accepted	Fair
Spilling	Experimental	Contentious	Accepted	Good

NOTE: Many of the downstream passage technologies and devices discussed in this report are being experimented with in the Columbia River Basin. For further discussion of these, see chapter 4. For further discussion of the Columbia River Basin, see appendix A.

SOURCE: Office of Technology Assessment, 1995.

alterations and increased predation pressure caused by hydropower dams are significant issues, but fall beyond the central scope of this report.

This study was initiated because of significant controversy about technical issues related to fish passage and the relicensing of a large number of hydropower facilities, beginning in 1993 and continuing through 2010. Major points of controversy are discussed below.

CONTROVERSIES

The need for fish passage facilities is widely accepted for anadromous fish (i.e., fish that migrate from the ocean to spawn in freshwater) (see box 1-2). Considerable controversy exists between resource agencies and hydropower operators about the passage and protection requirements for riverine fish (i.e., the so-called resident species that spend their entire lives in freshwater) (see chapter 2).

BOX 1-2: Chapter 2 Findings—Fish Passage and Entrainment Protection

- The need for entrainment protection and passage for riverine fish is very controversial. There is a growing body of evidence that some riverine fish make significant movements that could be impeded by some hydropower facilities. The need for passage for riverine fish is most likely species- and site-specific and should be tied to habitat needs for target fish populations. This will be difficult to determine without establishing goals for target species.
- The acceptability of turbine passage for anadromous fish is site-specific and controversial. There is major concern when anadromous fish must pass through multiple dams, creating the potential for significant cumulative impacts. Passage of adult repeat spawners is also a major concern for most Atlantic Coast species.
- The effects of turbine passage on fish depend on the size of the fish; their sensitivity to mechanical contact with equipment and pressure changes; and whether fish happen to be in an area near cavitation or where shearing forces are strong. Smaller fish are more likely to survive turbine passage than larger fish. Survival is generally higher where the turbines are operating with higher efficiency.
- Riverine fish are entrained to some extent at virtually every site tested. Entrainment rates are variable among sites and at a single site. Entrainment rates for different species and sizes of fish change daily and seasonally. Entrainment rates of different turbines at a site can be significant.
- Turbine mortality studies must be interpreted with caution. Studies show a wide range of results, probably related to diversity of turbine designs and operating conditions, river conditions, and fish species and sizes. Turbine mortality study design is likely to affect results. Different methods may yield different results.
- Methods for turbine mortality study include: mark-recapture studies with netting or balloon tags, and observations of net-caught naturally entrained fish, and telemetry. Methods for entrainment studies include: netting, hydroacoustic technology (used especially in the West), and telemetry tagging. These methods have advantages and disadvantages depending on target species and site conditions. Hydroacoustic technology and telemetry tagging can provide fish behavior information (e.g., tracking swimming location) useful for designing passage systems and evaluating performance.
- Early agreement on study design would help minimize controversies between resource agencies and hydropower operators. Lack of reporting of all relevant information makes it difficult to interpret results. Standardized guidelines to determine the need, conduct, and reporting of studies could help overcome this limitation.
- Mitigation by financial compensation is very controversial. The degree of precision necessary for evaluation studies and how fish should be valued are items of debate.

SOURCE: Office of Technology Assessment, 1995.

This controversy over whether riverine fish need safe passage relates to whether or not movement to habitats blocked by a dam have adverse impacts on the population. Although the paradigm is beginning to change, the predominant thinking has been that riverine fishes have restricted movements. This may be true at some sites, but the generalization may in part be an artifact of the movement studies that have been done. Recent research has identified major differences in fish movements among different species of riverine fish and there are some studies that document different movements of the same species in different watersheds. The need for mitigation to provide passage for riverine fishes is most likely site- and species-specific and should be tied to the specific habitat needs for target fish populations in a given river reach.

The controversy over whether riverine fish need protection from entrainment is largely unrelated to issues about passage requirements (see chapter 2). The controversy centers on the lack of information on the impact of entrainment on the overall fish population. Population impact studies would be exceedingly complex, time consuming and costly, and are rarely, if ever, done (146). The hydropower industry and resource agencies take very different positions about the need for entrainment protection, given the lack of good site-specific information. Industry generally says that entrainment protection is not necessary for riverine fish. Resource agencies consider entrainment a chronic loss of fish that requires mitigation, or at least compensation. As a result of this controversy, entrainment and turbine mortality studies are frequently done. These studies also have limitations.

The National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (FWS), referred to throughout this report as federal resource agencies, have the authority to prescribe mandatory fish passage mitigation under section 18 of the Federal Power Act, as amended (FPA). These agencies, along with their state counterparts, may also make additional recommendations to protect, mitigate, and enhance fish and wildlife affected by hydropower development under section 10(j) of the FPA. The decision to include section 10(j) recommendations in a hydropower license order rests with the Federal Energy Regulatory Commission. FERC is required to balance developmental and nondevelopmental values of hydropower development in the licensing process. This requires an evaluation of the need for (i.e., benefits) and costs of recommended mitigation compared to the benefits of the hydropower project; such evaluations have many limitations.

Apart from the controversies about the need for fish passage and protection, there are issues about the technologies (boxes 1-3 and 1-4). For upstream technologies, the issues relate to proper design, operation and maintenance, understanding fish behavior, and the need to develop technologies for additional species (see chapter 3). These upstream technology issues are not particularly controversial.

For downstream technologies, the primary controversy is the value of investing time and money in alternative behavioral technologies, especially for conditions where conventional methods with high levels of effectiveness are possible. This issue is highly controversial and complex (see chapter 4). It is not readily explained without an understanding of the technologies for fish passage and the different positions of key stakeholders, including:

- resource agencies with responsibilities for protection of fish species, many of which are in serious decline;
- hydropower operators with the mission of providing a renewable form of electricity without the emissions and adverse environmental effects associated with alternative generation methods; many operators are seriously concerned about their viability in anticipated deregulated markets; and
- developers of new technologies who are convinced they have viable approaches to fish passage and protection that will cost much less than conventional methods.

Resource agencies take the position that conventional downstream passage technologies should be installed because the alternative meth-

BOX 1-3: Chapter 3 Findings—Upstream Technologies

- There is no single solution for designing upstream fish passageways. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.
- Technologies for upstream passage are considered well-developed and understood for particular species.
- Upstream passage failure tends to result from less-than-optimal design criteria based on physical, hydrologic, and behavioral information or from a lack of adequate attention to operation and maintenance of facilities.

SOURCE: Office of Technology Assessment, 1995.

BOX 1-4: Chapter 4 Findings—Downstream Technologies

- There is no single solution for designing downstream fish passage. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.
- Physical barrier screens are often the only resource agency-approved technology to protect fish from turbine intake channels, yet the screens are perceived to be very expensive.
- The ultimate goal of 100 percent passage effectiveness is most likely to be achieved with the use of physical barrier technologies; however, site, technological, and biological constraints to passing fish around or through hydropower projects may limit performance.
- Structural guidance devices have been shown to have a high level of performance at a few studied sites in the Northeast. The mechanism by which they work is not well understood.
- Alternative behavioral guidance devices have potential to elicit avoidance responses from some species of fish. However, it has not yet been demonstrated that these responses can be directed reliably; behavioral guidance techniques are site- and species-specific; and it appears unlikely that behavioral methods will perform as well as conventional barriers over a range of hydraulic conditions and for a variety of species.

SOURCE: Office of Technology Assessment, 1995.

ods are unproven, will likely remain highly site specific, and may never provide the levels of protection of well-designed and operated conventional measures under the wide range of conditions present at a site. On the other hand, hydropower operators and promoters of new technologies want the opportunity to find lower cost solutions to fish protection.

Hydropower licensing is a highly controversial issue among the many stakeholders involved in the process (see box 1-5). State and federal resource agencies, the hydropower industry, special interest groups (e.g., environmental), Native American tribes, individual owner/operators, and the public at large are all involved. Balancing all of these competing interests in licensing is a complex process, generating much dispute among the participants. Key areas of controversy include: adequacy of FERC's balancing of developmental and nondevelopmental values; defining the baseline goal for mitigation; timeliness of the licensing process; license reopeners; and dam decommissioning and/or removal (see chapter 5).

OTA does not resolve these controversies in this report. OTA does, however, discuss the issues underlying these controversies and the context in which they have developed. This chapter continues with policy directions, a summary of technologies, and overall conclusions related to technologies and hydropower licensing.

BOX 1-5: Chapter 5 Findings—Federal Role

- The Federal Energy Regulatory Commission (FERC) has exclusive authority to license nonfederal hydroelectric facilities on navigable waterways and federal lands, which includes conditioning of licenses to require operators' adoption of fish protection measures.
- Section 18 of the Federal Power Act gives the federal resource agencies authority to prescribe mandatory fish passage conditions to be included in FERC license orders. Section 10(j) recommendations relate to additional mitigation for rehabilitating damages resulting from hydropower development or to address broader fish and wildlife needs (e.g., minimum flow requirements). Yet, these recommendations are subject to FERC approval.
- FERC's hydroelectric licensing process has been criticized as lengthy and can be costly for applicants and participating government agencies. In some cases, the cost of implementing fish protection mitigations from the utility perspective may render a project uneconomical.
- FERC uses benefit-cost analyses in its final hydroelectric licensing decisions; yet economic methods for valuing habitat or natural resources are not well established and many economists feel that they fit poorly in traditional benefit-cost analysis.
- There is no comprehensive system for monitoring and enforcing resource agency fish passage prescriptions. FERC's monitoring and enforcement authority has been used infrequently, and only recently, to fulfill its mandate to adequately and equitably protect, mitigate damages to, and enhance fish and wildlife (including related spawning grounds and habitat) affected by the development, operation, and management of hydroelectric projects.
- Parties must perceive a need to negotiate in the FERC hydropower licensing process, beyond the regulatory requirements of applicants and agencies, in order to achieve success. FERC must be seen as a neutral party to motivate participants to find mutually acceptable agreements in accommodating the need for power production and resource protection. If FERC is perceived to favor certain interests, the need to negotiate is diminished or eliminated.
- There are no clearly defined overall goals for North American fishery management, and Congress has not clearly articulated goals for management of fishery resources and/or priorities for resource allocation.
- Fish protection and hydropower licensing issues return repeatedly to the congressional agenda. The 1920 Federal Power Act (FPA) was designed to eliminate controversy between private hydropower developers and conservation groups opposed to unregulated use of the nation's waterways. Greater consideration of fisheries and other "nondevelopmental" values was called for in the Electric Consumers Protection Act of 1986 (ECPA) and oversight on these issues continued with the passage of the Energy Policy Act of 1992. In the 104th Congress, efforts continue to address power production (e.g., sale of PMA's; BPA debt restructuring) and developing sustainable fisheries (e.g., Magnuson Act Amendments; Striped Bass Conservation Act).

SOURCE: Office of Technology Assessment, 1995.

POLICY DIRECTIONS

Three key areas exist for policy improvements: establishing sustainable fisheries, improving performance of fish passage technologies, and advancing fish passage and protection technologies.

First, to establish and maintain sustainable fisheries, goals for protection and restoration of fish resources need to be clarified and strengthened through policy shifts and additional research. Congress could give FERC responsibility to sustain fish populations through legislative language similar to that used in the Central Valley Improvement Act (title 34 of the Reclamation Projects Authorization and Adjustment Act, PL 102-575), which elevates the importance of fish and wildlife protection in Central Valley Project management. Congress could direct FERC to expand river-wide planning and cumulative analysis in the hydropower relicensing process by synchronizing license terms on river basins. Additional research would be needed on the effects of obstructions and habitat alterations on fish populations.

Second, mechanisms to ensure the good design, construction, and operation and maintenance of all fish passage technologies are needed. Improved coordination is needed among fishway design engineers, and fisheries biologists, and hydropower operators, especially during the design and construction phases. Also, institutional mechanisms must be improved for adequate oversight, commitment, and enforcement of fishway operations and maintenance activities. An increased emphasis on monitoring and evaluation of fish passage performance could provide useful feedback information on the performance of technologies that could be used to make improvements.

Third, new initiatives are needed to advance fish passage technologies, especially for safe downstream passage. This area, the focus of this report, was addressed in an OTA-sponsored workshop, and is discussed in detail below.

Advancing Fish Passage Technologies

For the successful development of new fish passage technologies, there is a critical need for good science and independent evaluation of technologies. This is essential for experiments that are currently underway, future site-specific studies, and for any efforts to create more systematic and comprehensive research programs in the long term. A sound scientific approach to developing, executing, and evaluating a field study is critical to the successful advancement of fish passage technologies. The elements of a good test include the establishment of clear objectives, agreement amongst all parties on the study design including quantifiable standards of acceptability that are measurable in the studies, and a protocol that lends itself to repeatability. Studies should be designed by an interdisciplinary team including not only those knowledgeable about fisheries, hydrology, hydraulics, and hydropower operations, but also biologists knowledgeable about fish behavior and sensory response. In addition, there must be a proper accounting of environmental variability and documentation of underlying assumptions. Studies should span multiple seasons in order to collect adequate data and include appropriate statistical evaluation. Regular communication among stakeholders should occur throughout the study process. Evaluative reports on the work should be peer reviewed by credible professionals with no vested interest in the results, and then published. Agreement on performance criteria and standards prior to study will facilitate acceptance of data and recommendations (210). An effort to systematically evaluate the potential for acoustic technologies is underway in the Columbia River Basin. This may serve as a useful model for systematic research. However, a mechanism to transfer results and expand investigations to fish guidance problems in other parts of the country is needed (see box 1-6).

If Congress decides that a coordinated effort to advance fish passage technology is desired, a technology certification organization could be established that would provide unbiased data.

BOX 1-6: Columbia River Acoustic Program—A Model For Systematic Research

The U.S. Army Corps of Engineers and Department of Energy initiated a program to develop acoustic technologies to improve fish passage in the Columbia River Basin at the end of 1994 (165). This multi-year program provides a systematic guide for evaluating existing technologies; conducting needed research that prevents immediate application of acoustic methods; developing prototype systems; and evaluating their feasibility and potential effectiveness. It also demonstrates field performance of sound-based fish behavior modification systems under normal operating conditions for extended time periods. Specific research areas include: sound characterization, fish hearing characterization, target behavior stimulus identification, fish behavioral models, target behavior stimulus delivery, behavioral response monitoring and evaluation, assessing predictive tools for sound fields, and evaluating other potential behavioral stimuli. The program is directed at solving problems of downstream fish passage on the Columbia River, including need for increased bypass screen guidance efficiency, enhanced surface collection, increased spill effectiveness, and reduced predation losses. The Columbia River Acoustic Program involves technical reviewers as well as resource agencies, Indian tribes, Bonneville Power Administration, and the Corps of Engineers.

It is not clear how transferable results from these investigations will be for other smaller hydropower sites and water diversions in other parts of the country. Basic research to develop evaluation tools for fish behavior in sound fields, and information on fish hearing capabilities will be useful at other sites. If the background studies resolve uncertainties associated with the use of sound to guide targeted fish, then a similar effort to meet needs of targeted species in other parts of the country should be pursued.

It must be recognized, however, that other fish species in other locations will likely need different behavioral stimuli and delivery systems. Thus not all of the results that emerge from the Columbia River program will be applicable to other settings. However, a mechanism (e.g., a workshop) could be designed to review progress and evaluate transferability of results to other fish guidance problems. A parallel and broader research, development, demonstration, testing, and evaluation program, possibly centered at the Conte Anadromous Fish Laboratory of the National Biological Survey, could be developed to meet the needs for fish guidance at FERC relicensing sites. Additional centers of research may be needed to address other fish populations, such as riverine fish in the Midwest and declining populations in the Central Valley of California.

SOURCE: Office Of Technology Assessment, 1995.

This group would have no proprietary interest in the technology under investigation. It would carry out applied laboratory and field tests of newly developed technologies (as well as conventional technologies) and verify claims of performance and cost. The certifying organization would set the standards for methodology of investigation, would test the system, and would define the conditions under which certain levels of performance could be expected. It could arrange for pilot test locations on federal properties or private sites, and have a mechanism to compensate vendors as appropriate. The organization would not actually approve a technology, but would provide a controlled evaluation of its effectiveness under specific conditions. It would provide data on performance that would be the equivalent of peer reviewed material, thus removing the possibility of the misuse or misinterpretation of data. The work of such a certification organization would be considerably enhanced with the availability of clear standards and expectations for protection of species of fish in different regions.

The certification organization could produce a catalog similar to a physician's desk reference. Information would be provided on conditions where the technology is likely to be useful, counter-indications, possible problems, and performance at other sites. It would evaluate applications of the technology. All technologies to be included in the catalog would need to undergo the same levels of testing.

The certification organization should be adequately and independently funded and free of political pressure. One option might be to have a surcharge placed on all electricity generated through hydropower plants; this would be placed into an escrow account to pay for the operations of the organization and the dissemination of data. Alternatively, a portion of FERC license fees might be diverted to support such an organization. Other sources of funding that could be considered would be a tax on utilities, or the diversion of some public funds or taxes since hydropower sites are often not the only contributors to fishery problems in a watershed. However, one can be certain that any efforts to increase fees on electricity or raise taxes would be strongly resisted.

Congress could give certification responsibility to the National Biological Survey. This may only be feasible if NBS remains as an independent research group and is not reconsolidated with the FWS. (The FWS has a key role in recommending and prescribing fish protection in the FERC-relicensing process, and thus is not considered to be entirely objective in this arena.) This option would take advantage of the unique NBS Conte Anadromous Fish Laboratory. Other research facilities may be needed in other parts of the country.

Alternatively, Congress could create an independent, non-profit fish passage certification organization, modeled as a research and educational foundation. Possible models might be the Electric Power Research Institute (EPRI) or the Rocky Mountain Institute. EPRI knows the power generating industry, issues of concern and the stance of most of the parties involved. Although EPRI is now linked to industry, the new organization would be independent and impartial in its approach. The Rocky Mountain Institute has a broader mandate, crossing boundaries and addressing a number of disciplines. Both organizations provide an indication of the form that such an organization could take.

SUMMARY OF FISH PASSAGE TECHNOLOGIES

This section summarizes fish passage research programs and technologies for upstream and downstream passage. Brief mention is given to new concepts in hydropower generation.

Fish Passage Research Programs

Federal agencies play a pivotal role in water resources management and research and development of fish protection technologies. The National Biological Survey (NBS), Bureau of Reclamation (BuRec), U.S. Army Corps of Engineers (COE), Department of Energy (DOE), and the Bonneville Power Administration (BPA) are key agencies involved in current fish passage and protection research, and development and evaluation of technologies. Research on fish passage technologies under investigation by these federal agencies is summarized in table 1-2.

The need for more research and development in the area of fish passage is great. Federal money for fish passage research is extremely limited and funneled to a few research facilities. Although these centers conduct hydraulic modeling and behavioral analysis and develop their research agenda to generate broadly applicable results, the task is much broader than what they can accomplish alone. Partnerships between the agencies and the private sector show some promise in this respect. For example, Alden Research Laboratory and Northeast Utilities are testing a new weir design at the NBS Conte Anadromous Fish Research Center for application at projects on the Connecticut River and elsewhere.

Many unanswered research questions remain, and the scope and variety are extensive. Despite this, the hydropower industry is becoming increasingly unwilling to provide high levels of financial support for research and development, and many feel that the burden for developing new and improved methods for fish protection should be borne by the resource agencies who

TABLE 1-2: Federal Agency Research on Fish Passage Technologies

Federal Agency	Upstream Conventional and physical barrier technologies	Downstream Conventional and physical barrier technologies (and other methods)	Alternative Behavioral guidance devices (and other methods)
Bonneville Power Administration		Flat plate and rotary drum screens	Surface collector Acoustics
U.S. Bureau of Reclamation		Hydraulic modeling	Archimedes screw pump Hydrostal-volute pump
U.S. Army Corps of Engineers		Advanced turbine design	Surface collector Acoustics
U.S. Department of Energy		Advanced turbine design	
National Biological Survey/ U.S. Fish and Wildlife Service	Denil Steeppass Denil Notching	NU-Alden weir Cabot sampler	

KEY: NU=Northeast Utilities.

SOURCE: Office of Technology Assessment, 1995.

prescribe their implementation. However, the Electric Power Research Institute (EPRI), and the Empire State Electric Energy Research Corporation (ESEERCO), organizations financed by industry contributions, have funded a large part of fish passage research in the field. EPRI has produced numerous publications highlighting experimentation with new and evolving technologies and summarizing performance of more conventional methods. Hydropower operators indicated to OTA that funds for research, including for support of research groups like EPRI, are declining.

Upstream Passage Technologies and Alternative Methods

Upstream passage technologies are in use at 9.5 percent of the 1,825 FERC-licensed hydropower plants (242). The need for upstream passage is well established for anadromous species, whereas the need for upstream passage for riverine species remains controversial.

Upstream passage technologies are considered well-developed and understood for certain anadromous species including salmon, American shad, alewives, and blueback herring. Upstream passages have not been specifically designed for riverine fish, although some of these fish will use them. Special designs for catadromous fish (i.e., fish that migrate from freshwater to spawn in the ocean) are used in Europe, but have not been used in the United States.

The upstream passage or transport of fish can be provided for through several means: fish ladders, lifts (i.e., elevators or locks), pumps, and transportation operations. Ladders and lifts, or fishways, are widely accepted technologies. Pumps are a more controversial method. Transportation operations are often used as an interim measure until fishways are completed, especially when there is a series of dams that must be passed. Transportation is also used as the long-term solution at some high-head projects. Site- and species-specific criteria, project scale, and economics help to determine which method is most appropriate. Fish passage success is highly dependent on creating a "fish friendly" environment.

Fish Ladders and Lifts

Some fish ladders perform well because they accommodate fish behavior and the target species' ability to respond to particular hydraulic conditions. An understanding of fish swimming performance and behavior is essential to fish passage success. It is difficult to pinpoint the range of responses that fish might exhibit under natural conditions, but significant knowledge exists which must be applied to fishway design. Species require different types of flows and conditions to encourage and support movement, or in some cases to prevent movement of unwanted species. There is some controversy over the use of certain ladder types for some species.

Fish ladders (e.g., pool and weir, Denil, Alaska steeppass, vertical slot, hybrid) can be designed to accommodate fishes that are bottom swimmers, surface swimmers, or orifice swimmers, fishes that prefer plunging or streaming flow, and weak or strong swimmers (102). But not all kinds of fish will use ladders. Fish lifts, including elevators and locks, are favored for species that will not use ladders. Fish elevators can move fish to a high vertical level. Locks, like boat locks, where the water level is controlled to move fish to a slightly higher elevation, can move a large number of fish.

Poor fishway performance, on the other hand, can generally be attributed to inadequate operations and maintenance including ill-maintained flow regime; and poor design including inappropriate siting, inadequate capacity, inadequate coordination between design of fishway and hydropower generation, inadequate attraction flow, or excessive fishway length (e.g., fish become fatigued or delay in resting areas). Water quality may also affect passage performance. Lack of goals for fish passage often contributes to design failures.

Attraction flow can make the difference between fish passage success and failure. This is true for fish ladders and lifts. A lack of good attraction flow, or the inability to maintain the appropriate flow, can result in delays in migration as fish become confused, milling around looking for the entrance. The proper location and position of the fishway entrance will help enhance effectiveness by decreasing the time fish can spend looking for a means past the obstruction.

Conventional fish ladder designs have been experimented with and used often enough to pass certain species that the design criteria are almost generic. However, because river systems are varied and dynamic, each site presents the possibility of new challenges. The full involvement of agency personnel with the experience and expertise necessary for designing effective fish passage systems may not be possible, due to lack of sufficient staff and/or their time constraints. In addition, the individuals responsible for fish passage may not be as experienced or may not have the information necessary for proper design. As a result, a fishway may be inappropriate. Therefore, a successful passage project will likely depend on the cooperative efforts of the project owner, the resource agencies, consultants, and research scientists. In the Northeast, the FWS reviews and comments on all fish passage facility final designs under FERC project licenses.

Fish Pumps

The use of pumps for fish passage at dams is controversial and largely experimental. There are several different types of fish pumps in existence, a few of which are new methods under development, while others are technologies being transferred from other applications. This technology is relied upon in aquaculture for moving live fish, and in fishing operations for off-loading dead fish from boats. It has recently been tested at government-owned fish hatcheries. These pumps can be used to force both juveniles and adults into bypass pipes for passage either downstream or upstream of projects.

The FWS in the Northeast and some state resource agencies do not support the use of pumps due to the nature of the passage method. Fish movement is completely facilitated and fish are subjected to an artificial environment. Pumping of fish can lead to injury and de-scaling as a result of crowding in the bypass pipe (196). Pumping fish may also cause them to be disoriented once released back into the river environment. These conditions support the conventional wisdom of the agencies to use passage methods, like ladders, which allow fish to move of their own volition (196). The agencies also have concerns about capacity, and reliability of parts, and overall system operation. However, the resource agencies have approved the use of a fish pump as an interim measure for the upstream transport of adult alewives at the Edwards Dam on the Kennebec River in Maine. In the Northwest, the Bureau of Reclamation is currently testing two types of pumps for downstream passage of juveniles at the Red Bluff Diversion Dam on the Sacramento River.

Transportation

The use of trucks to move adult migrants upstream is somewhat controversial. (Downstream transportation is discussed below.) Some practitioners have concerns regarding the effect that handling and transport has on fish behavior, health, and distribution. On the other hand, transportation using trap and truck operations has been successful in some cases for moving adults upstream of long reservoirs where they might become lost or disoriented on their way to spawning grounds.

The trap and truck technique for transporting upstream migrants has been used as an interim measure until upstream fish ladders or lifts are constructed. In some high-head situations, transportation is the long-term passage method. Where dams occur in series and fishway installation occurs as a staged process, trucking may be used as an interim measure. For example, on the Susquehanna River in Pennsylvania, fish elevators are in operation at the downstream-most dam to assist a trap and truck operation which supports the restoration of American shad, blueback herring, and alewives. The fish are transported upstream of the four projects on the river and released in the highest headpond near to spawning grounds. The 10-year-old program supported by state and federal resource agencies is considered to be successful.

Trap and truck techniques can work well for some species, provided there is a good method for collecting and handling fish. However, resource agencies have concerns about potential adverse effects of handling on some species, the potential for trapping non-target fish, and the intensive labor requirements to implement trap and truck operations. In addition, objections can be raised by some fishing interests if fish are removed from key stretches of a river. For example, the proposed trucking of Atlantic salmon around the proposed Basin Mills hydropower project on the Penobscot River in Maine would remove fish from the usual and customary fishing locations of the Penobscot Indian Nation—one of their negotiated treaty rights.

Downstream Passage Technologies

Downstream passage technologies are in use at 13 percent of the 1,825 FERC-licensed hydropower plants (242). The primary passage method at other sites is through turbines. The need for downstream passage is well established for anadromous species, whereas the need for downstream passage for riverine species remains controversial.

Accepted Downstream Passage Technologies

There are regional differences in the recommendations of resource agencies for downstream passage. Variations relate to differences in target fish, including differences in swimming ability of down-migrating juveniles, susceptibility to injury, and the history of concern for endangered and threatened species. Structural methods, including screens that physically exclude fish from turbine entrainment and angled bar racks and louvers that may alter flow patterns and rely on fish behavior for exclusion, are the most widely accepted technologies for downstream passage. Downstream technologies that are accepted by resource agencies in different regions of the country, and those that are considered experimental, are summarized in table 1-3.

Resource agencies generally prefer physical barrier screening techniques with associated bypasses for downstream passage (e.g., drum, traveling, and fixed screens). This type of technology is well understood. Physical barrier and bypass systems can prevent entrainment in turbines and water intake structures. Design criteria incorporate hydraulic characteristics and take into account the swimming ability and size of fish present to avoid impingement problems. A commonly cited advantage of these systems is

TABLE 1-3: Downstream Fish Passage Technologies: Status and Use

Downstream passage technology	Accepted in the Northwest and California	Accepted in the Northeast and Midwest	In use	Considered experimental
PHYSICAL BARRIER DEVICES				
Drum screen	✓		✓	
Travelling screen (submersible; vertical)	✓		✓	
Fixed screen (simple; inclined)	✓		✓	
Eicher screen			✓	✓
Modular inclined screen				✓
Barrier net		✓	✓	✓
STRUCTURAL GUIDANCE DEVICES				
Angled bar/trash rack		✓	✓	
Louver array		✓	✓	
Surface collector			✓	✓
COMPLEMENTS TO TECHNOLOGIES				
Bypass chute or conduit	✓	✓	✓	
Sluiceway		✓	✓	
ALTERNATIVE BEHAVIORAL GUIDANCE DEVICES				
Acoustic array			✓	✓
Strobe and mercury lights			✓	✓
Electric field			✓	✓
OTHER METHODS				
Trapping and trucking	✓	✓	✓	✓
Pumping			✓	✓
Spilling	✓		✓	✓
Barging	✓		✓	✓
Turbine passage	✓	✓	✓	

SOURCE: Office of Technology Assessment, 1995.

that they are effective for any species of the size and swimming ability for which the system is designed. This type of downstream passage technology is usually recommended in the Pacific Northwest and California. Acceptance is based on experience at many sites and non-peer reviewed (i.e., gray literature) evaluations of performance. Design criteria are mandated for some species by some state and federal agencies. Criteria vary among the agencies but generally address approach velocities and flow-through velocities, size of mesh, and materials, for different sizes and species of fish. Designs generally must be tailored to the individual site and target fish.

In the Northeast, resource agencies more frequently recommend the use of angled bar racks with relatively close spacing and an associated bypass for down-migrating anadromous juveniles. This approach is also supported by favorable evaluations in one peer reviewed study (167) and a small number of gray literature studies, although the mechanism that leads to successful performance is not understood (198). A similar approach is louvers, a behavioral system that alters the flow characteristics of the water that fish are able to respond to. Louvers are viewed favorably by some, but have been criticized by the NMFS NW region as having unacceptably high entrainment rates for small fish, even with favorable hydraulic systems (see appendix B) (236,236a). In the Northwest, many poorly performing louvers have been replaced by physical barrier screens and bypass systems.

Screens built prior to the mid-1980s sometimes experienced poor performance in guiding juvenile fish. Since then, new screen designs in the Pacific Northwest and California have achieved nearly 100 percent guidance efficiency (59,245). However, these screens can be expensive. A significant portion of costs are due to structural measures required for proper anchoring and installation and there are frequently operation and maintenance deficiencies. Incompatible operation of hydropower facilities or water diversions may also reduce the effectiveness of the technology. These accepted technologies are usually designed to withstand normal variations in flow; however, flow conditions can be highly variable. In some cases, changes in the river itself can cause problems; the position of the river can actually change over time, resulting in screen failure.[2] This is more likely to be a problem at water diversions where there are no dams controlling water flow.

Adequate operation and maintenance is required to optimize the performance of these accepted technologies. Preventive maintenance can minimize failure. Manual methods of cleaning are generally favored to reduce capital costs, but few resources are devoted to ensuring that manual cleaning occurs. Frequent cleaning may be needed where there is a lot of debris. Some of the more sophisticated and expensive designs provide automated cleaning, but these are rarely installed due to the high capital costs.

Controversial Downstream Passage Techniques

There are some downstream techniques in use, especially for juvenile salmon in the Columbia River Basin, that are controversial. These techniques include: transportation (trap and truck, and barging) and spilling. Controversy centers around whether the techniques are actually beneficial to the fish populations. Both the trap and truck method and barging depend on the successful collection of fish. Methods are being explored to improve collection for transportation, including surface collectors and behavioral guidance, which are described below.

Transportation

Transporting juvenile out-migrants around dams in trucks or barges helps to prevent the loss of fish in long reservoirs, avoids the potential impacts of nitrogen supersaturation[3] that may be associated with spilling water, and decreases the possibility of turbine entrainment and predation problems at intervening dams and reservoirs. In the Columbia River Basin the use of transportation to move juvenile salmon is controversial. Benefits of transportation during low flow periods are generally recognized because transportation may reduce the time it takes fish to move through the system. The controversy mainly centers around transportation during the mid-range of flows. Delay in migration may have a negative impact on the physiological development of smolts which is critical to survival. Transportation may expose juveniles to disease, cause stress from overcrowding, and increase the chance of predation upon release.

Whether transportation contributes to more adult returns to spawning grounds does not appear to be conclusive. There is some agreement that barges are preferable to trucks. However, agencies indicate that barging should be regarded as experimental (251). Yet transportation is only as good as the collection technology; juveniles not collected pass through the turbines. Efforts are ongoing to improve the collection phase of this passage technology (see chapter 4).

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[2] The Glenn-Colusa Irrigation District in Hamilton City, CA, is an example. A drum screen was built for the site, then the river changed course and gradient, and the technology was no longer appropriate.

[3] As spill water plunges below the dam, the hydrostatic pressure causes air—mostly nitrogen gas—to be entrained in the flows. The pressure at the bottom of the stilling basins forces the gases into solution, creating a supersaturated condition. When a fish is exposed to this supersaturated water, gas bubbles can form in its bloodstream and result in a variety of traumatic effects and even death.

Spilling

Spilling water to pass juvenile fish is a technique used to move down-migrants past hydropower projects in the Columbia River Basin. The COE considers the use of spills to pass fish to be one of the lowest mortality options for getting fish past dams, yet recognizes that spill has its own associated risks (231). There has been some dispute over the effects of spilling on the health of fish. However, recently the NMFS NW office and the Intertribal Fish Commission, which represents tribes in the Columbia River Basin, recommended that spilling should be implemented on a broader scale to support juvenile downstream migration.

Experimental Downstream Passage Technologies

There is a strong desire to have downstream passage technologies that are less expensive to design, install, operate, and maintain; easy to retrofit into existing facilities; and water-conserving with respect to the primary purpose of the facility. This desire has led to the investigation of methods to improve performance of currently used methods (e.g., surface collector) and alternatives to accepted passage methods. These alternatives include both physical barrier approaches and behavioral guidance techniques. (Fish pumps are also being investigated for downstream passage of juveniles, but are discussed previously under upstream passage technologies.) Efforts are underway to develop new turbine designs that reduce problems of turbine entrainment and mortality. New concepts in hydropower production that would eliminate some of the dangers for fish passing through generation systems also are being explored (box 1-7).

Improving current passage technologies

The COE has been working for decades in the Columbia River Basin to identify modifications that can be made at specific sites on the Columbia River to improve fish passage performance. One example of this effort is a new emphasis on surface collector technology that will capitalize on the surface orientation behavior of the juvenile fish. The concept was derived from observations of high levels of safe juvenile passage at Wells Dam, which uses a hydrocombine configuration where spill intakes are located directly above turbine intakes. If successful, the method may be useful for attracting juveniles to bypasses, or allowing more efficient collection of fish for transportation (40).

Experimental high-velocity screens

The development and application of the Eicher screen and the Modular Inclined Screen (MIS) have followed similar paths. Both have undergone a deliberate process of development which has included extensive laboratory testing with a variety of species, as well as prototype development and field evaluation. These efforts have been championed largely by EPRI, in some instances working jointly with Alden Research Laboratory (ARL) and Stone and Webster Environmental Services. Successful laboratory experimentation led researchers to identify appropriate sites for field testing of prototypes. These applications have shown both screening technologies to be successful in guiding certain types and sizes of fish under a range of high-velocity conditions. However, these screens only collect fish when water is flowing over them. Operational changes may be necessary to ensure adequate flow to the screens, especially during seasons when reservoirs are filling and little power is produced.

Research and evaluation of the Eicher screen has led to approval from agency personnel for specific sites. Eicher screens are in use at the Elwha Hydroelectric Project on the Elwha River in Port Angeles, Washington, and at the Puntledge Hydropower Project in British Columbia. Resource agency approval for use at other sites will depend on documentation that the design performs well for target fish at velocities present at the site.

A prototype (reduced-scale) MIS has been constructed and will be field-tested in the spillway sluice gate at Niagara Mohawk Power Corporation's 6-MW Green Island hydropower plant on the Hudson River in New York during Sep-

BOX 1-7: New Approaches to Hydropower Generation

Turbine passage in current settings potentially exposes fish to blades and physical contact, which can either de-scale or kill them, and pressure changes, which may cause physical injury and/or death. Turbine entrainment has become a major issue in FERC relicensing. Turbine entrainment levels and mortality vary widely from site to site. Results of studies of turbine passage vary and there is some dispute over the necessity and interpretive value of these studies. Entrainment studies are most common when relicensing applicants question the level of adverse impact and the need for protection measures, especially for riverine species. Nevertheless, the cumulative impact of entrainment on juveniles passing through turbines, especially where dams exist in a series, can have a significant impact on the population.

The Department of Energy's (DOE) Hydropower Program and the hydropower industry have cofunded the Advanced Hydropower Turbine System Program. It is an effort to look at innovative solutions to problems associated with the operation of turbines at hydropower projects. DOE has the lead role in program development, proposal review, and implementation. The program is meant to stimulate and challenge the hydropower industry to develop new environmentally friendly concepts in power generation by applying cutting edge technology and innovative solutions to support safe fish passage. The Army Corps of Engineers-Portland District is also working to develop relatively minor modifications of existing turbines in the Columbia River Basin to increase survival of downstream migrants.

Technologies that can produce large quantities of electricity without adverse effects to river ecosystems may be feasible. However, a significant commitment to research and development, demonstration, testing, and evaluation will be required. The current hydropower generation technologies were developed with the objective of producing power. Although the need for fish passage was recognized when many of our nation's existing dams were built, effective passage was not incorporated into designs. New designs that simultaneously optimize for energy production, fish protection, and ecosystem integrity are conceivable. OTA received information on more than one concept of this nature during the course of this study. However, evaluation of these ideas was beyond the scope of this study.

SOURCE: Office of Technology Assessment, 1995.

tember of 1995. This test is important in the development and acceptance of the technology. However, resource agencies will be unlikely to approve full-scale applications of the MIS without additional testing (12).

Barrier nets

Barrier nets are used to prevent fish entrainment and impingement at water intakes. The ability of the net to exclude fish depends on local hydraulic conditions, fish size, and the size and type of mesh used (59). Low approach velocities, light debris loading, and minimal wave action are critical to success. Barrier nets are not considered to be appropriate at sites where the concern is for entrainment of very small fish, where passage of fish is considered necessary, and/or where there are problems with keeping the net clear of debris. At sites where icing is a problem, nets may be difficult to use in winter and thus may only provide seasonal entrainment protection.

Alternative behavioral guidance methods

Experimentation with various stimuli (e.g., lights, sound, electricity) to elicit a response in fish has been going on for decades. With a few notable exceptions for specific species at specific sites, there is no behavioral guidance technology that has been used to meet resource agency objectives and guide fish downstream at hydropower sites or at water diversions. Behavioral methods can repeatedly elicit startle responses in various species of fish, but the problem of getting fish to move consistently in the desired direction has proven to be more difficult. Given the limited swimming ability of many down-migrating juveniles, behavioral mechanisms may not be able to direct fish to bypasses that are small compared to an intake or river flow. It is rarely economical to devote a significant percentage of flow to a hydropower fish bypass.

Successful guidance has been reported for clupeids (e.g., blueback herring and shad) using ultrasound and strobe and mercury lights. Experimentation with sound has also shown some promise with salmonids. General claims of high performance and low cost cannot be verified with the limited experience available. However, there are indications that lower costs than conventional methods and good performance may be possible for some systems at some sites.

Sound is a potentially useful stimuli to guide fish. Advantages of sound are that it is directional, rapidly transmitted through water, not affected by water turbidity, and unaffected by light changes (i.e., diurnal changes). Sound is used by fish to get a general sense of their environment (207). There is some evidence that fishes may respond to sounds that are produced in association with structures such as barrier screens and turbines (6,164), although little is known about the actual behavioral response to these sounds.

Various species have narrow ranges of sound which they can detect, and some species respond differently at different times of the day. This may be an advantage or disadvantage, depending on which species are targeted for guidance. It may be possible to develop systems that species respond to differently, allowing management objectives for different species to be met. One disadvantage of sound stimuli is that they can be masked by dam noises and other ambient sounds.

Experimental sound guidance technologies include several methods that use various frequency ranges. For the purposes of this discussion, methods are loosely divided into three frequency ranges: ultrasonic (above 30 kHz), low-mid frequency (50-900 Hz), and infrasonic (<50 Hz).[4] The response of fish to ultrasonics was discovered in experiments with a high-frequency fish counter. Most of the work has been done with clupeids (especially *Alosa* spp., including blueback herring, alewives, and American shad). Signals from 110-130 kHz have been used for clupeids. The COE is completing testing of a system at the Richard B. Russell pumped storage site in South Carolina. A commercial system, FishStartle™, by Sonalysts, Inc., has been tested at hydropower facilities on the Connecticut and Susquehanna Rivers and at other kinds of generating stations.[5] Other species have been evaluated in laboratory cage tests with variable, species-specific results.

Low-mid frequency sound experiments have included historic tests of pneumatic poppers and hammers conducted by Ontario Hydro. Results with these technologies were variable, and problems with the reliability of the equipment led to the utility abandoning the effort.

Another low-mid frequency concept of playing back modified fish sounds was developed and tested by American Electric Power (141). This system has been further refined and is currently being marketed by Energy Engineering Services Company (EESCO) and has been undergoing testing since 1993 at a number of water diversion sites on the Sacramento River. Much of the work on this system has been focused on defining the appropriate array of transducers, dealing with equipment anchoring and reliability problems, and establishing appropriate testing protocols and statistical methods. Investigations have been hampered by difficulties installing equipment due to extreme flows and high water levels. There have also been delays in the studies due to the presence of endangered species. The experience at several sites has been very contentious and the evaluations have failed to reach the efficiency goals of the resource agencies. The process has been proceeding best at Georgiana Slough, a natural diversion site

[4] OTA did not identify any mid-high frequency (900 Hz–30 kHz) systems.

[5] Full-scale sound system tests of the Sonalyst, Inc., Fish Startle System at a nuclear power plant on Lake Ontario have been peer reviewed and are highly regarded. However, the hydraulic conditions at this site are very different from those at hydropower facilities.

which carries about 15 percent of the flow, where there are no practical physical barrier alternatives. An interagency group is involved in the tests, and results during the spring of 1995 were considered encouraging (50 percent overall guidance at a statistically significant 95 percent level) by at least one agency (100).

The EESCO technology is also undergoing tests on the Columbia River system in 1995 as part of the new Columbia River Acoustic Program, sponsored by DOE and COE to evaluate existing sound-based fish guidance and deterrence systems for the Columbia River system (see box 1-5). The EESCO system uses military grade speakers, originally designed for use by the U.S. Navy, that weigh 50 pounds and can be installed on buoys (170). The speakers produce a sound field with very little particle motion (39). Field test results are not consistent with what is known about sound detection capabilities of salmonids, thus some reviewers are very critical of this system (179). However, the mechanisms that fish use to respond to other more accepted technologies are not well understood either.

Infrasound has shown some success in highly controlled field experiments in Norway with Atlantic salmon. A consistent behavioral response was demonstrated in laboratory experiments. The developers of this approach are now working with the Columbia River Acoustic Program on Pacific salmonids. This approach requires large displacement transducers of special design that generate a sound field with large particle motion. The current system only works with fish within a few meters of the sound source. This finding is consistent with what is known about the sound detection capabilities of salmonids (39). Other private initiatives are underway to develop infrasound systems (50, 219).

Lights are also a potentially useful stimulus to guide fish. Light is directional, is transmitted rapidly through water, and is not masked by noise. However, light may be hampered by turbidity. Although it is most effective as a stimulus when there are sharp contrasts between the light and background (usually at night), this may not be an issue if the target species move downstream primarily at night (as is the case with juvenile American shad).

Mercury or other forms of incandescent illumination and strobe lights have undergone laboratory testing for a number of species. Field testing also has been conducted for a few selected species. The effect of the lights varies by species and the type of lights. Some species are attracted to the lights, others are repelled. And the response may change with age of the fish, physiology, motivation, etc. EPRI has supported research in this area and has developed guidelines for implementing light systems at water intakes (60). These guidelines recognize the need for careful site-specific evaluation of field conditions.

Strobe lights have been receiving considerable attention in recent fish guidance studies in the mid-Atlantic region and New England. A multiyear testing effort has been underway to guide juvenile American shad to a bypass at the York Haven Hydropower Plant on the Susquehanna River (61,152). These tests have often been hampered by water conditions, years when there were few fish, and other environmental variables. Nevertheless, there are positive indications that the lights can increase use of the bypass, although effectiveness varies with environmental conditions. At this site, preliminary tests combining strobe lights and ultrasonic methods have had encouraging results. Tests of strobe lights are also being conducted at other hydropower sites in New England. These tests are primarily being done as enhancements to conventional trash rack measures. Yet, the installation of some of the conventional measures and dam operation has not been in accordance with resource agency expectations at some of these sites.

Electrical barriers have been successfully used to prevent upstream passage of fish. Systems are operating in Salt River Project irrigation canals in Arizona to prevent the mixing of species of fish from the Colorado River and other Rocky Mountain streams.

Development of downstream protection is more challenging. Key requirements are favorable flow conditions and adequate security to ensure safety of people and other animals. There have been field trials that were abandoned due to problems in these two areas. Other problems have been encountered with corrosion of electrodes. A number of questions about the impact of electrical pulses on fish have been raised by resource agency biologists reviewing experiences with electric barriers (111). Field tests of the Smith-Root Graduated Field Fish Barrier (GFFB) are underway at a water diversion on the Sacramento River. In this test, major efforts have been devoted to ensuring appropriate flow conditions with the installation of structural devices (209). Tests by the manufacturer have indicated that flow (i.e., velocity) requirements will vary with different species. Yet, results of the 1995 tests were inconclusive and indicated that flow and velocity conditions were still difficult to control (100).

Alternative behavioral guidance issues

Several generalizations can be made from experiments to date with alternative behavioral guidance measures. Response to various behavioral stimuli is very species specific and is variable even for a single species, depending on conditions at the site. Site conditions are influenced by environmental variables (e.g., weather, time of day, flow conditions) as well as the way the facility is operated. It is also likely that the response of a single species will vary depending on its life stage and motivation. Favorable hydrology is a key element to the success of any of these systems. Fish must be capable of moving in the desired direction for a stimuli to be effective. Many juvenile fish have very limited swimming abilities.

For the most part, knowledge of fish behavior is very limited. Nothing is known of how fish of many species respond to various stimuli, flow conditions, and structures. In the more well-studied species, major informational gaps remain in our knowledge of behavioral responses and mechanisms.

Field investigations of behavioral methods have for the most part been weak. Analysis and statistical methods have been too limited to assess the effectiveness of the techniques. Much of the work is not peer reviewed, and the gray literature often does not contain sufficient information to allow critical analysis and possible replication of the experiment. In some cases, claims of high levels of guidance and reliability of equipment have not been supported in further field tests.

There is general consensus among resource agencies and scientists that development of new behavioral approaches requires a combination of lab and field experimentation. Because there are many variables at work when dealing with living organisms, especially in uncontrolled environments, there have been many cases when lab results of response to stimuli have not been repeatable in field tests. Thus, laboratory investigations of fish behavior are not sufficient. Nor are field tests alone. Data from field studies need to be evaluated in the lab to fully understand the nature of the results.

Studies to determine the basic sensory abilities of fishes are best done in the laboratory, while studies of overall fish behavior in response to environmental variables might be started at field sites. But there needs to be close interaction between lab and field work if the mechanisms by which behavioral methods work are to be fully understood. Understanding mechanisms of response is necessary to design widely applicable systems to control fish behavior.

Many of the technology vendor companies are frustrated in their efforts to conduct field investigations. Generally, they must obtain agreement from the hydropower operator and resource agencies to conduct a test. Hydropower operators are motivated by a desire for lower cost fish protection, yet they have little interest in participating in a test, let alone helping to finance it, if they cannot be assured that positive results will be viewed favorably by the resource agencies. Hydropower operators are concerned that they may be forced into paying for conventional measures after having invested in testing new approaches, or even penalized with fines if the experimental methods result in significant loss of fish.

A technology company may be successful in getting an initial field test sited at little or no cost to the hydropower operator. If positive results are obtained, the next hurdle is locating another appropriate test site and possible sale. Yet, major questions exist regarding the transferability of performance information from one site to another.

Performance of any passage technique is generally considered to be site specific. Information that is most transferable from one field site to another concerns what went right and what went wrong. One would also generally expect that the operation of the device would be similar from site to site. It is the species response that may be expected to vary, due to different site and environmental conditions.

In general, the resource agencies' responses to requests to test new technologies have been negative. Yet they are under considerable pressure to allow field testing. Resource agencies are skeptical about performance claims, and are concerned that testing of unproved technologies is time consuming, expensive, and may detract from hydropower operators' willingness to spend funds to install the technologies agencies prefer. Resource agencies are concerned that technologies installed for experiments tend to become the permanent solution at the test site, despite substandard performance relative to conventional measures. Resource agencies are concerned that experiments with alternative technologies may be used as a delay tactic to avoid expenditures for conventional technologies. Resource agencies are more willing to entertain innovative approaches, either as an enhancement to conventional measures or at locations where conventional measures are not practical. The NMFS regional offices in the Northwest and Southwest have developed policy statements that allow testing of experimental systems, provided a tiered process of research and evaluation is followed, along with the simultaneous design for a physical barrier/bypass system for the site (237,238,239). By setting standards and criteria for effectiveness, NMFS establishes goals for technology vendors and state agencies to follow. The FWS has no similar policy.

The current system of site-by-site investigation, short-term funding of experiments, lack of rigorous scientific methods, and lack of wide dissemination of favorable and unfavorable results is unlikely to result in robust technologies acceptable to agencies within a time frame relevant for relicensing activities in the next 10 years. Even with a major coordinated research and development effort to advance alternative behavioral technologies, it is unclear whether significant progress will be made in developing behavioral systems to guide fish past hydropower generation facilities and water diversions. And yet, if behavioral methods prove successful, they could mean large cost savings for the industry.

Is it worth pursuing a significant research program on behavioral methods, for settings where conventional approaches are available? On the one hand, there are few demonstrated successes with behavioral systems and so little is known about the behavior of fish that further investment may not be warranted. The process of applying a system developed for one site to another will require significant expenditures and time for testing and fine tuning. Also, too many species are involved at most sites to assume that a single control system will be effective. On the other hand, the successes with sound and lights suggest that behavioral systems have real potential for at least some species. Alternative behavioral systems, if perfected, may be very cost effective; and they may be particularly useful when several are combined, or they are used to enhance the performance of physical barriers.

CONCLUSIONS

The incomplete state of knowledge regarding fish population dynamics, the impacts of hydropower development on fish, the need for mitigation in various contexts, and the protection/passage effectiveness of available mitigation technologies exacerbates the sometimes adversarial relationships among stakeholders. This situation is unlikely to be alleviated unless a solid, science-based process for mutual understanding and rational decisionmaking can be developed (see box 1-8).

BOX 1-8: Development of Fish Passage Technologies: Research Needs

There are no "sure things" in the world of fish passage technology. The technologies themselves, which are based on hydraulic engineering and biological science, can be designed to accommodate a wide range of environmental conditions and behavioral concerns, but in the real riverine world *anything* can happen.

Upstream and downstream fish passage problems differ considerably and both present a range of obstacles and challenges for researchers and practitioners. Despite these differences, common considerations in design and application exist, including: hydraulics in the fishway, accommodating the biology and behavior of the target fish, and considering the potential range of hydrologic conditions in the waterway that the passage technology must accommodate. Engineers and biologists in the Northeast and Northwest are collaborating in a number of research programs designed to improve understanding of the swimming ability and behavior of target fish. Understanding how fish respond to different stimuli, and why, is critical to improving passage methods.

Using a scientific approach to explore as many scenarios as possible, and collecting data in a careful manner, can improve researchers' abilities to design improved technologies. In addition, producing information that all parties can acknowledge as credible is key to the successful advancement of fish passage technologies. A sound scientific approach to developing, executing, and evaluating a field study is critical to the successful advancement of fish passage technologies. The elements of a good test include the establishment of clear objectives, agreement among all parties to the study design, and a protocol that lends itself to repeatability. In addition, there must be a proper accounting of environmental variability, documentation of all assumptions, and sufficient replications to support findings. Regular communication among stakeholders and peer-reviewed research results are key requirements.

Employing a process of this type could increase the potential for information transfer between sites. That information might include data regarding the response of the device to hydraulic parameters (e.g., flow/acoustical response), fish response to stimuli under hydraulic parameters, and basic biological information within species. Agreement on performance criteria and standards prior to study will avoid lack of acceptance of data and recommendations in the long term.

SOURCE: Office of Technology Assessment, 1995.

A combination of academic, government, and industry expertise is needed in a concerted effort to focus science and technology resources on the question of the effects of hydropower development on fish population sustainability; and on the assessment of available and developing fish passage and protection technologies at hydropower facilities.

Technologies

Technologies for upstream passage are more advanced than for downstream passage, but both need more work and evaluation. Upstream passage failure tends to result from less-than-optimal design criteria based on physical, hydrologic, and behavioral information, or lack of adequate attention to operation and maintenance of facilities. Downstream fish passage technology is complicated by the limited swimming ability of many down-migrating juvenile species and by unfavorable hydrologic conditions. There is no single solution for designing up- and downstream passageways; however, both types must be designed and applied in such a manner that in theory, model, and reality they should suit the range of conditions at the site—structurally, hydraulically, and biologically. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.

Downstream passageways for fish and protective measures to reduce turbine mortality are probably the areas most in need of research. Many evaluations of conventional and alternative technologies have not been conducted with scientific rigor. This results in unsubstantiated claims and arguments. Moreover, some experimental results contradict others. Ambiguous or equivocal results of many fish passage studies have caused concern as to whether certain technologies are effective or generally useful. The variability of results may reflect site variability; uncontrolled environmental conditions in field studies; or incomplete knowledge of fish behavior. Thus, some performance claims may be based on incomplete assessments. Advocates on both sides of the fish/power issue can select from a diverse body of scientifically unproved information to substantiate their points of view. Care must be taken in interpreting much published information on fish protection, arguments drawn from it, and conclusions reached. When good scientific research and demonstration is carried out, results can be dramatic.

Hydropower Licensing[6]

Controversy abounds in the FERC hydropower licensing process. In part, this may be a result of the lack of clearly identified *goals* to be achieved through mitigation. Although *objectives* exist in the legislative language of the FPA, as amended, these lend themselves more to a philosophy than to hard goals that describe numbers, timeframes, and methods for achieving and measuring the stated goal. Clearly defined goals for protection and restoration of fish resources might refer to numbers or percentages of fish expected to successfully pass a barrier and/or projected population sizes. Since resource management goals are rarely articulated, mitigation and enhancement measures are judged on a case-by-case basis, with no means for assessment or comparison.

The lack of clear goals is, in part, reflected in the disjunction between section 18 prescriptions and section 10(j) recommendations of the FPA. Section 18 fish passage prescriptions are mandatory; however, section 10(j) recommendations may be altered based on consistency with other applicable law or the goals for the river (e.g., whitewater rafting/recreation, power production needs). Yet, the recommendations made under section 10(j) may be critical to maintaining habitat for fish populations or promoting timely migrations for certain species. FERC, as the final authority for balancing developmental and nondevelopmental values, is not specifically charged with sustaining fish populations. Without clear identification of the goal for mitigation, monitoring and evaluation become less meaningful and fail to become critical to the process.

Monitoring and evaluation conditions for hydropower licenses are infrequently enforced, resulting in little information on how effective available mitigation technologies are in improving fish passage and survival at hydropower plants. Operation and maintenance failures have been implicated in poor efficiency of fishways. Forty percent of nonfederal hydropower projects with upstream fish passage mitigation have no performance monitoring requirements. Those that do generally only quantify passage rates, without regard to how many fish arrive at and fail to pass hydropower facilities. Moreover, most monitoring has dealt with anadromous salmonids or clupeids; much less is known about the effectiveness of mitigation measures for "less-valued" or riverine fish. Research is needed to determine whether river blockage is even negatively affecting riverine species.

Relicensing decisions often are not based on river-wide planning and cumulative analysis. FERC is required to review existing river management plans to assure that the project will not interfere with the stated goals (pursuant to section 10(a) of the FPA). Yet, comprehensive river basin planning is fragmented. Synchronizing

[6] These conclusions are largely based on discussions with the OTA Advisory Panel for this project. Due to the elimination of OTA, this project was terminated early, without an opportunity to analyze fully many of the issues addressed in this section.

license terms on river basins could improve the relicensing process and promote cumulative impact analyses. Terms could be adjusted to meet the ecological needs of the basin and to provide timeliness and predictability for licensees. Under such a plan, multiple sites could be relicensed simultaneously, although operators may be unlikely to respond positively to undergoing the relicensing process "early." On the other hand, consolidation could yield benefits, allowing licensees to develop integrated management plans to maximize the energy and capacity values of their projects; making it easier for all involved parties to view the projects and their impacts in their totality; and facilitating understanding of cause and effect relationships.

There is a need for further research on cumulative fish passage impacts of multiple projects, and for consideration of fish needs at the watershed level. In several northeastern states, cooperative agreements between resource agencies and hydropower companies have generated successful approaches to basin-wide planning for fish protection. Carefully planned sequential construction and operation of fish passages could provide significant opportunities for restoring historic fish runs. In the western states, watersheds on national forests provide about one-half of the remaining spawning and rearing habitat for anadromous fish in the United States. Ecosystem or watershed management in these areas could have immediate and long-term impacts on fish populations.

The following chapters provide detailed information about current understanding about the need for fish passage and protection associated with hydropower facilities (chapter 2); the status of fish passage technologies, both conventional and emerging (chapters 3 and 4); and the federal role in fish passage at hydropower facilities (chapter 5). Appendices provide historical information on fish passage research in the Columbia River Basin (appendix A); experimental guidance devices and resource agency policy statements (appendix B); and additional suggested readings related to fish passage technology issues (appendix C).

Fish Passage and Entrainment Protection 2

PART 1: ISSUES AND CONTROVERSIES

This chapter focuses on the need for fish passage and entrainment protection at Federal Energy Regulatory Commission (FERC)-licensed hydropower dams (see box 2-1). Hydropower-related habitat changes, habitat accessibility, and predation are discussed where they directly relate to the passage or protection needs of various fish species.

It is often unclear to what extent fish populations are affected by the impacts of blockage, entrainment, and turbine mortality associated with hydropower (71). Theoretically, considering the great diversity of fish species, hydropower dam designs, and river basin types involved, fish mitigation should be highly site-specific. In addition, the lack of information regarding the biology of some target fish may add further uncertainty to mitigation decisions (215).

This study focuses on two categories of obligatory freshwater fish, since these are the most common fishes that come in contact with hydropower facilities. The first category is the **riverine fishes** (the so-called *resident* or *non-migratory* species[1]) that cannot tolerate long-term exposure to salt water (108). These fishes include all of the freshwater species that use the river or stream as residence for their entire life. Such fish include the sunfishes, catfishes, minnows, suckers, perches, and many other families. The second category is the **anadromous fishes**, which are born in freshwater streams and rivers, migrate to saltwater for their adult phase, and return to freshwater to spawn (see box 2-2).

This chapter is divided into two parts. Part 1 is a discussion of the controversial issues concerning the need for fish mitigation at hydropower projects. The emphasis is largely on passage and protection for the riverine fishes, because at present this is where the most controversy is. Part 2 provides more technical information regarding experimental design for entrainment and turbine mortality studies.

Anadromous Fish Protection

The significance of delaying or blocking fish movements within rivers and the possibility of

[1] These two terms are highly controversial. The terms "non-migratory" and "resident" are often misinterpreted to mean that these fishes do not engage in biologically significant movements within the river basin. As a matter of biological terminology, these fish are perhaps best described as "freshwater dispersants." This term is used by zoogeographers to describe fish that have evolved in freshwater and that cannot disperse via marine routes due to their low tolerance for high-salinity water.

BOX 2-1: Chapter 2 Findings—Fish Passage and Entrainment Protection

- The need for entrainment protection and passage for riverine fish is very controversial. There is a growing body of evidence that some riverine fish make significant movements that could be impeded by some hydropower facilities. The need for passage for riverine fish is most likely species- and site-specific and should be tied to habitat needs for target fish populations. This will be difficult to determine without establishing goals for target species.
- The acceptability of turbine passage for anadromous fish is site-specific and controversial. There is major concern when anadromous fish must pass through multiple dams, creating the potential for significant cumulative impacts. Passage of adult repeat spawners is also a major concern for most Atlantic Coast species.
- The effects of turbine passage on fish depend on the size of the fish; their sensitivity to mechanical contact with equipment and pressure changes; and whether fish happen to be in an area near cavitation or where shearing forces are strong. Smaller fish are more likely to survive turbine passage than larger fish. Survival is generally higher where the turbines are operating with higher efficiency.
- Riverine fish are entrained to some extent at virtually every site tested. Entrainment rates are variable among sites and at a single site. Entrainment rates for different species and sizes of fish change daily and seasonally. Entrainment rates of different turbines at a site can be significant.
- Turbine mortality studies must be interpreted with caution. Studies show a wide range of results, probably related to diversity of turbine designs and operating conditions, river conditions, and fish species and sizes. Turbine mortality study design is likely to affect results. Different methods may yield different results.
- Methods for turbine mortality study include: mark-recapture studies with netting or balloon tags, and observations of net-caught naturally entrained fish, and telemetry. Methods for entrainment studies include: netting, hydroacoustic technology (used especially in the West), and telemetry tagging. These methods have advantages and disadvantages depending on target species and site conditions. Hydroacoustic technology and telemetry tagging can provide fish behavior information (e.g., tracking swimming location) useful for designing passage systems and evaluating performance.
- Early agreement on study design would help minimize controversies between resource agencies and hydropower operators. Lack of reporting of all relevant information makes it difficult to interpret results. Standardized guidelines to determine the need, conduct, and reporting of studies could help overcome this limitation.
- Mitigation by financial compensation is very controversial. The degree of precision necessary for evaluation studies and how fish should be valued are items of debate.

SOURCE: Office of Technology Assessment, 1995.

fish being injured or killed in turbines was rarely considered when hydropower dams were initially designed and built. However, stocks of some high-profile anadromous fish species such as Pacific salmon (157,162), Atlantic salmon (152,154,155,166), and American shad (155) have severely declined. These declines have been linked to a combination of environmental impacts, including hydropower dams, water diversion projects, cattle grazing, water pollution, and over-fishing. It is unknown which of these has had the greatest impact on fish stocks. However, it is widely agreed that the recovery of many of these socially and economically important fish species is in part dependent on providing safe and efficient passage around dams that have excluded them from historically critical habitat (155).

BOX 2-2: Fish Terminology and Life History Notes

Fishes Found At Hydropower Dams

Many different species of fish may come into contact with hydropower dams at various stages in their life cycles. Depending on the site, the species may range in size from a few centimeters to a few meters and display an astounding plethora of behaviors and life histories. Some species complete their life cycles entirely within the boundaries of freshwater rivers, streams, and associated lakes (riverine), while others move between marine and fresh water (diadromous).

In this report, fish that spend their entire lives in freshwater are referred to as **riverine**. This group includes sunfish, perch, gar, catfish, minnows, suckers, trout, paddle fish, bowfin, some sturgeon, herring, lamprey, and many others. The terms *resident* and *non-migratory* have also been applied to these fish, but can be misinterpreted to mean that such species do not engage in biologically significant movements within the river basin. The term riverine was specifically chosen for this report because it does not group fish together based on their movement patterns.

The hundreds of fish species included in the riverine category have such extremely diverse life histories that no generalizations concerning their propensity to make biologically significant movements can be made. Some riverine fish species may be quite mobile and others highly sedentary. In addition, their movement patterns may change from site to site (i.e., a species may be mobile in one river, and sedentary in another).

Some of the riverine fish may exhibit spawning migrations between lakes and rivers, or from one area of a river to another. This migratory pattern is referred to as **potamodromy**. Some common examples of fish that engage in potamodromous migrations include trout, sauger, mooneye, some redhorse, some suckers, some sturgeon,[a] some lamprey, etc.

Some fish exhibit specialized migratory patterns involving regular, seasonal, more or less obligatory movements between fresh and marine waters. This strategy is generally referred to as **diadromy**, and there are three distinct forms.

First, in some species, sexually mature adults migrate from the sea to spawn in freshwater streams/rivers and associated lakes. This migratory pattern is called **anadromy**. Examples of fish that engage in anadromous migrations are Pacific and Atlantic salmon, American and Hickory shad, Atlantic sturgeon, alewife, searun lamprey, etc.[b]

Second, sexually mature adults of some species migrate from freshwater streams/rivers and associated lakes to spawn in the sea. This migratory pattern is called **catadromy**. The most notable example of species that make catadromous migrations is the American eel.[c]

Third, some species make seasonal movements between estuaries and coastal rivers and streams. This migratory pattern is called **amphidromy** and is typically associated with the search for food and/or refuge rather than reproduction (149). Examples of fish that engage in amphidromous movements include striped mullet and tarpon.

Diadromy is relatively rare, represented by less than 1 percent of the world's fish fauna. Of the diadromous fish, anadromy (54 percent) is most common, followed by catadromy (25 percent), and finally amphidromy (21 percent). In the United States, anadromy is by far more common than catadromy or amphidromy.

As with every artificial classification scheme for organisms, some species will not fit neatly into the groups. Some species may have populations that would be classified as riverine and other populations that make anadromous migrations. For example, steelhead, rainbow, and Kamloops trout are three different types of the same species. Steelhead stocks are anadromous, rainbow stocks are riverine, and Kamloops stocks are lake-resident.

(continued)

BOX 2-2: Fish Terminology and Life History Notes (Cont'd.)

Life History Details

Riverine

The riverine fishes are an incredibly diverse freshwater group represented by nearly 1,000 species from over 40 families. The various species exhibit a multitude of life styles, and within its scope, this chapter could not begin to describe all of the diversity. The different species occupy virtually every kind of riverine habitat.

Unlike the diadromous fishes, the riverine species do not require a marine phase to complete their life cycles. The various kinds of habitats in the river (and associated lakes and streams) must meet all of the biological needs of these fishes. For instance, the river must provide habitats to hunt prey, hide from predators, engage in courtship, build nests, spawn, and over-winter. Quite often fish must use very different areas within a river to accomplish these activities. In addition, habitat requirements of most riverine fish species change with their size, age, and with the season. In order for their populations to survive, they must be able to access sufficient quantities of each important habitat type. For example, some species prefer deep pools with muddy bottoms and slow-moving water to feed and/or to seek refuge in, but require shallow riffles with pebbly bottoms in which to spawn.

Because of the sheer diversity within the riverine fish group and the unique (site-specific) conditions created by the interplay of different rivers with different hydropower designs, very few useful generalizations can be made concerning the potential impacts from hydropower dams on riverine fish populations. However, the distribution and abundance of the various riverine fish species in a given river reach can be altered by changes in the quantity and quality of macro- and/or micro-habitat. These changes will likely favor some species while selecting against others that lose access to crucial habitat.

Hydropower dams do alter the natural riverine environment to varying degrees and, in the process, often replace the original habitat types with different habitat types. For example, many hydropower dams create reservoirs which provide pool-type habitat. Bluegill, crappie, and largemouth bass which may have been rare or even absent in the river reach prior to damming, may become the dominant species in these reservoirs.

On the other hand, the populations of some species may be diminished, displaced, or even extirpated from a given river reach due to the changes in the environment up- and downstream of a hydropower dam. For example, fish species that prefer or require riffle-type habitat may disappear from reservoirs.

Some hydropower dams have turbine intakes that draw cold and clear water from near the bottom of their head ponds (hypolimnetic releases). These releases often change the pre-dam water flow, temperature, and turbidity patterns, as well as changing the topography of the river bottom. These tailwater conditions may support productive trout fisheries, even in a river reach where trout are not native and probably could not have survived prior to the hydropower facility.

Anadromy

Fish that exhibit anadromous migrations are born in freshwater streams and rivers and spend a period of time in their natal stream. At some point they begin a migration toward the ocean and then spend one to several years there. After a period of growing in the marine environment they migrate back to a river where they will ultimately spawn, thus completing the life cycle.

Various species of anadromous fish home in on their natal streams and rivers with different degrees of precision. There is also a great deal of variation in the distance upstream that they migrate and the kinds of freshwater spawning habitats they utilize, both within and among species. In addition, while some species, or some individuals within a species, may repeat the cyclic migration several times, others will die after one completed migration cycle.

(continued)

BOX 2-2: Fish Terminology and Life History Notes (Cont'd.)

Even with the incredible diversity and variation within this life style, these fishes all have at least one important thing in common: a need to enter freshwater to spawn and return to saltwater to feed and grow. This biological requirement is the reason that such species are highly vulnerable to impacts related to hydropower dams.

Hydropower dams may alter the quantity of spawning habitat for anadromous fishes. Adult upstream migrations are blocked by hydropower dams unless fishways are in place. If fishways are present, they must be designed to accommodate the biology of the target species and must be maintained properly, or migrations can be delayed. Juveniles and adults that are migrating downstream toward the ocean may be delayed in slack-water reaches of reservoirs or if they cannot locate a route past the dam. If the turbines are used as the migratory route, some fish will be injured and killed.

Catadromy

Catadromy is less common than anadromy in North America. In the United States, the American eel is the only catadromous species that has been well documented. In general, fishes that exhibit catadromous migrations require a fresh- and saltwater phase to complete their life cycles. They are known to migrate hundreds and even thousands of miles between their fresh and salt water habitats and, thus, are highly likely to encounter dams and other blockages. Catadromy is essentially the ecological opposite of anadromy.

These fishes migrate out of lakes and rivers into estuaries and finally to offshore marine waters where they will spawn. The juveniles migrate from the ocean to an estuary and eventually swim up the river. They grow and mature for several months or years in freshwater until they reach sexual maturity and begin to migrate back to the ocean to complete the life cycle.

Adult fish migrating downstream may be injured or killed in turbines. They may also be delayed in slack-water reaches of reservoirs. Juvenile fish migrating upstream can be blocked by hydropower dams unless fishways are in place. Fishways must be designed to accommodate the biology of the target species and must be maintained properly, or migrations can be delayed.

Amphidromy

Amphidromous migrations are much less studied and understood than anadromous and catadromous migrations. Fish species that spawn in freshwater (freshwater amphidromy) and in the sea (marine amphidromy) can exhibit this migratory pattern (149).

Amphidromy is not directly related to spawning and may occur at many life stages. Some species may not necessarily require a freshwater or saltwater phase to complete their life cycle, and thus amphidromous migrations may be less obligatory than catadromous and anadromous migrations. However, coastal weirs, which are used to control water levels in fresh- and saltwater marshes, may block some amphidromous movements, effectively eliminating or limiting important rearing habitat. Hydropower dams located in proximity to estuaries could also block amphidromous movements, but at the time of this report, we could not find an example in the United States of a request for fish passage at a hydropower dam for a fish species classified as amphidromous (i.e., movements between rivers and marine waters for purposes other than spawning).

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[a] See box 2-5 for more detail on lake sturgeon.

[b] Some salmon and sturgeon have become "landlocked," either naturally or due to human intervention. These fishes may now migrate from lakes into rivers and streams to spawn. This migratory pattern (either between a lake and a river/stream or entirely within a river/stream), which is also adopted by many riverine species, is referred to as **potamodromy**.

[c] In North America, the anadromous strategy is more common than the catadromous pattern. However, the catadromous migratory strategy is more prevalent than the anadromous pattern in Australia (149).

SOURCE: Office of Technology Assessment, 1995.

In addition, hydropower dams are also known to kill fish that pass through their turbines. However, the percentage of fish that die from turbine exposure is a matter of debate and also a great deal of research. Prior to the 1950s, fish protection efforts were focused on establishing upstream fish passage facilities at hydropower plants. By the middle of that decade there were growing concerns about the potential hazards of turbine passage for some fish, especially those that migrate between the sea and inland streams. Since the 1950s there has been extensive research on fish turbine mortality. Even with this considerable base of research, there is still some disagreement over the risk to various kinds of fish that pass through turbine designs.

Fish Passage for Anadromous Fish

Fish passage is widely accepted as necessary for anadromous fish. This may be due to the fact that anadromous fish migrations are conspicuous and have been observed and studied extensively. Although there is a great deal of variation in the seasonal timing, duration, distance, and homing accuracy, etc., it is widely known that anadromous fishes must migrate upriver to their spawning grounds to complete their life cycle. In addition, it is also known that anadromous juveniles and some anadromous adults must migrate downstream to the ocean. Consequently, there is general consensus that anadromous fish need safe and efficient passage routes around the dams that are located between their marine and freshwater habitats.[2]

The catadromous migrations of eels have also been studied. Adults must return to the ocean for spawning and juveniles must migrate upriver to their rearing habitat. Logically, fishes that have catadromous migratory patterns (American eels are the most conspicuous example in the United States) need safe and efficient passage around dams just as much as the anadromous fish. However, at least in this country, there is very little knowledge as to how to provide this passage. Consequently, resource agencies more commonly request passage for anadromous fish than for eels (see box 2-3).

BOX 2-3: Eel Biology and Protection

The American eel (*Anguilla rostrata*) is native to the North Atlantic and may be found in the United States along the Atlantic coast and throughout the Gulf of Mexico. They do not occur on the Pacific Coast of North America. The American eel is catadromous, migrating from inland freshwater lakes, streams, and rivers to spawn in the open ocean.

American eels spawn in the southwest part of the North Atlantic Ocean, at a location known as the Sargasso Sea. The adults spawn at great depths and die after spawning. Unlike most fish, eels have a true larval stage (called leptocephalus larvae), in which the young eels do not resemble the adults. Rather, they are transparent ribbon-like creatures with very conspicuous eyes.

The eels spend several months growing in the ocean and arrive in coastal waters about one year after birth. The larval eels metamorphose at about 2.5 inches, which typically takes place during the winter months just prior to entering, or while swimming in coastal waters. Metamorphosed eels look more like the adult eels and gradually become pigmented as they grow. When they become entirely pigmented, which generally happens by the time they move into the streams and rivers, they become known as elvers. As they grow and become better swimmers they are referred to as “young” or “small” eels.

(continued)

[2] There is often argument over what constitutes “safe and efficient passage routes.”

BOX 2-3: Eel Biology and Protection (Cont'd.)

Elvers often occur in great numbers and may be fished along the shores of some rivers and streams with stationary nets. The elvers make their way upstream, where they may live in shallow streams or deep rivers or even associated lakes and ponds. They typically bury themselves in muddy or silty areas or hide beneath large rocks during the daylight hours and generally feed at night, consuming a wide variety of fish and invertebrates.

Very little is known of the early life history of this species. Females generally grow to 25 to 40 inches in length, while males seldom exceed 24 inches. Little is known concerning their age at reproduction, although it is likely to be between six and 12 years. During their freshwater stay, they are generally yellow or orange in color, leading to the term "yellow eel." However, when they reach sexual maturity and begin their downstream migration, they take on a metallic shine and are known as "silver eel." Adults migrate all the way back to the Sargasso Sea (reportedly, as far as 5,600 km) where they will complete the life cycle (158, 208).

The European eel (*Anguilla anguilla*) also migrates to the Sargasso Sea to mate. The two species are exceedingly similar and differ mainly in the number of vertebrae (103 to 111 for American eels and 110 to 119 for the European eels) and adult size (American eels are bigger). European eels apparently take three years on average to get to coastal waters, as compared to one year for American eels. However, most arrive as elvers at about the same size (2.5 inches) as the American eels and thus it seems that the European eels grow considerably slower, at least during the early life stages in the ocean. They are similar in that they migrate long distances upstream in many stream and rivers. Like American eels, they are often found in great numbers and may make a significant contribution to the biomass of certain ecosystems.

The predatory habits, long stay in freshwater, large numbers, and migratory habits have caused some authors to speculate that the decimation of the American and European species could have a considerable impact on the nutrient cycles and energy relationships within lakes, streams, rivers and associated terrestrial habitats (212). Hydropower dams may affect eels in a variety of ways, including killing or injuring some eels as they pass through turbines (92), as well as blocking elvers from migrating upstream (183).

Some biologists, especially in Europe, have explored new technologies to protect eels at hydropower dams and cooling-water intakes (92). For example, lights, air bubbles, and electrical screens have all been tested to keep eels from being entrained. While most of these methods did not work, the experiments with lights were promising. In these tests, eels tended to avoid areas that were illuminated with either incandescent or high-pressure mercury vapor lamps (or both). More research will be needed to determine the efficacy of such technologies to protect eels from entrainment at hydropower dams.

Other scientists have been working on providing upstream fishways for elvers. They are relatively small (10 to 40 cm) and are poor swimmers, thus some traditional fishway designs used for salmon, etc., may not be appropriate. In addition, fishways for elvers may need to accommodate millions of fish in a brief time period. Specially designed fishways for young eels are being developed, mainly in France, where this species is of considerable economic importance (183).

SOURCE: Office of Technology Assessment, 1995.

Turbine Mortality

If a dam has no downstream bypass, every individual of an anadromous fish population reaching the dam must either pass by the turbines, sluiceways, or spillway during their seaward migration. If fish migrate at times when sluiceways are closed and during times of no spill, the majority (or all) of the fish must use the turbine channels as their migratory route (56,193). Therefore, the question of whether these anadromous fishes are being entrained is often moot. However, the question of whether the fish are injured or killed during turbine passage is still somewhat controversial.

Scientists began studying turbine mortality in the United States in the late 1930s. Nearly all of this research was focused on juvenile anadromous salmon (19,199,224). Beginning in 1980 the experimental effort expanded somewhat to include other anadromous species, especially American shad and alewives (18,87,135,206,222).

There is much variation in the data gathered from these experiments. In fact, turbine mortality has been estimated anywhere from 0 to 100 percent (19,46). This wide variance is probably due to the great diversity of turbine designs and operating parameters, as well as the different river conditions and fish species where the mortality tests were done. However, in some cases there may be large differences in turbine mortalities estimated by different studies at the same turbine, and using the same or similar fish species (55).

Studies of turbine mortality have identified four potential categories of dangers to fish: mechanical damage, pressure changes, cavitation damage, and shearing damage.

Mechanical damage is caused by contact with fixed or moving equipment, and is a function of the characteristics of the turbine (number of blades, revolutions per second, blade angle, runner diameter, hub diameter, and discharge) and the size of the fish. Models have been developed to estimate the number of fish of various size that will come into contact with the turbine machinery. Among other things, these models predict that fish size is positively correlated with the potential for physical strikes (35).

The pressure changes that entrained fish experience are a function of the turbine design and flow rate, as well as the location of the fish in the water column prior to entering the intake. Fish that are swimming at depth will be acclimated to relatively high pressure and will experience little change in pressure when entering a submerged turbine intake. Surface swimmers will be acclimated to near atmospheric pressure and will experience an increase in pressure as they "dive" to locate the intake. Just on the downstream side of the turbine blades, fish will experience a region of subatmospheric pressure and then quickly be returned to atmospheric pressure in the draft tube and tailwaters. The region of subatmospheric pressure will only be slightly less than the pressure that a surface swimmer was adapted to, but may be a substantial decrease for bottom swimmers. The amount of pressure damage may depend on the depth of the intake, net head, as well as the pressure tolerance and the acclimation pressure of the target fish species or life stage.

Cavitation is caused by localized regions of subatmospheric pressure (on the trailing edges of runner blades). Air bubbles form when the hydrostatic pressure decreases to the vapor pressure of water. These air bubbles, which can be relatively large, are then swept downstream into regions of higher pressure, which causes them to collapse violently, creating localized shock waves that are often strong enough to pit metal runner blades. The shock wave intensity dissipates rapidly with distance from the center of collapse. Undoubtedly, if fish are passing near a region of collapse, they will be damaged or killed. However, it is difficult to predict how many fish will pass nearby such regions. Cavitation is an undesirable and costly condition for hydropower operators and fish alike. The interplay between turbine setting (centerline of the runner in relation to tailwater elevation) and net head affects turbine efficiency, and often measures can be taken to increase this efficiency. The incidence of cavitation decreases with increasing turbine efficiency, and therefore it is desirable to maintain high turbine efficiency to reduce fish mortality.

Shearing occurs at the boundaries of two adjacent bodies of water with different velocities. Passing through such a zone can spin or deform a fish, which could lead to injury or death. Shearing is most pronounced along surfaces, like walls or runner blades, but is extremely difficult to quantify in a turbine. Therefore it is difficult to determine what percentage of fish deaths from turbine exposure are caused by shearing forces.

It is often difficult to ascertain which type of damage caused the visible injuries to the fish, as they are often manifested similarly (205). In general, there appears to be a positive correlation between turbine efficiency (less cavitation with higher efficiency) and fish turbine passage survival and there is generally a negative correlation between fish size and fish turbine passage survival (64,55).

Early studies of turbine mortality typically only estimated immediate mortality. In other words, investigators focused on fish that were collected dead or dying after passing through the turbines. However, some biologists assert that delayed mortality is also possible and as a result, some investigations have attempted to estimate total mortality by studying both immediate and delayed mortality (62,205). Bell has suggested that, for salmon smolts, 72 hours is an acceptable time period to judge total mortality (17). Delayed turbine mortality estimates are often difficult because of problems associated with maintaining the fish for a period of time after turbine exposure. For example, if control fish have a high mortality level (or a highly fluctuating mortality level among control replicates) due to stress caused by various parts of the experimental apparatus, it becomes difficult to test for statistical significance of test fish mortality (62,64,203,206).

Resource protection agencies also suggest that turbine mortality studies probably underestimate the number of fish that die from turbine passage, because many study designs do not take predation into account. They suggest that as fish emerge from draft tubes they are often subjected to high predation in the tailwaters (or even in the draft tubes). This is due to a variety of tailwater conditions, including the supposition that fish are disoriented after turbine passage, fish getting caught in hydraulics that detain them in the tailwater, increased predator habitat, and the general concentrating nature of turbine passage. Some study designs may be able to include predation in their estimate of turbine mortality, but they may suffer from low re-capture rates, which require using very large sample sizes and may confound statistical comparisons of control and test fish.

Scientists have also been concerned with the general stress, shy of immediate physical injury or death, that could be acting on fish that pass through turbines. The hypothesis is that all fish that are exposed to turbines are affected to some degree. This hypothesis suggests that different individuals react to turbine exposure to varying degrees, and thus even though many fish may survive the initial passage, their chances of future survival are reduced by the exposure. However, in a review of the salmon turbine mortality literature, Ruggles concluded that "... fish that survive passage through turbines without physical injury, by and large, do not have their chances for subsequent survival reduced" (205). However, some studies have shown that even minor de-scaling can reduce the ability of fish to cope with other environmental stress (24).

In general, the experimental design used to study turbine mortality is likely to affect the results considerably (62). A good example is the controversy over turbine mortality estimates for the American shad, blueback herring, and alewife juveniles. Using standard netting techniques, scientists have estimated mortality rates for American shad and blueback herring juveniles at between 21.5 and 82 percent in a Kaplan turbine at Hadley Falls Hydropower Station in Holyoke, Massachusetts, on the Connecticut River (18,222). However, several studies using a different collection technique (balloon tags) estimated turbine mortalities much lower, 0 and 3 percent on average, for these same species at the same (144) and similar (103) Kaplan units.

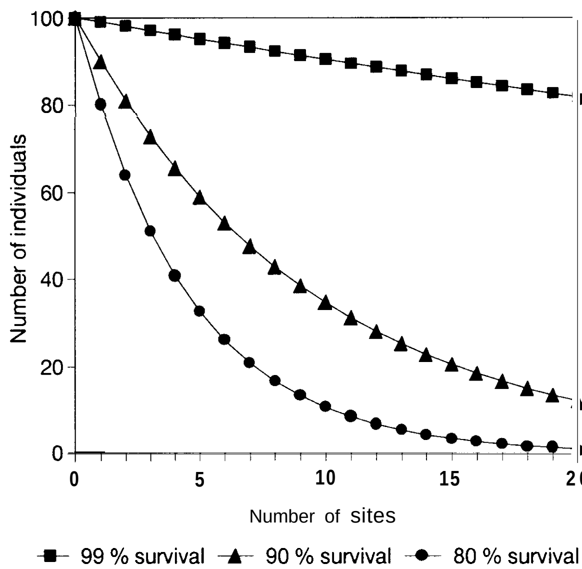
In addition, other aspects of experimental design may also affect results. For instance, the way the experimenter defines "dead" is critical. Some experiments have included fish that are swimming "normally" but that are noticeably damaged (i.e., scrapes, cuts, bruises, loss of scales) in the "dead" column. If another experimenter included that type of fish in the "live" column, the same study results may estimate considerably different mortality rates (see Part 2 of this chapter for more details on turbine mortality studies).

Despite some controversy over the extent of turbine mortality, it is still widely believed to be a significant factor in the reduction of many anadromous fisheries around the country. The concern is greater when there are multiple dams in a system, because of the potential cumulative impact (193). If there is only one dam to pass, mortality rates lower than 10 percent may not seem so alarming. However, when fish must pass multiple dams, as is often the case with anadromous fish, the cumulative impact of several distinct low mortality rates can result in severe losses (35). For instance, a group of salmon smelts migrating downriver will be decreased by half after passing seven dams, each with a 90 percent survival rate (see figure 2-l).

Therefore, downstream protection to reduce entrainment and also some measure of safe downstream passage is often sought for anadromous fishes (i.e., fish bypass, spill measures, trap and truck, etc.). However, all bypass systems are not harmless to fish. Some fish may be killed in bypasses, and thus the mortality rate from the bypass should be compared to the mortality rate of other possible routes (i.e., turbine, spill, sluiceway) (78). In some cases hydropower operators have tried to establish that turbine mortality on anadromous fishes is minimal, suggesting that turbine passage is a viable migratory route for some species at some sites (103). For example, the Federal Energy Regulatory Commission (FERC) has approved turbines as the preferred passage route for juvenile American shad at Safe Harbor hydropower facility on the Susquehanna River in Pennsylvania and for juvenile blueback herring at Crescent hydropower facility on the Mohawk River in New York. The United States Fish and Wildlife Service (FWS) has supported the conclusion at Safe Harbor and is contesting the Crescent case (29,30).

However, accepting turbine passage as a migratory route is still highly controversial and will certainly be highly site-specific. In addition, many anadromous fish have repeat spawners. These fish migrate back to the ocean after

FIGURE 2-1: Cumulative Mortality



SOURCE: Office of Technology Assessment, 1995.

spawning and return the following year to reproduce again. In fact, on the Atlantic Coast, every anadromous fish species, except the sea lamprey, has repeat spawners. Therefore in addition to providing safe passage for down-migrating juveniles, many projects must also provide safe downstream passage for adult repeat spawners (32). Since turbine mortality is more severe with increasing fish size (62,64), presumably turbine passage would not be an acceptable route for adults of most species (18,134).

■ Entrainment Protection for Riverine Fish

The relatively new interest in riverine fish at hydropower dams has mainly been concerned with entrainment and turbine mortality. Research has focused on determining the magnitude and the species and size composition of entrainment and turbine mortality. Hydropower operators may have the option to forgo these studies and develop and implement an enhancement plan for minimizing the entrainment of fishes at their project(s).

Entrainment Studies

A wide array of study designs and methods has been employed to study entrainment at hydropower dams. The diversity in experimental design may be partly linked to site-specific logistical constraints or safety concerns. Dam and powerhouse design, as well as river hydrology, hydraulics and geo-morphology, may limit the methods that can be used. In addition, study goals, experimenter preference, and financial constraints may also play a role in determining what methods are employed.

Unfortunately, the diversity in study methods limits our ability to compare entrainment results from site to site. Two major reviews of recent entrainment studies have been done. Both reviews focused on studies done at sites east of the Mississippi river, primarily Michigan and Wisconsin. The Electric Power Research Institute (EPRI) contracted Stone and Webster Environmental Services (SWEC) to prepare a review of entrainment (and turbine mortality) studies (62). The Federal Energy Regulatory Commission also contracted SWEC to prepare an assessment of fish entrainment at hydropower projects (71).

The following findings regarding entrainment of riverine fish are largely drawn from the FERC 1995 review *Preliminary Assessment of Fish Entrainment at Hydropower Projects* (unless otherwise cited). In general, riverine fish of various species are entrained to some extent at virtually every site that has been tested. Entrainment rates are extremely variable among sites. Smaller fish tend to be entrained at higher rates (62,71). For example, more than 90 percent of entrained fish in several studies were less than 20 cm in length (62). However, the entrainment of large fish is not uncommon.

The location of the intakes relative to fish habitat may be a key factor in determining how many and what types and sizes of riverine fish species are entrained. Penstocks that are located far from shore in open water may tend to entrain different kinds (and quantities) of fish than intakes that are located near the shoreline.

The species, size, and number of entrained fish may differ significantly between units at the same site. The operating time, flow volume, and relative location of the various units may be important in determining the entrainment rate of each. In general, the longer a unit is operated and the greater the flow volume per unit time, the more fish are entrained. Intakes that are positioned near areas where fish like to spawn or feed may entrain more of these fish than units that are further away. Therefore, extrapolation of entrainment data from one unit to another is often controversial. State and federal agencies generally do not like studies that attempt to sample entrainment from a subset of turbines and extrapolate these values to other untested units. In addition, the efficacy of extrapolating entrainment rates will depend on how similar the sites are in fish composition, powerhouse and dam design, as well as on many physical characteristics of the river.

Research concerning the entrainment of fish eggs and larvae at hydropower projects is very rare. Studies that collect fish eggs and larvae are expensive and difficult. However, it is well established that the egg and larval stages represent a critical period that often determines the strength of a given year-class of many fish species (2,129,138). Some studies have suggested that entrainment of larvae and eggs at hydropower facilities can be very high and can affect the abundance of some species (256). Similar results have been obtained at pumped-storage facilities (184,214). However, at least one study found no direct link between entrainment of larvae and population size (48).

Several models have been developed to estimate the impact of egg and larval entrainment at nuclear power plants on fish populations, and they may be applicable to hydropower dams (116). This seems to be an area that deserves more attention in the hydropower arena, but will be difficult and costly. In addition, a recent report on the potential for mortality of fish early life stages (i.e., eggs and larvae) suggested that turbine mortality may be low (35).

Some state and federal resource agencies have drafted specific guidelines on how entrainment and turbine mortality studies should be done

(35,264). Some argue that studies should be conducted over a period of at least three years, and in some cases five, because of changing weather patterns (which affect river flow, etc.) and natural fluctuations in fish population levels (264). Presently studies are generally one year in duration and are relatively expensive. For example, the mean cost of seven different 12-month entrainment studies (using nets to capture fish) was reported to be $273,006 (71). Extending studies for three to five years would substantially escalate these costs, especially when the costs of a turbine mortality study are included.

Standardizing the types of experimental designs that can be used would help in attempts to compare data from several studies. Agreement on study designs between resource agencies and hydropower operators could minimize controversies about how to interpret results. Such comparisons could also be important in identifying trends that might help to guide fish protection mitigation. Suggested guidelines for determining the need for entrainment studies, as well as for conducting studies (e.g., defining target fish and sizes, the appropriate use of hydroacoustic and netting studies, sampling schedules) and reporting results (e.g., the type of information to include, such as sampling times and frequencies, entrainment rates and flows for different hydroplant units, appropriate information on environmental variables, methods used to account for unsampled periods, statistical methods) are provided in the FERC 1995 *Preliminary Assessment of Fish Entrainment at Hydropower Projects.*[3]

Turbine mortality

Estimates of turbine mortality specifically for riverine fishes were rare until recently, and they are still less common than for anadromous species. However, a number of recent studies suggest that smaller fish experience less mortality than larger fish, similar to findings for anadromous fish discussed above (62). Cada reviewed the scientific literature pertaining to the kinds of stresses that fish are exposed to in turbines (i.e., shear, cavitation, subatmospheric pressure, physical strikes) (35). The review suggested that mortality rates may be low for fish eggs and larvae. However, direct measurements of turbine mortality for fish eggs and larvae have never been done.

It is simply too early to make any generalizations about turbine mortality of riverine fish. Resource agencies currently prefer that turbines run at or near peak efficiency to reduce cavitation damage. More research is needed to better determine the risk of death from turbine passage for various sizes and species of riverine fish. Guidelines for turbine mortality studies would also help to standardize results.

Population perspective

Most research on entrainment and turbine mortality has not attempted to determine the fishery impacts at the population level. The entrainment and turbine mortality rates for riverine fishes, which have been gathered now at many hydropower facilities, only represent part of the picture. While entrainment (risk of injury or death) is obviously significant to the individual fish, it is not necessarily significant to the population. For instance, entraining 100,000 fish per year with a 30 percent mortality rate may represent a tragic consequence for one species, while the exact same rates may represent a lesser impact for another. The severity of the impact will depend on many aspects of the population biology of the fish species being entrained. Such parameters include the size of the population, the length, weight and age structure of the population, the reproductive potential of the population, and the natural survival rates (unrelated to entrainment) of the population.

It would be ideal to know the effects of entrainment and turbine mortality on fish populations. However, studies designed to determine these impacts would be very time consuming and expensive, if not impossible. The FERC has recently issued a statement concerning the need for proving population impacts when requesting mitigation at hydropower projects (71).

[3] The Electric Power Research Institute is also currently preparing such guidelines (219).

> Ohio Power's argument appears to be that an effect on fish population as a whole is necessary before any mitigation may be required, and that no such effect has been demonstrated here. However, there are many other environmental variables that influence fish populations, particularly in a large system like the Ohio River. *Consequently, it would be very difficult, if not impossible, to isolate the effects of turbine mortality on fish populations in the vicinity of the Racine Project.* Clearly, there is the potential for an effect on a fish population when a large number of its individuals are removed. These effects can range from the dramatic, such as a reduction in numbers sufficient to affect the long-term viability of the population, to the subtle, such as changes in the average size of fish or their growth rates. *Mitigation can be required even if it cannot be proven that project operation threatens the long-term viability of the entire population* (emphasis added).

There is disagreement on who should bear the "burden of proof" (36). The agencies feel they are often asked to prove that fishes are being negatively affected by dams, and the dam owners feel they are obligated to show that the project does not have a negative impact on the fish. Neither objective is easy.

Controversy concerning entrainment

In general, the industry views entrainment and turbine mortality as a minimal risk to the riverine fish since the bulk of entrainment consists of small fish (primarily young of the year) and the turbine mortalities associated with these small fish are low (35,62). In addition, in some cases there are viable fisheries above and below dams (48). They argue that any negative effects on the population due to fish being entrained will be countered over time by "compensatory mechanisms" at the population level. This theory suggests that as the population gets smaller due to entrainment, the competition over limiting resources between the remaining individuals decreases. Those fish that are not entrained will benefit from the decrease in competition for important resources and this benefit may lead to increased reproductive potential and/or survival. Thus the positive impact of the "compensatory mechanism" could counteract the negative impact of the entrainment.

On the other hand, the resource agencies and conservation groups view entrainment as a significant and chronic source of fish loss. Regardless of turbine mortality, entrainment decreases the populations of upstream fisheries that cannot be replenished by downstream stocks because of the blockage created by the dam. The resource agencies generally disagree with the "compensatory mechanisms" theory. They suggest that individuals in many fish populations are not limited in reproduction, growth, or survival by intense competition over limited resources with other members of the population (88,259). Thus, eliminating "x" number of fish from a population may free up "y" amount of resource, but if the individuals were not limited by that resource in the first place, they are not likely to benefit appreciably from the additional amount. While the compensatory mechanism may occur in some populations for some animals, there has been no research to date that shows that it does (or does not) work for riverine fish species at hydropower projects.

Financial compensation for fishery losses

At some sites, hydropower operators may have to pay a fee equivalent to the value of the fish that are killed by turbine passage. This is known as "compensatory mitigation" and has also been referred to as "fish for dollars" mitigation. This type of mitigation is controversial for several reasons as discussed below.

Techniques that can be used for environmental mitigation have been identified and prioritized by the President's Council on Environmental Quality (CEQ) (40 C.F.R. S 1508.20) as follows:

- avoiding the impact altogether by not taking a certain action or parts of an action;
- minimizing impacts by limiting the degree or magnitude of the action and its implementation;
- rectifying the impact by repairing, rehabilitating, or restoring the affected environment;

- reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action; and
- *compensating for the impact by replacing or providing substitute resources or environments* (emphasis added).

Thus, financial compensation is an acceptable form of mitigation when all of the other preferred forms of mitigation are deemed impossible or inappropriate. The United States Fish and Wildlife Service (FWS) defines "compensation" as "full replacement of project-induced losses to fish and wildlife resources, provided such full replacement has been judged by the FWS to be consistent with the appropriate mitigation planning goal." It defines "replacement" as "the substitution or offsetting of fish and wildlife resource losses with resources considered to be of equivalent biological value" (253).

The hydropower operators pay a yearly financial compensation to the state resource agencies, which is said to be equivalent to the estimated yearly amount of fish killed by a project. Unlike screens, monetary compensation does not directly protect the fish that are being entrained and killed, but rather the monies can be used to support other fishery enhancement projects (habitat restoration, artificial production, etc.).

Compensatory mitigation is becoming more common for projects that entrain riverine fish, but it is controversial. For instance, there is disagreement over the degree of precision that should be required for the entrainment and turbine mortality studies that are used to determine the compensation amount. In general the utilities believe that order-of-magnitude estimates are adequate while resource agencies contend that a higher degree of precision is required to ensure that the level of mitigation is equivalent to the fish loss. FERC discussed study precision in an order issued concerning Ohio Power's 40-megawatt Racine Project, on the Ohio River at a Federal Dam in Meigs County, Ohio, and Mason County, West Virginia (71).

> In this case, we understand that the Commission staff sought to calculate a compensation amount that is roughly equivalent to the replacement cost of the fish lost. 44/ However, we think that the parties misapprehend the nature of the undertaking to the extent they believe that the defensibility of the amount to be set aside for compensatory mitigation turns on the precision of the estimates of lost fish and their associated replacement costs. No such precision is called for; rather, the goal is to establish a reasonable expenditure with which to compensate for the project impact on fish....
>
> 44/ The Division Director referred to the "value" of killed fish, but clarified that the "value" reflected only the cost of hatchery production of the different species and size classes of fish (71).

There is also debate over how to value the fish that are killed. The American Fisheries Society (AFS) Handbook on the Valuation of Fish Kills is often used to determine the value of the turbine-killed fish. This publication values fish based on the cost to replace the fish with hatchery-raised fish of equivalent size (5). The agencies claim that this is not appropriate and that this type of valuation ignores the other intrinsic and economic values of the fish (264). They claim that the AFS replacement values underestimate the "true" value of the fish by as much as 90 percent (see chapter 5).

Passage for Riverine Fish

Though some resource agencies are beginning to make an issue of it, fish passage has rarely been requested for riverine species (relative to the number of requests for anadromous species). Some argue that the fish populations that became established after a hydropower dam was constructed (often 30 to 100 years ago) have been relatively sustained without the existence of fish passage. This argument would apply to fish passage requests during FERC relicensing. However, it is also argued that since the riverine fishes spend their entire lives within freshwater, they may not necessarily need to move past a dam to complete their life cycles.

Some resource agencies have begun to argue that some riverine fish species do make significant movements within the river. Depending on habitat availability at a given river segment and the biological needs of the target fish species, dams may (or may not) separate certain riverine fishes from critical habitat (e.g., spawning areas) that could be important for enhancing or sustaining their populations. Some scientists have also speculated on the ecosystem level impacts of providing or denying fish passage (see box 2-4). The assumption that riverine fish do not require passage may reflect a lack of knowledge of the magnitude and significance of their movements.

Methodology and fish movements

Though the paradigm is beginning to change, the predominant thinking has been that riverine fishes have restricted movements (i.e., "sedentary").[4] The theory that riverine fishes are largely sedentary is partially attributable to the methods used to study their movements (89). The vast majority of studies since the 1940s used the "Mark-Recapture" technique which involves capturing fishes, tagging them, releasing them, and then attempting to recapture them. In many of these studies those fish that were recaptured apparently remained very near the initial capture site, causing the investigators to conclude that these fish are relatively sedentary. However, only a small percentage of fish were recaptured in many of these studies and thus conclusions concerning the amount of fish movement ignore the portion of fish that are not recaptured.

There are several ways that mark-recapture studies may bias results about fish movements. First, there is no information about the movement patterns of the fish that are not recaptured, and in many cases this is the majority of the tagged fish. This could mean that these fishes have moved beyond the boundary of the study or that they may have evaded recapture for some other reason (e.g., mortality, large population size, etc.).

Second, by setting the spatial and temporal boundaries of the study the investigator is presupposing how far and when the fish will move. For instance, if the study concentrates recapture effort on a small region of the stream and a tagged fish ventures beyond the study boundaries, it will not be recaptured and thus its movements cannot be known or included in analyses. To alleviate the bias, researchers can focus recapture efforts over a larger area (e.g., by including angler returns). Recapture efforts should also have a broad temporal focus, so that seasonal fish movements can be detected.

Third, fish that are recaptured in the same stream reach where they were initially caught are assumed to have been there all along. This could considerably underestimate the propensity of a species to move if the fish had left and returned to the area between the two capture events.[5] Mark-recapture studies can provide useful data concerning fish movements and populations size when they are designed to alleviate these potential bias problems.

Other studies have attempted to use radio telemetry to study fish movements. This technology allows the investigators to track individual fish from a population over long distances from the point of initial capture. These studies do not pre-suppose how far the fish move and thus are less likely to bias the results. However, logistics and cost may limit the number of fish that can be followed, which has sometimes led to basing conclusions about fish movements on data from a relatively small number of fish. In addition, transmitter life-span limits the length of time a fish can be followed.

Telemetry and mark-recapture studies can provide data on where a fish is at a particular

[4] The theory that most stream (i.e., riverine) fish are "sedentary" originated in 1959 with a paper entitled *The restricted movement of fish populations* (86).

[5] A fish may be captured and released at "point A," swim some distance to "point B" and then swim back to "point A" and be recaptured. This fish would be incorrectly counted as not having moved. For example, a walleye was captured, fitted with a radio transmitter, and released at Prairie du Sac dam in Wisconsin. The walleye was then radio tracked for 10 months and found to have traveled a distance of 40.6 miles during that period. Three years later, the same fish was caught by an angler behind Prairie du Sac dam. Had there been no radio-tracking data this fish would have appeared (incorrectly) to have restricted movement.

BOX 2-4: Ecosystem Perspective for Fish Passage

The need for fish passage can be considered at the population and ecosystem levels. Most research has focused on the need for passage as it relates to the sustainability of a particular fish population or species. However, some scientists have theorized about the potential ecosystem level impacts related to fish passage. In other words, hydropower dams can preclude fish from migrating or moving to a given river reach. This may or may not have a negative impact on that particular fish population, but it could have a negative impact on other organisms that depend to a greater or lesser extent on the presence of those fish (146).

For instance, many species may depend on fish resources in a given stream reach. Some mammals, birds, reptiles, amphibians, fishes, and invertebrates may prey on fish eggs, larvae, juveniles, or adults. These predator-prey relationships may in some cases represent important ecological interactions between aquatic and terrestrial ecosystems, or within the aquatic ecosystem. Such interactions can be affected (interrupted, decreased, or severed) if some fish can no longer swim to a historic portion of their range.

In addition, many species of anadromous fish die after spawning and their carcasses provide energy to some of the organisms that live in the area. Studies have shown that the carbon from salmon, shad, and lamprey is recycled in the local stream environment and may make a significant contribution to the energy flow of the local ecosystem (261).

Thus, hydropower dams may affect the natural flow of energy through the river basin by impeding natural fish movements, thereby fragmenting the environment and having a negative impact on the entire ecosystem (140,261). Even though the movements of a particular fish population may not always be critical to its own sustainability, the movements may still be critical for other species and thus overall ecosystem health and stability.

These ecological interactions may be more profound in certain river basins and less important in others. Most of the current empirical evidence relates to anadromous fish movements, but the same concept would apply to the riverine and catadromous fishes as well (212,261). More research is needed to examine the significance of ecosystem fragmentation at a level that can guide mitigation.

SOURCE: Office of Technology Assessment, 1995

time and the minimum distance it moved within a given time frame. However, these data must be carefully analyzed before making judgments concerning the biological significance of the observed movement patterns. Fish may move within a body of water for many reasons (see table 2-1). Studies of movement patterns using telemetry or mark-recapture may provide little evidence to draw conclusions about the reasons for the observed movement patterns. Other experiments and natural observations regarding the fish and their habitat may provide supporting evidence to help formulate such conclusions.

Sedentary and mobile hypothesis

Telemetry studies (as well as some mark-recapture studies) have shown that some fish move long distances, while others remain very near the point of initial capture. Some scientists believe there may be a "sedentary" and a "mobile" portion of many fish populations (84,95,102,104,148,216,218). The proportion of the population that is "sedentary" or "mobile" seems to vary from species to species, population to population, and even year to year (89). Individual fish may be either "sedentary" or "mobile" for their entire lives or a fish that is sedentary at one point may become mobile at another time (89).

The significance of having mobile and sedentary subpopulations is not always well understood. However, some case studies have shown that the mobile portion of the population benefited substantially from roaming. For example, individual Arctic char that migrated from their

TABLE 2-1: Some Widely Recognized Riverine Fish Movements

Dispersal	
	Passive fry dispersal with water flow
	Active fry or juvenile dispersal, possibly mediated by competition
	Specialized dispersal with patchy resources
Habitat shifts	
	Shifts in microhabitat related to life stage (age or size)
	Seasonal movements between summer and winter habitat
	Daily movements between feeding and resting positions
Spawning migrations	
	Potamodromous migrations between lakes and rivers
	Movements in all directions when spawning and rearing habitats are interspersed
Homing movements	
	Following displacement (floods, capture and release, etc.)
Home Range Movements	
	Daily movements related to territory defense
	Daily movements related to feeding

SOURCE: Office of Technology Assessment, 1995.

home lake to a more highly productive lake 5 km upstream grew faster and reached sexual maturity two years sooner than their sedentary counterparts that remained in the home lake (160,161).

Study examples

Lower Connecticut River Catfish and Perch: An intensive mark-recapture study of several species of riverine fish was done as part of a major ecological investigation of the Lower Connecticut River (1968 to 1972) (143). Thousands of fishes (9,817) were captured, tagged, and released. For all the years that data were taken, recapture rates ranged between 3.8 and 10.7 percent (918 total recaptured; 9.4 percent). The data indicated that the recaptured fishes of some species were far from stationary and that some individuals occasionally traversed the entire 85.3 km of the lower Connecticut River from Old Saybrook to Enfield Dam. White catfishes (range: 23 km downstream and 61.2 km upstream; average of 15.4 km from tagging site) and yellow perch (range: 23.3 km downstream and 54.7 km upstream; average of 13.5 km from tagging site) moved the furthest from the point of initial capture and the brown bullhead catfish (average 3.6 km from tagging site) moved the least.

Smallmouth Bass (Wisconsin and New York): Mark-recapture and telemetry were used to study smallmouth bass movements between winter and summer habitat in the Embarrass and Wolf rivers in east-central Wisconsin. It was concluded that decreasing water temperature at the summer habitat in the Embarrass River caused smallmouths to travel 40 to 60 miles downstream in search of deep pools for over-wintering in the Wolf River. The following spring with increasing water temperatures the bass returned to the Embarrass River, most to the same three-mile reach of river where they were found the previous year (137). The extensive migration pattern observed in this study may be linked to wide spatial separation between prime summer and winter habitat.

In contrast to this example of long-distance directed movements by smallmouth bass (i.e., migration), other studies have concluded that smallmouths are less mobile. For instance, McBride, using mark-recapture, found smallmouth bass in the Mohawk Watershed in New York to be highly sedentary (148). Ninety-one percent of the bass were recaptured within the same sub-reach of the river that they were initially caught and tagged. However, seasonal migrations, if they occurred, may have been missed because sampling was concentrated in one month only. Recaptures occurred from one to 22 days after initial tagging. McBride interpreted these data to mean that Mohawk River smallmouth bass populations had a relatively large "sedentary" and a smaller "mobile" component, similar to earlier findings about smallmouth bass movements in Missouri streams (84,148).

Largemouth Bass: Largemouth bass movements have also been extensively studied. Most studies (mark-recapture) indicate that adult largemouth bass exhibit limited movement showing a high degree of fidelity to home areas. For example, one study recaptured 96 percent of the tagged fish within 100 m of their respective release sites (139). However, radio telemetry studies on Florida largemouth bass indicated that adults moved out of home areas to locate suitable spawning habitat (44,151).

A mark-recapture study of largemouth bass in Jordan Lake, North Carolina, focused on the movements of juveniles (young-of-the-year and yearlings). Researchers tagged 1,619 fish over two years and recaptured 87 (5.4 percent) of these from one to 133 days after initial release. The vast majority of recaptured juveniles (young-of-the-year and yearlings) were caught in the same cove or area where they were initially captured and released. A few fish (eight; or 9.2 percent of recaptured fish) did move beyond the point of initial release. Unfortunately nearly 95 percent of the fishes were not recaptured and no data is available about their movement patterns (45).

Yellow Perch: Yellow perch from Lake Winnebago in Wisconsin migrate into the Fox River in search of spawning habitat and travel as far Eureka Dam, 40 km upstream from the mouth of the river. After spawning they return to Lake Winnebago and repeat the migration the following year, with the majority (85 percent) homing to the same spawning sites that were used in the previous year (258). In the Chesapeake Bay region, yellow perch migrate from downstream stretches of tidal waters seeking spawning habitat in upper reaches (less saline) of feeder streams and rivers. The migration distance depends on the location and availability of spawning habitat (83).

Shortnose Sturgeon: Annual movements of shortnose sturgeon were studied in the Connecticut (31) and Merrimack (125) Rivers in Massachusetts. In the Connecticut River shortnose sturgeon exhibited two distinct migration patterns prior to spawning. Some of the sturgeon (estimated 25 to 30 percent) spent the latter part of the summer, the fall, and the winter about 24 km downstream of their spawning grounds. In the spring this portion of the population migrated the 24 km and eventually spawned. Following spawning, the spent sturgeon moved back to downstream feeding and overwintering sites. The majority of the sturgeon (estimated 70 to 75 percent) spent the winter at the spawning grounds, thus requiring no spring spawning migration. However, after spawning these fish migrated downstream to two distinct summering sites (23 to 24 km or 54 to 58 km). These sturgeon leave the summering sites in fall (August to October) and migrate back upstream to the spawning/overwintering sites.

In contrast, all of the sturgeon in the Merrimack River overwintered downstream of the spawning site and made a spring migration to those areas. The different movement patterns observed for these populations of shortnose sturgeon are probably related to the availability and the location of the critical habitat. If the spawning areas are far removed from feeding areas, the fish may conserve energy by making an early migration during the fall to coincide with low river flows. On the other hand, if feeding and spawning sites are in close proximity, spring migrations are not as energetically costly.[6]

[6] Shortnose sturgeon are anadromous in southern rivers (e.g., Savannah River), spending the summer, fall, and winter in saltwater. They make long-distance upstream spawning migrations in the spring (between 175–275 km), traveling as many as 30 km a day. Shortly after spawning they return downstream and enter brackish waters by two weeks post spawning (93).

Implications of riverine fish movements for fish passage mitigation

The need for passage for riverine fishes is most likely site- and species-specific. An excellent illustration of site variation is the biology of the Colorado squawfish. Colorado squawfish have been extensively studied in the Green, White and Yampa Rivers in Colorado and Utah and results indicate that adults make seasonal long-distance migrations upstream (65 to 160 km) to locate spawning habitat. After spawning the adults return downstream, often homing within a few miles of where they were prior to the spawning migration. Squawfish larvae in these rivers drift to nursery areas far downstream of the spawning sites (as far as 100 to 160 km) (225,226,227,228,260).

However, McAda and Kaeding studied the same species in the upper Colorado River and found that adult squawfish had much shorter spawning migrations (< 50 km; mean = 23.2 km) than those described for populations in the Green, White and Yampa Rivers (65 to 160 km) (147). The availability of spawning habitat may help explain the difference in the movement patterns of these populations. Spawning habitat was abundant and widely distributed in the upper Colorado River and consequently the fish did not require long-distance spawning migrations to locate suitable areas. In contrast, in the Green River spawning habitat was less common and was highly clumped, requiring fish to swim long distances to locate acceptable areas.

These studies underscore the point that mitigation concerning fish passage will have to be site- and species-specific and should be tied to the specific habitat needs for target fish populations in a given river reach. Seasonal habitat types (e.g., rich feeding habitats v. spawning sites) are sometimes widely spatially separated and may require extensive migrations of some riverine species (169). Goals concerning the target species' population sizes as well as size and age class structure, etc., will be important in determining whether fish passage is needed.

Some riverine fish may need to make long-distance movements past one or more dams to locate critical habitat (e.g., spawning, overwintering, etc.). Some species that make long potamodromous migrations from lakes into streams or rivers may need safe passage routes around hydropower dams to allow access to spawning habitat (see box 2-5).

BOX 2-5: The Lake Sturgeon

The lake sturgeon, *Acipenser fulvescens,* has one of the widest geographic ranges of all freshwater fish. It is found in three major drainage basins: the Mississippi, the Great Lakes, and the Hudson Bay. This species, which once ranged so widely throughout North America, is now nearly decimated throughout most of its native range (110,118). Lake Michigan in 1880 produced a commercial catch of over 3,800,000 pounds of lake sturgeon (15a). A combination of overfishing, dam construction and pollution nearly eliminated these vast populations, to the point that today they are considered threatened or endangered species throughout most of their range. The Menominee River, a boundary water between Wisconsin and the upper peninsula of Michigan, is currently the only tributary to Lake Michigan that still contains a fishable lake sturgeon population. This same scenario has been played out numerous times throughout the historic range of these fish. The lake sturgeon is included on the U.S. Fish and Wildlife Service's list of candidate species being considered for listing as endangered or threatened. It is considered a "Category 2" species which comprises taxa for which information now in possession of the Service indicates that proposing to list it is possibly appropriate, but for which conclusive data on biological vulnerability and threat are not currently available to support proposed rule making.

(continued)

BOX 2-5: The Lake Sturgeon (Cont'd.)

Lake sturgeon are considered living fossils. They have many primitive characteristics which have been lost on most of our modern-day fish. These include a large cellular swim bladder, a heterocercal tail, a cartilaginous skeleton and a notochord, instead of bony vertebrae. These fish are long-lived and often reach a large size. On average females do not reach sexual maturity until they are 25 years old and approximately 50 inches long, while males generally mature around 15 years of age when they are around 45 inches in length. There are records of these fish living over 100 years and attaining lengths in excess of six feet and weights over 200 pounds.

Lake sturgeon are generally found in large river systems or in lakes connected to these rivers. They often move long distances, over 100 miles, to reach suitable spawning habitats. Seasonal movements of lake sturgeon outside of spawning time are not well documented. Lake sturgeon spawn in the spring or early summer. Most spawning occurs in rivers below falls or in rapids. High-velocity water with a rock rubble substrate is preferred. Eggs adhere to these bottom substrates prior to hatching in 7 to 10 days after deposition.

Dams have impacted lake sturgeon populations in a number of ways. Lake sturgeon have been blocked from obtaining their traditional spawning areas by dams that are located at or near the mouths of rivers (15a,96). Brousseau and Goodchild describe how fluctuating flows in a spill channel can adversely impact lake sturgeon populations (28). Low and/or fluctuating flows immediately after spawning will affect spawning success as eggs experience variable water temperatures, low oxygen concentrations and exposure to the atmosphere. Fry become trapped in shallow pools and are subjected to heavy mortality through predation, temperature stress, and oxygen depletion. Water level fluctuations between dams, both seasonal and periodic, have caused decreased production and loss of species such as lake sturgeon from some reaches (173). In addition Altufyev et al. (4), Khoroshko (124), Voltinov and Kasyanov (255) and Kempinger (122) have all shown that changes in magnitude and timing of river flows below hydroelectric dams have affected the reproduction and early life stages of several sturgeon species. Auer has documented significant changes in behavior and population characteristics in the spawning run of lake sturgeon when a project was converted from peaking to run of the river (8,9,10,11). The following changes were documented: 1) an increase in the average size of the lake sturgeon; 2) an increase in spawning readiness; 3) a decrease in the amount of time the spawning fish remained in the area of the spawning grounds, thus decreasing their exposure to adverse conditions and poaching; and 4) an increase in the overall size of the spawning run. Lake sturgeon are adversely impacted by daily flow instability like that created by peaking hydroelectric projects, thus run of the river flows in the main channel and stable spillway flows are critical to the rehabilitation and restoration of lake sturgeon populations.

A key component to lake sturgeon restoration is to provide a means for fish to return upstream to suitable spawning, summer, and winter habitat. By allowing adult sturgeon to pass these dams, historic spawning, nursery and foraging habitat could be utilized by these fish. This could be accomplished by installation of upstream fish passage facilities. Upstream passage of lake sturgeon at dams with heads higher than five to 10 feet has not been successfully accomplished with traditional-style fish ladders. Resource agencies in the Midwest and Ontario are currently working on developing the technology to safely and effectively pass lake sturgeon over these dams. Research is currently being conducted by the National Biological Survey and researchers in Canada on swimming speeds of adult and juvenile lake sturgeon and behavioral response of lake sturgeon to various fishway types. This information is critical to designing an effective upstream fishway for lake sturgeon.

SOURCE: Thomas Thuemler, Area Fisheries Supervisor, Wisconsin Department of Natural Resources, August 1995.

Other fishes may find adequate habitat within the dammed portion of the river. For example, hydropower dams often change the habitat upstream by creating head ponds (i.e., reservoirs) which provide different habitat than the original flowing environments that they replace. There is often a change in species composition favoring fish species that prefer lake-like or pool-type habitat. Such species include some sunfishes like bluegill, largemouth bass, and crappie. Some of these fish are generally structure oriented and may not need to leave the reservoir to locate critical habitat.

PART 2: STUDY METHODS

Entrainment and Turbine Mortality Studies

Entrainment studies quantify the numbers, sizes, and species of fish that pass through the turbines at hydropower facilities. Turbine mortality studies (which are often done in conjunction with the entrainment studies) determine the risk of death caused by passing through a given turbine for the various species and sizes of fish. Prior to 1980, nearly all of the research on entrainment and turbine mortality examined anadromous juvenile salmon (17,19,199,224). Between 1980 and 1990 the experimental effort expanded somewhat to include other anadromous species, especially American shad and alewives (18,87,135,206, 222).

Since 1990 there have been intensive efforts to study entrainment and turbine mortality at sites that primarily or solely support riverine fish. Many of these studies were requested by state and federal resource agencies during the Federal Energy Regulatory Commission (FERC) relicensing process. The results of these studies are used to determine what level of mitigation and what kinds of mitigation are appropriate.

Entrainment Study Methodology

Netting

Netting is the most common method used to measure entrainment. Full tailrace nets (most preferred netting technique) are anchored to the exit of the draft tube and sample the entire discharge from one or several turbine units. Floating mesh boxes of various sizes and types (i.e., "live cars") are often attached to the end of the net to reduce mortality caused by fish scraping and entangling in the net (i.e., net impingement). Partial tailrace netting may be used where full tailrace netting is impossible or prohibitively expensive or even dangerous due to the physical and hydraulic conditions of the tailrace. These nets are usually anchored in the tailrace on a metal frame held in place by guy-wires, or some other anchors, and they sample some portion of the discharge from one or several turbines. Nets may also be deployed some distance downstream of the tailrace and may cover the entire width of the stream.[7]

The main problem with full and partial tailrace netting is contamination of the sample by fish that did not pass through the turbine (i.e., residing in the draft tube or the surrounding areas of the tailrace). This is particularly true for partial nets because they do not completely isolate fish that reside in the tailrace from swimming into them. In addition, fish may be able to escape partial nets. This is the primary reason that full tailrace nets are preferred. However, tailrace and draft tube intrusions may also occur in full net deployments, due to gaps between the draft tube and net frame, gaps between the net frame and the net itself, or ripped portions of the net. Obviously, gaps or rips may also allow entrained fish to escape. These problems can be minimized by careful net anchoring to avoid large gaps and frequent net inspections to locate rips which may develop.

[7] In general such deployments suffer from low recapture rates of entrained fish because the fish can reside in the tailrace upstream of the net for considerable time, where they may suffer from other sources of injury or death (e.g., predation). There is also high incidence of capturing non-entrained fish that were naturally residing in the tailrace prior to the study.

Intrusions may also occur if the net is raised allowing some fish to swim into the draft tube, and later be captured when testing resumes. Most studies guard against this type of intrusion by running the turbine for a period of time without the net in place so that the draft tube will be flushed of fish when netting begins. However, the effectiveness of this technique is unclear.

Nets may be deployed within the turbine intake. Intake collection nets are relatively short so as not to interfere with turbine function, and usually several smaller nets are used rather than one large net. This is accomplished by anchoring the nets onto a frame which slides down into the gatewell. Problems of intake netting include the possibility that some of the fish that are sampled in intake nets may not have been committed to passing through the turbine, as well as the possibility of injury to collected fish because live cars cannot be used. In addition, nets that come apart from the frame may become lodged in the turbine, which could cause considerable damage.

Partial netting techniques, whether located in the tailrace or intake, assume that there is equal distribution of fish throughout the sampled area and that fish cannot avoid the nets or netted areas. These assumptions are not always, and probably rarely, tested in the field or based on any supporting evidence. Estimates of entrainment using partial netting techniques are only as good as these assumptions.

If both tailrace and intake netting are ruled out, nets may be deployed in the power canal entrance. Fish that enter the canal are assumed to be bound for turbine passage, but this may not always be the case, as there are often resident populations of fish within the power canals, or groups of fish that frequently move between a reservoir and its associated power canal. This method may be acceptable for downstream migrating anadromous fishes or when other methods are ruled out.

One of the most critical features of netting studies is "net efficiency." Since sampling nets are almost never 100 percent efficient, good entrainment studies (even with full tailrace nets) should include net efficiency tests. Testing is typically done by introducing marked fish of various sizes and species into the turbine intake at a point where they are committed to passage through the unit. Good net efficiency studies should test with both live and dead fish. In some cases, it may not be possible to introduce fish at a point in the intake where the fish are committed to turbine passage. In such cases, fish may be directly introduced into the collection nets. However, the distribution and behavior patterns of specimens entering the net from the introduction apparatus may be different than fish entering from the draft tube.

There is some argument concerning the net efficiency level that is acceptable for entrainment studies. EPRI suggests that 85 to 100 percent net efficiency is required to demonstrate the efficacy of a full-flow recovery net (62). Low net efficiency may result from rips or gaps in the net apparatus which allow fish to escape. In some cases, strong-swimming fish may be able to maintain positions within, or near, the draft tube, thus avoiding capture. Finally, the net mesh size may allow certain fish shapes and sizes to escape.

Partial flow collection nets will have much lower net efficiencies, the range of which may depend on the fish size and behavior, net size and location, and the flow conditions. Net efficiencies less than 10 percent are common. As previously discussed, net efficiency is assumed to be proportional to flow (i.e., even distribution of entrained fish) and often entrainment rates from partial-flow nets are extrapolated to the full plant flow. In these cases net efficiency testing should be repeated to test the reliability of the estimates, especially given the possibility of intrusions of non-entrained fish and avoidance behavior of entrained fish.

Hydroacoustic Technology (HAT)

Hydroacoustic technology (HAT), also known as SONAR, has been widely used to estimate fish entrainment at hydropower facilities, especially on the West Coast. This technology involves using a transducer to alternately transmit sound waves of a known frequency, usually between 40 and 500 kHZ, into the water and then monitor for any returning sound waves that may bounce off of an object.[8] Most of the newer systems require state of the art computers to decode the data and may rely on various software packages or human judgment to determine whether signals are from debris or from fish.

For entrainment studies there are basically three methods of HAT sampling: echo integration, echo counting, and target tracking. Echo counting and target tracking count individual fish, allowing a direct estimate of fish abundance. These methods are often preferred over echo integration, which is used to get an estimate of fish biomass over time. Echo integration is usually used when fish are swimming in large, tight schools, and individual fish cannot be recognized by the system. Echo integration is more susceptible to background noise levels and errors in estimates of target strength, especially when schools are not of homogeneous species or size.

The major advantage to this technology is that it is often cost effective over the long run as compared to netting. HAT sampling can operate 24 hours a day for months at a time with very little labor cost. HAT counts all fish (within chosen size limits) that swim into the ensonified region without harming or delaying the animal. In comparison, nets may detain, injure, or kill fish and are subject to avoidance behavior.

Recent HAT equipment, in addition to providing size and abundance of entrained fish, can also determine the temporal distribution of entrainment and the spatial distribution of fish as they enter a power canal, forebay, or intake. Information on important fish behaviors like swimming velocity and trajectory is also available. These data can help experimenters detect when, how, and where fish enter turbine intakes and thus may provide assistance in designing mitigation. Real-time data analysis is available, which may be used to alert plant operators when fish are passing the plant in large numbers.

The major disadvantages include the initial cost of the system, which is generally much higher than nets. The technology is also very complex and requires experienced personnel or considerable training (months or years). By design these systems collect a tremendous amount of data, much of which may not be relevant to the study (detection of debris or entrained air). In addition, fish that lie on the bottom or swim very close to a boundary (like a retaining wall, etc.) are very difficult, if not impossible, to detect with HAT. HAT studies should not be conducted in areas with electrical interference or turbulent water flow with entrained air bubbles. No (or little) information can be obtained concerning the species of the fish being detected, and fish which are milling around rather than actively migrating are likely to be counted more than once.

HAT has been used to study entrainment on the West Coast since about 1976. There have been more than 100 HAT entrainment studies (mainly targeting juvenile downstream migrating salmonids) on the Columbia River alone. Several sites have had multiple-year studies (e.g., Wells Dam has had more than 10 consecutive years of HAT entrainment sampling). In many cases, the study objectives went beyond simply quantifying the size and number of fish that were entrained. Studies have been used to evaluate different bypass alternatives (e.g., submerged spill orifices v. surface sluiceways (191) and the efficacy of vertical inclined traveling screens and other structural devices) which have led in some cases to increased bypass efficiencies (130).

HAT has also been applied at some sites in the Midwest and on the East Coast, but has been far more limited in scope. Early HAT studies in the Midwest (especially Wisconsin and Michigan) were not very successful, leading resource agencies in that area of the country to be very skeptical of the applicability of HAT to entrainment studies. Many factors may have limited the results of these early studies. HAT investigations

[8] Typically, the technique involves a pulsed cycle of alternating "transmitting" and "listening" sequences that may be repeated as many as 50 or 60 times per second.

in the Columbia Basin are usually done with state-of-the-art equipment and multiple transducers. This allows full coverage of intakes, etc., and increases the likelihood of gathering statistically useful data. The initial cost of these systems is relatively high, as compared to older HAT technologies and to using fewer acoustic samplers. Cost may not be a limiting factor at many Columbia River sites where adequate budgets allow state-of-the-art research. However, in the Midwest there is generally less money available to fund entrainment studies, and therefore HAT studies tended to use cheaper technologies and designs.

There are several substantial differences between the Columbia River sites and the Midwest sites, including fish fauna (size range, species richness, behavioral diversity), hydropower designs and operations, and overall scale. For example, most studies on the Columbia River have targeted juvenile downstream migrating salmonids which are generally of uniform species, size, and behavior. Studies in the Midwest must typically contend with numerous species with a broad size and behavioral range. These differences result in more complexity that must be addressed in the early design phase of HAT studies. However, these challenges can often be met with the proper experimental design and adequate technologies. The efficacy of HAT, like other methods to study entrainment, is highly site-specific. At some sites HAT may be impractical, while at others it may be highly feasible. If budgets (or logistical constraints) do not allow for adequate HAT equipment, then other study methodology should be sought.

Netting studies are often used in concert with HAT. This can be useful if species identification is important. In addition, the entrainment rates estimated from each method can be compared to one another, which may give a good idea of study accuracy. Comparisons of HAT and net-catch estimates of entrainment have been done at several sites (e.g., Tower and Kleber dams in Michigan (119); Ice Harbor, Rocky Reach, Lower Granite, and Wanapum dams on the Columbia River (192)) and have generally compared favorably.

Telemetry Tagging Technologies

Telemetry tagging technologies, including radio tags, sonic tags and Passive Integrated Transponder (PIT) tags, can be used to study the behavior of fish that are approaching or swimming in the neighborhood of a dam. While these types of studies cannot be used to quantify natural entrainment, they can provide valuable information that can aid in the interpretation of the potential for a problem. For instance, such studies can be used to estimate the percentage of fish that use various routes past a dam (spill, log sluice, bypass, turbine, etc.) or to estimate the risk of entrainment for different species of riverine fishes that are caught, tagged, released and then monitored in various parts of a reservoir.

Radio tags have been developed to transmit both pulsed and continuous signals. Continuous signals are easier to distinguish from background noise and are perceptible from greater distances. Pulsing systems use less energy, so batteries last longer, and individual fish can be distinguished by adjusting the length, rate or interval between pulses.

Transmitters can be attached externally, or placed in the stomach, or implanted surgically. Thus the size of the fish will determine the size of the transmitter. A small whip antenna sends the signal. Prior to attachment, transmitters are covered with a variety of substances to protect them from corrosion during operation.

The signal is stronger when the tagged fish is closer to the surface. Turbulent as well as saline water may disturb the signal quality. Radio transmitters are best suited for surface-oriented fish that are swimming in calm freshwater. Lower frequencies are transmitted further than higher frequencies, but require larger batteries and receiving antennae.

The receiver unit must be able to detect the bandwidth and exclude ambient noise. Wider bandwidths are easier to detect, but will include more background noise. Receivers may be mounted on boats or airplanes, or may be portable. Radio tags are comparatively expensive, often leading to relatively small sample sizes.

Sonic tags are used less frequently than radio tags because they operate over a more limited range, underwater hydrophones must be used, and fewer unique signals can be simultaneously monitored. The tags operate from 30 to 70 kHz, and therefore do not work well in areas of high background noise in overlapping frequency range (e.g., waterfalls, spillways, underwater movable machinery, etc.).

PIT tags have been developed over the past 10 years and allow billions of different codes. They have no internal power source and are only activated in the presence of an electromagnetic field. They are thus suited to monitor longer term migrations of adult salmonids, because the devices can be implanted during downstream migration and still be functioning when the fish return. Since the returning adults must pass through confined areas to get past dams, PIT monitors, when installed in a series of dams, can provide information on many fish passage questions. These include rate of passage, mortality during upstream migration and success rate of individual bypass facilities. The principal drawback of the technology is the need for the fish to be within a highly confined area to be detected. Depending on the transponder, the range of detection is 7 to 33 cm.

Turbine Mortality Study Methodology

Turbine mortality may be assessed using three basic types of studies: mark-recapture studies (e.g., tailrace netting, balloon tags), observations of net-caught naturally entrained fish, and telemetry techniques.

Mark-recapture studies are preferred because they allow for the use of control groups. Currently there are several methods of marking and recapturing the fish. The most common marking techniques include one or a combination of mutilation (fin clipping, branding, etc.), painting, external tags (physical items attached to the fish), and internal tags (e.g., coded wire tags). Fish may be recaptured in the tailrace with various net designs, or in some cases for anadromous fish they may be captured when they return as adults. If the latter method is used, careful control groups must be used and a very large sample size is required. However, it does have the advantage of taking predation on turbine-passed fish into account. Another recapture method involves attaching "balloon tags" to the fish that inflate after a given time and cause the fish to be buoyed to the surface where they can be captured by personnel working from a boat.

Observations of naturally entrained fish have also been used. Fish that are captured in tailrace nets (partial or full flow netting) can be retained in a live car and observed over a given time frame to check for mortality. Advantages of testing naturally entrained fish include sampling fish species and sizes that actually are entrained at the project, elimination of stresses associated with handling, holding, tagging, and introducing fish, and elimination of any potential bias associated with the placement of the introduction pipe. Disadvantages include inability to control for the number, size, and species of the fish, the occurrence of pre-existing injuries on fish, and the unpredictable nature of the timing of fish turbine passage. These problems often lead to meager statistical analyses of turbine mortality risk and therefore resource agencies do not recommend them.

Mark-recapture—Tailrace Netting

Partial or full tailrace nets are the most frequently used system for estimating turbine mortality. Full tailrace netting is preferred where feasible.[9] Experimentally introduced fish should be released at a point where they cannot avoid being entrained. This usually means using a section of pipe (usually PVC of four to six inches in diameter) to introduce the fish. A funnel may be attached to the top of the pipe and fish are usually flushed out with water, compressed air, or by

[9] See section on entrainment netting methods for a critique of net designs.

a physical plunger. There is some possibility that the introduction apparatus may bias the results if it introduces fish in a non-optimal location within the intake or if fish are disoriented when they exit the pipe thus altering their behavior in the turbine. It is also possible that the results could be biased by the number of fish introduced at one time. In other words, fish introduced in sequence may suffer different mortality rates than those that pass in large groups.

The most common problems with tailrace netting studies are intrusion of non-entrained tailrace fish into the net,[10] escape of some entrained fish causing less than 100 percent net efficiency, and injury and/or stress caused by handling or subsequent capturing and holding of entrained fish.

The intrusion of non-entrained fish should not typically be a problem for most mark-recapture studies, because the non-entrained fish should be unmarked. However, the escape of some entrained fish can be a problem. If injured and non-injured fish are caught at different rates, mortality estimates will be compromised. To alleviate this problem, experimenters try to maintain nets so that rips are not allowed to form. In addition, net mesh size must be smaller than the smallest target fish, and gaps between the net and frame (and the frame and draft tube) should be minimized.

The third problem—handling, holding and net capture stress—is one of the most controversial aspects of mark-recapture turbine mortality studies. Test fish typically must be transported to the study site, held in various types of pens, cages, and/or tanks, and physically handled while transferring, measuring, tagging, and finally injecting them into the turbines. To counter the problem, studies must include control groups that expose fish to all of the associated stresses besides turbine passage. These control groups should theoretically be able to identify the expected mortality due to handling, holding, or collecting stresses, and this amount of mortality can then be factored out of turbine mortality estimates of the test groups.

However, some scientists have argued that control groups may not be capable of factoring out all of the mortality associated with handling stress. The concept is that the stresses of handling and turbine passage are synergistic rather than discrete, thus the mortality caused by the combination is greater than the sum of the individual effects. In other words, test fish (passing through turbines) that survive turbine passage may be stressed to some degree and may be killed by a level of handling stress that would not kill a "normal" fish. In other words, control fish are not previously stressed by turbine passage, and may be more able to survive the handling. Thus, the mortality rate calculated for the control fish would not properly account for the synergistic effects on the test fish. In such cases, an overestimate of turbine mortality may result (202,203,206).

Mark-recapture—Balloon Tags

The balloon tag technique involves attaching a self-inflating tag to the test fish, introducing the fish into the turbine, and recovering the fish in the tailrace after the balloon inflates and forces the fish to the surface. This method eliminates the need for tailrace nets (which can be very expensive at large projects) and thus eliminates the stresses associated with net capture. However, recovery can be difficult as personnel must use boats to locate and capture fish, and thus radio tags are often used to help locate the floating fish. Fish recovery is typically better than 85 percent (62), and predation on floating fish and evasion by floating fish have been identified as contributing factors to the percentage of fish that is not recovered. The treatment of these non-recovered fish is one of the most controversial issues concerning this recapture technology. Presently, most studies simply include all non-recaptured fish in the dead column, which might slightly overestimate turbine mortality. How-

[10] See section on entrainment netting methods for a critique of tailrace intrusions.

ever, professional judgment may sometimes be used to determine whether non-recaptured fish are “dead” or “alive” (29).

This method has been identified as useful for frail species that are easily harmed or stressed by net capture (e.g., shad, herring, and alewife). The balloon tags themselves have not been found to kill the fish. The main disadvantage of this technology is the cost of labor-intensive fish recovery. Therefore sample sizes are usually low (total samples less than 200 are most common). If multiple species and size classes of fish need to be tested at more than one operating scheme, netting techniques are more practical.

Telemetry

Radio tagging has been used with limited success to study turbine mortality, but is less common than netting. This approach compares the movements of live and dead fish that are implanted with radio transmitters after turbine passage. In general, fish are counted as living if they move beyond the point where dead fish typically settle to the bottom. This technique assumes, among other things, that any fish that moves beyond the typical settling point of dead fish will survive (i.e., no delayed mortality), fish that settle are dead and not just stationary, fish that are counted as having moved beyond the settling point have not been ingested by another fish and taken downstream, and no fish regurgitate tags. Results may also be confounded by the loss of signals related to fish moving to areas beyond the reach of the transmitter device. In general, resource agencies prefer netting or balloon tagging methods over telemetry for turbine mortality studies.

Upstream Fish Passage Technologies: How Well Do They Work? 3

Fish ladders, fish elevators (lifts) and locks, and trapping and trucking are the three main methods of upstream passage technology (see box 3-1) (36). Fish are "passively" transported via lifts and trucks, but must actively swim or leap up fish ladders. Ladders are the most frequently used means of transporting fish upstream past hydropower facilities. Ladders of various types are distinguished by hydraulic design and the degree to which they are hydraulically self-regulating, the species and numbers of fish they most readily accommodate, and their operability over a range of flows. Fish lifts can be automated and are best for high head sites or for loading trucks. Trapping and trucking fish is a labor-intensive measure, but may be appropriate when fish need to be transported long distances upstream or around a number of obstacles (i.e., hydropower plants) (243).

A **fishway** can be defined as any artificial flow passage that fish negotiate by swimming or leaping (i.e., fish ladders) (243). In an engineering context, it is a waterway specifically designed to afford fish passage around a particular obstruction (121). It may be any structure, or modification to a natural or artificial structure, for the purpose of fish passage. Fishway systems often include attraction features, entrances, auxiliary water systems, collection and transport channels, exits, and operating/maintenance standards (15). A fishway can be a simple culvert under a country road or a complex bypass system at a huge hydropower facility.

UPSTREAM FISH PASSAGE DESIGN

The success of a fish passage system (i.e., ladders, lifts, and trap and truck) at a hydropower facility is dependent on many factors. Effectiveness is directly related to biology and behavior of the target species, as well as hydrologic conditions both up- and downstream of the project. Ultimately, a fishway must be designed to be "fish friendly" by taking into consideration all of the above. At some sites, two types of upstream mitigation may be required to provide effective fish passage.

The hydrologic conditions of the waterway above and below the project will influence the location of the fishway exit and entrance, and influence conditions within the fishway itself. The fishway should be designed to be effective under a range of conditions while accommodating the swimming ability and behavior of the

BOX 3-1: Chapter Findings—Upstream Technologies

- There is no single solution for designing upstream fish passageways. Effective fish passage design for a specific site requires good communication between engineers and biologists and a thorough understanding of site characteristics.
- Technologies for upstream passage are considered well-developed and understood for particular species.
- Upstream passage failure tends to result from less-than-optimal design criteria based on physical, hydrologic, and behavioral information, or lack of adequate attention to operation and maintenance of facilities.

SOURCE: Office of Technology Assessment, 1995.

target species and the targeted run size.[1] In addition, physical and environmental conditions will influence location and effectiveness of the fishway, especially under changing flow conditions (133).

Hydraulic engineering plays a large role in fishway design. An understanding of how to create, manipulate, and maintain appropriate flows in a fishway is critical to success. If available, historical flow data for the waterway can have bearing on hydraulic decisions. There is a significant need for stream flow data from gauging stations to create databases to support good fishway design. Alaska, for example, has an average of one stream gauge per 7,600 square miles versus the lower 48 states average of one gauge per 400 square miles (see box 3-2) (67). As a result, hydropower project planning or development for many of the ungauged rivers in the state must be based on rough flow estimates generated from hydrologic models, unless a project can be delayed until adequate data collection can occur (66). Flow data is important information for determining the depth of the fishway entrance to assure access, and for maintaining appropriate flow in the fishway itself. Flow data will also help site the fishway exit, which must be far enough upstream to prohibit “fall back” while putting fish in a position to respond to instream flows and continue in their migratory path.[2]

An understanding of fish swimming performance and behavior is also essential to fish passage success. It is difficult to determine the exact performance of fish under natural conditions. However, significant knowledge exists in this area for some species, which can be applied to design. Species of fish and individuals within species behave and respond differently, requiring various types of flows and conditions in waterways and subsequently in fishways. Fishway design should consider and accommodate the life stages and unique characteristics of the target fish. Fish passage structures can be designed to accommodate fishes that are bottom swimmers, surface swimmers, or orifice swimmers; fishes that prefer plunging or streaming flow; and weak or strong swimmers (120).

Advances in fish passage will depend on fish behaviorists and biologists working cooperatively with hydraulic engineers to design appropriate fishway environments (133).

Fish Ladders

The actual physical structure that allows fish to climb or carries them to a higher elevation is the ladder, which is part of the entire fishway system. Ladders can be classified in categories based on

[1] In Washington, fish passage hydraulic criteria must be complied with 90 percent of the time during the migration season (12).

[2] Fall back refers to fish that climb the length of a fishway or part of a fishway and drop back to a previous pool to rest. This can be a response to fatigue, unfavorable hydraulic conditions, lighting, or other factors that influence behavior. Fall back also refers to fish that complete the passage of a fishway and exit successfully but are then swept back over the spillway or through the turbines. Shad tend to exhibit fall back, thus limiting the types of fishways that can accommodate the species.

BOX 3-2: The Special Case of Alaska

Alaska's rivers, streams, and lakes represent 40 percent of the nation's surface water (67) and support over half of North America's commercial salmon fisheries (109). Sport fisheries figure prominently in the state's economy, while Alaskan natives rely on subsistence fishing for economic and cultural reasons (200). Water-based navigation and recreation further contribute to the state's overall economy, as do industrial and municipal water uses such as hydropower development, community water supplies, etc. (97).

Presently, the majority of Alaska's water resources are high quality and unallocated (97). Alaska's stage of water development is equivalent to that of the western states approximately 150 years ago. During that time, the majority of water in the western states remained unappropriated and water was initially diverted from the Colorado River in Colorado (66). Increases in private, government, and commercial developments in Alaska, associated with increased population growth, urbanization, and resource development, can be detrimental to continued fish production if they impair or reduce fish habitat or result in higher than desired fish harvests. Proposals to export and sell large quantities of Alaskan water to other states and countries also have the potential to negatively affect fish production (67,68,97). Therefore, the continued production of Alaska's valuable fishery resources will be dependent upon maintaining the quality and quantity of its fish-bearing waters and actively managing fish harvests.

Based on the abundance of undeveloped water sources in Alaska, it is therefore not surprising that Alaska has more preliminary Federal Energy Regulatory Commission licenses in progress for developing new hydropower projects than other states. Unlike the Pacific Northwest and other portions of the country where flowing waters were impounded for hydropower development, Alaska has a unique opportunity to approach hydropower development with fish protection in mind while a project is in the early planning stages. For example, the Alaskan Department of Fish and Game attempts to work with developers to site project facilities so they do not impede fish passage and destroy spawning and rearing habitat. State statutes grant the Alaska Department of Fish and Game permitting authority to require that fish passage flows and physical structures (upstream and downstream) be provided to prevent impairment of fish passage (Title 16, AS 16.05.840) for all fish species, and that the spawning, rearing and migration habitat of 13,000 waters, classified as sustaining anadromous fish species, be protected (AS 16.05.870). Had North America's largest thin arch dam complex been built on the Susitna River in the mid-1980s, it would have been located upstream of a natural fish migration barrier in the Susitna.

Through its Title 16 permitting authority and recommendations to FERC, the Alaska Department of Fish and Game requests mitigation provisions and monitoring be integrated into the project plan during the early design phase. The Department may even require developers of large projects to deposit funds for mitigation and monitoring into an escrow account before project construction begins. Front-end funding insures that mitigation and monitoring can and will be executed, even if a project undergoes financial hardship or is sold or transferred to another entity during and after construction. In the past, many hydropower projects in the lower 48 states were built without implementing previously agreed upon mitigation.

One constraint to better fish protection in the state is a lack of baseline data required for planning and resource management decisions. One inch to a mile topographic maps for most of Alaska are outdated and undigitized, preventing the use of GIS for planning and analysis. It is likely that thousands of bodies of water that support anadromous and resident fish populations have yet to be identified. Further, many of the state's fish and wildlife personnel are unfamiliar with FERC processes and require basic training. The dearth of hydrologic data further hampers Alaska's ability to define water availability for instream flow and other water uses with confidence. Alaska has an average of one stream gauge per 7,600 square miles versus the lower 48 states average of one gauge per 400 square miles (67). Therefore, project planning or development for many of the ungauged rivers in the state must be based on rough flow estimates generated from hydrologic models, unless a project can be delayed several years to allow for data collection.

(continued)

BOX 3-2: The Special Case of Alaska (Cont'd.)

Fishing restrictions aimed at protecting Columbia Basin salmon have been inappropriately applied to Alaska's commercial and sport fisheries. The precipitous declines in some salmon stocks stem from habitat degradation and hatchery introgression, not commercial fisheries. Yet, under the provisions of the ESA and the Pacific Salmon Treaty signed by the United States and Canada, fishermen carry the regulatory burden for intensive development practices. Commercial fishermen, many of whom operate small-scale family-owned troll fisheries, question fishing restrictions that may cost them their livelihoods and save a handful of fish when so many are killed at dams hundreds of miles away. Sport fishing-related restrictions also negatively affect local economies. Restricting Alaska's fisheries is especially ironic in that chinook stocks harvested in Alaska are the healthiest on the coast (200). In that entire communities in Southeast Alaska earn their income primarily through trolling, fishery restrictions pose a serious threat to regional economies, while resulting in only marginal improvement in salmon resources.

SOURCE: C. Estes, Statewide Instream Flow Coordinator, Alaska Department of Fish and Game, August 1995.

hydraulic design and function: pool and weir; vertical slot; roughened channel; hybrid; mechanical; and climbing passes (15). For simplicity, all are commonly referred to as "fishways."

Pool and Weir

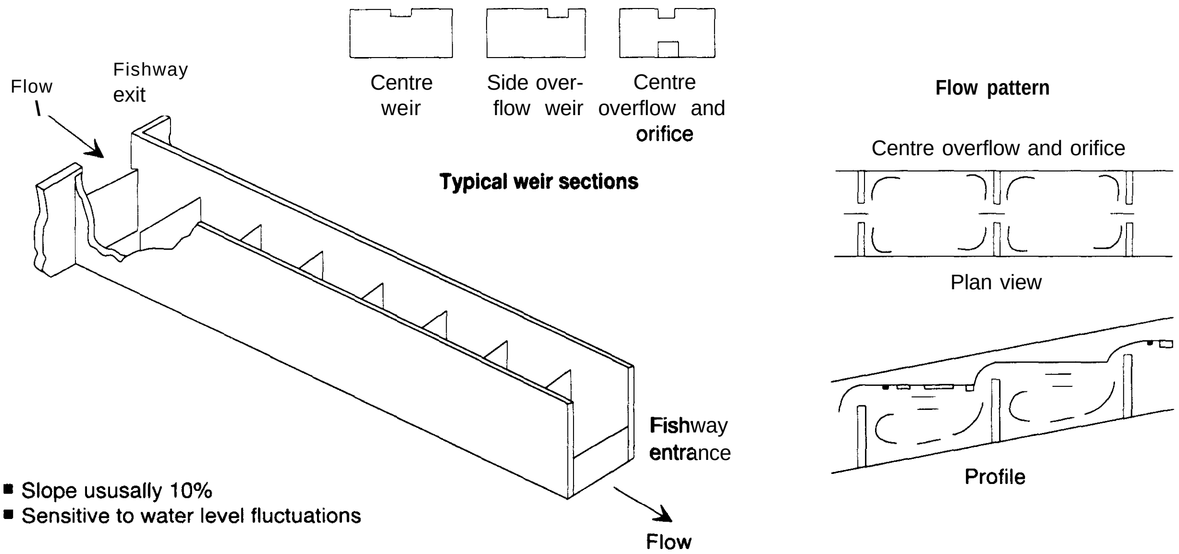
The pool and weir ladder has the longest history of use. Pool and weir fish ladders are designed primarily to provide plunging flow and ample resting areas that provide leaping fish with hydraulic assistance in moving upstream (15,120) (see figure 3-1). In these fishways, pools are arranged in a stepped pattern and are separated by overflow weirs (121). Ladders of the pool and weir type can be applied on any scale; they generally require a great deal of space, but little water (15).

Pool and weir ladders can operate under two hydraulic regimes. The normal flow regime in fish ladders is plunging flow; however, at higher velocities plunging flow converts to streaming flow at the water surface. In this instance, a continuous surface jet passes over the weir crests, skimming the pool surfaces. Streaming flows are difficult to manage and should be used with caution. Moreover, the transition between plunging and streaming flow creates a hydraulic instability that may delay some fish species (15). Streaming flow does not provide the hydraulic boost needed by jumping fish to successfully negotiate the ladder; however, streaming flow is often required because some species cannot or refuse to leap (12). Auxiliary water, beyond what flows down the ladder itself, is almost always needed to attract fish to the entranceway.

Design parameters for pool and weir ladders include receiving pool volume, head differential between pools, water depth in pools, and slope. Values can be calculated for different fish, different sized runs, and different project scales. For example, the recommended head differential between pools is one foot for most salmon and trout, which can leap from pool to pool, and three-fourths of a foot for chum salmon and American shad (15,121). Most pool and weir ladders have a slope of 10 percent and are sensitive to changing water levels (headwater variations) with a narrow range of operation if no other flow control is provided (121). An upper flow limit for effective passage is that at which energy cannot be dissipated from pool to pool (121).

Some pool and weir fishways have submerged orifices that allow fish to pass upstream without cresting each weir (121). Weir and orifice/weir fishways have been used successfully by anadromous salmonids, but not readily by alewife, shad and other fish that rarely leap over obstacles or swim through submerged orifices (121).

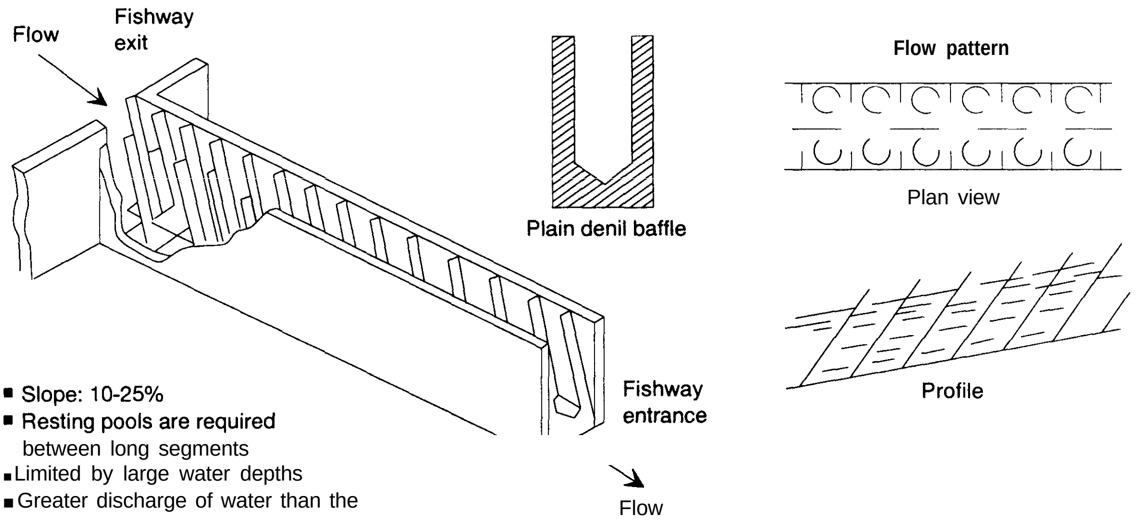
FIGURE 3-1: Weir Fishway



- Slope ususally 10%
- Sensitive to water level fluctuations

SOURCE: C. Katopodis, 1992.

FIGURE 3-2: Plain Denil Fishway



- Slope: 10-25%
- Resting pools are required between long segments
- Limited by large water depths
- Greater discharge of water than the other fishways are, therefore, a greater attraction capability.

SOURCE: C. Katopodis, 1992.

Denil

Denil fish ladders are rectangular chutes or flumes. These relatively narrow chutes have baffles extending from the sides and bottoms which point upstream (see figure 3-2). The internal roughness created by the baffling controls flow for fish passage. The Denil concept originated in the 1920s and was tested in Iowa in the 1940s. The ladders are widely used in the eastern part of the country, and are typically not deployed in the Northwest.

Denil fishways accommodate more different species of fish than other fishways and have been successfully used with a wide variety of anadromous and riverine fish. In the East, Denil fishways are most commonly deployed in small streams. The U.S. Fish and Wildlife Service (FWS) has very specific design parameters relating to slope, water depth and volume of flow to control turbulence and velocity for different species (197).

Flow through Denil fishways is very turbulent, with large momentum exchange and high energy dissipation (121). Fish must swim constantly in the Denil chute so resting pools must be provided in higher head situations. Pools are recommended at 10 to 15 meter intervals for adult salmon and at 5 to 10 m intervals for adult riverine species (120). The U.S. Fish and Wildlife Service, Region 5, suggests a resting pool for every six to nine feet of vertical lift in Denil fishways (186). The large, turbulent flows associated with the Denil decrease fishway sedimentation and provide good attraction capability (121,186). However, auxiliary attraction flows are often needed since flows are generally lower near the bottom and faster at the top depending on the specific fishway design and depth of the water (15,120).

Denil fishways are typically two to four feet wide and four to eight feet deep. Fish can ascend the fishway at their preferred depth. Fish ascending a Denil face varying water velocities depending on their preferred swimming depth (121). Fish generally move more quickly through Denil fishways than through pool and weir fishways (121), and the former can be more effective at steeper slopes than most other fishways (186). Operable slopes range up to 25 degrees for adult salmon; lesser slopes of 10 to 15 percent are more appropriate for adult freshwater fish. Denil fishways also accommodate a wider range of flow conditions than pool and weir ladders; thus, flow control to maintain operable depths is not as critical. However, forebay elevations generally must be maintained within several feet to maintain good passage conditions. For greater headwater variations, a stacked Denil with an intermediate bottom can be used to increase the range of flows over which the fishway can operate (121). Finally, debris blockage is a common problem associated with Denil fishways.

Alaska Steeppass

The Alaska steeppass is a prefabricated, modular style of Denil fish ladder originally developed for use in remote locales (see figure 3-3). The steeppass is a relatively economical, lightweight fishway, where one 10-foot aluminum unit weighs only about 1,500 pounds.

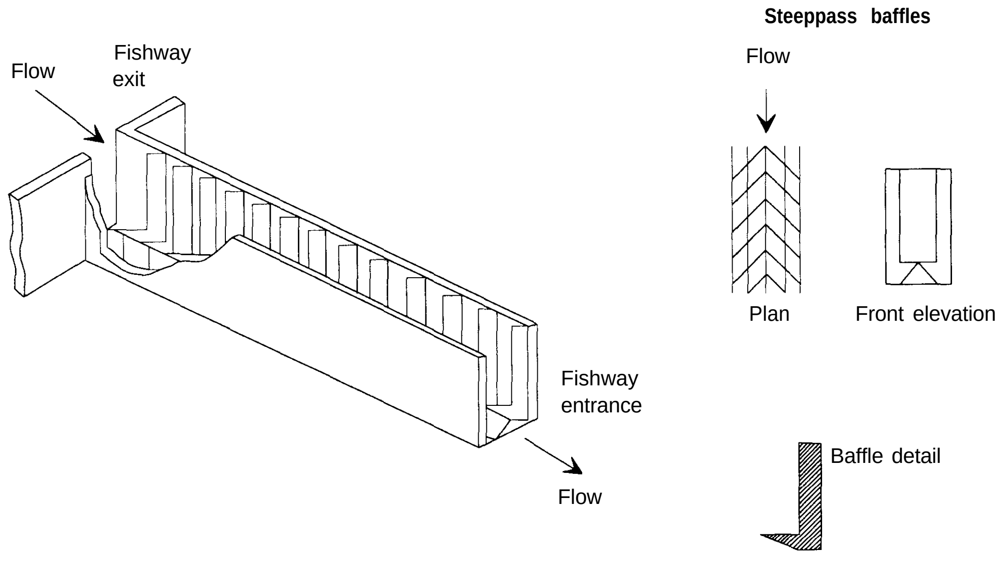
The steeppass has a more complex configuration of baffles than the standard Denil, is more efficient in controlling water velocity, and is operable at steeper slopes (up to about 33 percent for salmon and steelhead). The maximum slope, and therefore the water velocity within the fishway, is a design criteria dependent on species and size of fish to be passed (12). Less flow is required for successful passage. However, due to its smaller open dimensions, the steeppass has a more limited operating range and is more susceptible to debris problems than the plain Denil. Flow control is critical to successful operation of the steeppass. Forebay water surfaces cannot vary more than a foot without passage difficulties. Similarly, tailwater levels cannot fluctuate significantly without problems either with plunging flow or backwatering.

As is true of the plain Denil, water velocities vary with depth within the steeppass. At low depths, velocity tends to be higher near the bottom and to decrease toward the surface. At higher depths, flow divides into upper and lower layers with maximum velocities at mid-depth (15,121). The U.S. Fish and Wildlife Service Region 5, however, does not allow the use of the steeppass design at hydropower facilities because it cannot function under a range of flows (i.e., it is not hydraulically self-regulating) (186).

Vertical Slot

Like pool and weir ladders (and unlike Denil chutes), vertical slot designs have distinct steps. The basic design is a rectangular channel parti-

FIGURE 3-3: Steeppass Denil Fishway



SOURCE: C. Katopodis, 1992.

tioned by baffles into resting pools (see figure 3-4). Water flows and fish swim from pool to pool through slots oriented vertically (121). The vertical slot fishway was first developed for application at Hell's Gate, a barrier created by high-velocity flow through a narrow gorge of the Fraser River in Western Canada (15). The design has been used successfully in many locales for a wide variety of anadromous and riverine fish (121).

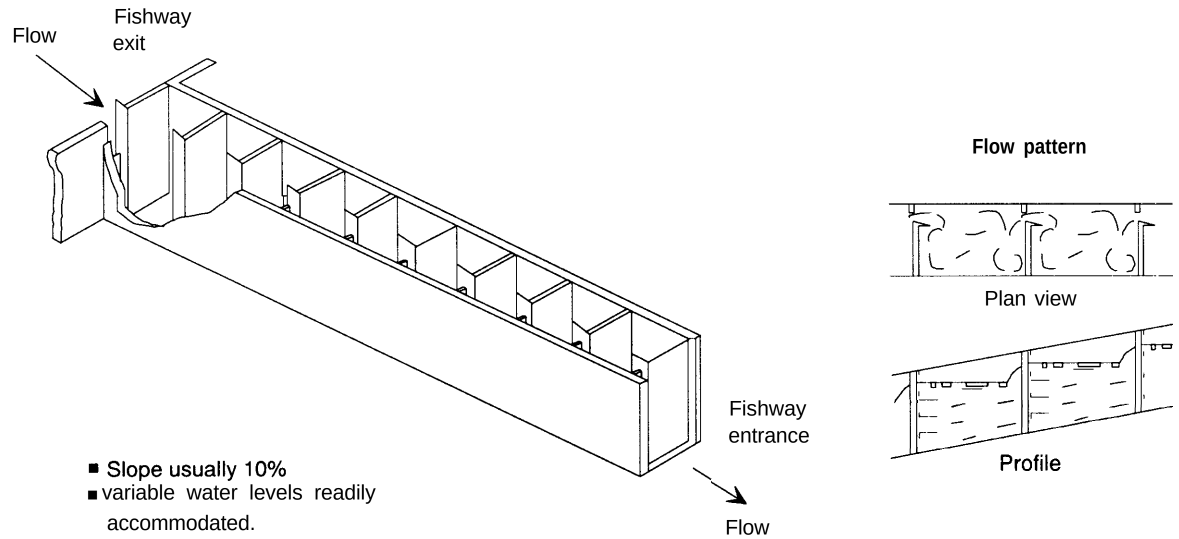
Fish are assumed to move from slot to slot in a nearly direct path (this has not, however, been verified) while swimming at their preferred depth (15). Fish use a "burst-rest" pattern to move up the fishway from pool to pool (121). Pools provide an opportunity to rest, but fish must exert a burst of speed to move upstream through the slots (186).

The dimensions of slots and pools are critical to the stability of flow in vertical slot ladders. Flow is a function of slot width and depth, water depth and the head differential across slots. Sill blocks can be installed in the bottom of the slot to reduce turbulence by reducing slot depth (15). Usually, a 300-mm and 200-mm water level differential between pools is appropriate for passage of adult salmon and riverine species, respectively (121). Slot width generally is based on the maximum size fish that is expected to use the fishway. However, many variations in design are possible by varying the slot arrangement, spacing, positions, width and materials, without significantly affecting flow patterns in the fishway (186).

Vertical slot fishways typically have a slope of 10 percent (121). The change in elevation from ladder top (exit) to bottom (entrance) is nearly equally divided among all the fishway steps; the number of steps is determined by the maximum forebay to tailwater head differential, whether this maximum differential is a feature of low or high flow conditions (15).

The greatest advantage of the vertical slot design is that it is hydraulically self-regulating through a large range of tailwater and forebay water surface elevations. Hydraulic control is provided by the slots, which are the zones of highest water velocity. Energy, in the form of water jets at each slot, is dissipated as the jet is cushioned and mixes with the pool water between baffles. The jet discharge pattern and drop between pools can be adjusted for a particu-

[redacted]



SOURCE: C. Katopodis, 1992.

lar target species. Water velocities are almost constant along the entire ‘slot height (15,121), and velocities are maintained for very large water depths. As flows increase, pools deepen and the appropriate level of energy dissipation is maintained. As a result, these fishways can be built to accommodate a large range of water levels (121). The only constraint to operable range is the depth of the slots.

Within this constraint, any change in forebay or tailwater surface is automatically compensated for and distributed throughout the fishway (15). Thus, vertical slot fishways may be the most effective design for localities where water levels are expected to vary significantly during periods of fish migration (121). Additional water generally is needed for attraction flow at the entrance of vertical slot fishways (187).

Vertical slot fishways have had considerable application across the country with wide success. These fishways seem to work well for a variety of species. In the Pacific Northwest, vertical slot fishways were constructed at 21 tributary sites in the 1980s. Radio telemetry studies showed that fish moved past these facilities in less than a day (187).

Hybrid

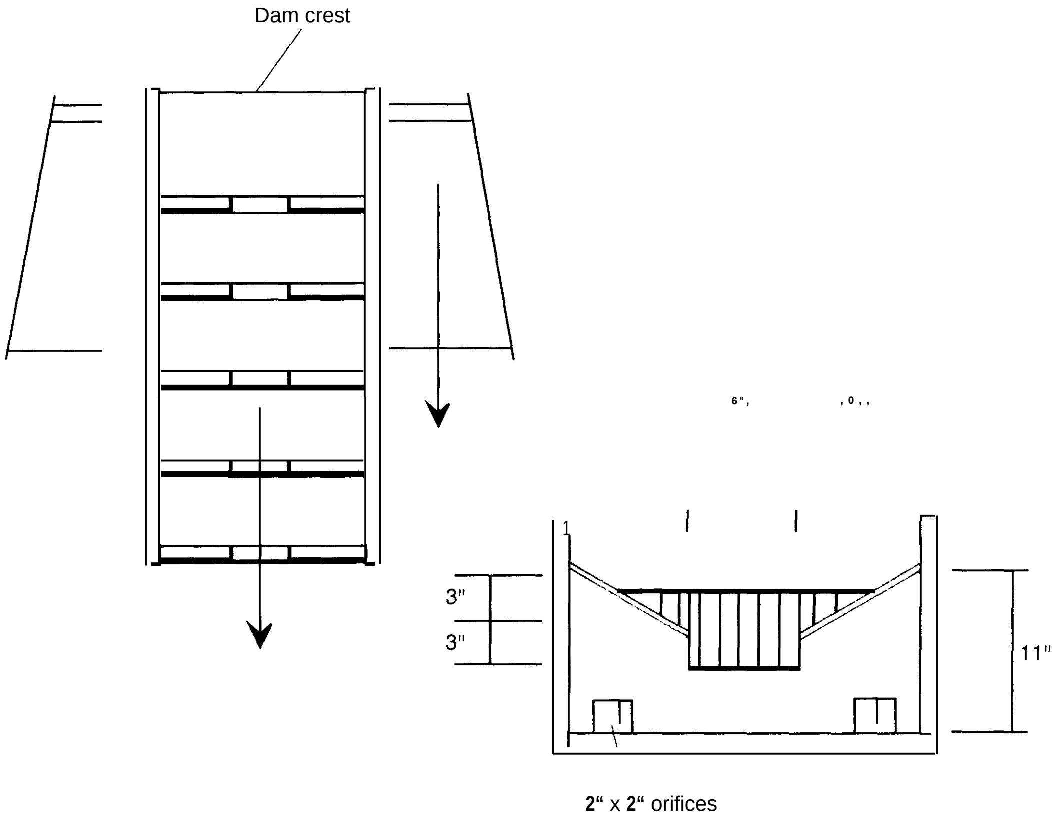
The design features of several types of ladders may also be combined in a single fishway design to accommodate variations in flows (186) or multiple target fish. Features of pool and weir, vertical slot and roughened channel (Denil) designs can be brought together (see figure 3-5).

For example, a “pool and chute” fishway may be constructed to accommodate a wider range of stream flows than pool and weir ladders without additional flow controls. The fishway essentially operates as a pool and weir facility at low flow and as a Denil-type chute at higher flow (15). Combination designs such as this have not yet been thoroughly tested and therefore have not been evaluated as to effectiveness in passing target fish.

■ Fish Lifts

Fish elevators and locks, which can be collectively referred to as *fish lifts,* are desirable in certain settings because they are not flow dependent, nor are they species specific (105). The strategy of the lift is to attract fish to a water-filled chamber at the downstream side of the project (i.e., tailrace area) and transport them

FIGURE 3-5: Pool and Chute Fishway



SOURCE: C. Katopodis, 1992

passively to the top of the project (i.e., headpond area) for release. This approach has advantages over ladder-based mitigation technologies under certain conditions where large numbers of fish must be accommodated, or if the target species are not well suited to ladders (including weak swimmers, and others that might not successfully negotiate ladders), or if the hydropower project is too large for cost-effective fishway installation (242). However, fish may experience crowding during peak migratory periods.

Elevators have the potential to accommodate large numbers of fish if operated with sufficient frequency based on population and migratory data (196). In order for elevators to be effective there must be adequate attraction flow out of the entrance gallery to guide fish. After attraction into the gallery, upward movement is mechanical. This technology can be a labor-intensive means of achieving mitigation; however, automation and the use of a bypass to get fish from the lift exit back to the river channel upstream of the project can help alleviate this drawback. While similar to fishways in capital costs, elevators involve higher operation and management expenses (243). Also, they may be susceptible to mechanical failure much more than fishways, which might cause significant problems for fish if out of commission during the peak migration period.

Like elevators, *locks* require a fish collection facility at the downstream side of the hydropower project level, with a fish entrance, **V** trap, and fish crowding device to force fish into a water-filled hopper (220). Locks are vertical chambers into which fish are crowded; they are then filled with water which raises fish to a higher level. The technology may require a substantial amount of water but is a less complicated device than an elevator.

Elevators and locks are used to lift fish to the forebay level where they may either exit into a bypass, which eventually exits into the river upstream of the project, or be transferred to trucks for release further upstream. A chief disadvantage of utilizing elevators is that automated operation may not be possible (220), and stress and mortality due to handling may occur. Counting and sorting of unwanted species can take place in the collection hopper or in the bypass, if the fish are crowded before release. Also, most lifts have an intermittent mode of operation which can delay fish at the base of a project for unacceptable periods of time (243). Multiple hoppers can be employed to alleviate this problem. Depending on site conditions, lifts can be much less expensive to construct than other fishways. The greatest advantage is for high head sites where fishways would be very expensive.

Trap and Truck (Transportation)

Trapping and then trucking adult migrants to move them upstream has become highly controversial. The lack of a conventional fishway and the cost of installing one are typical reasons for using this alternative means of fish transport. Some practitioners have concerns regarding the effect that handling and transport have on fish behavior and health. On the other hand, trap and truck operations have been successfully used in some cases to move adults upstream of long reservoirs, or multiple projects; fish can then be released close to spawning grounds.

Transportation operations should be executed under conservative conditions to minimize stress. Possible adverse impacts of trapping and trucking fish include disorientation, disease and mortality, delay in migration, and interruption of the homing instinct, which can lead to straying.[3] Additionally, in the case of a proposed trap and truck system for a proposed project on the Penobscot River in Maine, transport of fish would bypass traditional fishing grounds of the Penobscot Indian Nation (21). Additional adverse impacts include low capacity to move the peak of the run without delay and injury, and the cost of operation, leading to a reduction of the operating season or overloading of hauling trucks.

However, moving fish by truck can be a sound method of transport. On the Susquehanna River in Pennsylvania, fish lifts are in operation at the downstream-most hydropower project. They assist a trap and truck operation which supports the restoration of American shad, blueback herring, and alewives. The fish are transported upstream of the four projects on the river and released in the highest headpond near to spawning grounds. There are two lifts in operation at the Conowingo project, one on the west side of the dam and one on the east. Several improvements were made to trap and transfer operations in 1993, including development of new holding facilities at the east lift.

The 10-year-old Conowingo program, supported by state and federal resource agencies, has been quite a success. The transport survival of American shad ranged from 65 to 100 percent from the east lift, while the west lift transport survival ranged from 94.9 to 100 percent in 1993 (252). Holding facilities at both lifts were utilized to reduce stress, maximize transport operations, and release larger schools of fish (177). In addition, load size of fish transported was reduced to prevent undue stress due to crowding. A monitoring program was instituted to determine delayed mortality rates at the release sites. The evaluation of the program at Conowingo has led the agencies to investigate the installation of

[3] Returning adults are driven to spawn by biological cues; an upset of the physiological response can be detrimental. Fish may become disoriented and delay in the river near the release point rather than migrate upstream to spawning grounds. In instances where fish must spend long periods of time in the transport tank, the spread of disease and ultimate pre- or post-release mortality becomes a concern.

fish lifts at three upstream projects (177) and once built, trapping and trucking will be used at a minimum to move fish around the Conowingo hydropower facility.

Fish Pumps

The use of fish pumps to move adult fish upstream of hydropower projects is not widely accepted or used. The FWS Region 5 generally does not support the use of fish pumps due to the nature of the passage method which is completely facilitated and subjects fish to an artificial environment. Fish are pumped to a bypass conduit which releases them upstream of the project. Pumping fish has the potential to lead to injury and de-scaling as a result of crowding in the bypass pipe. This means of passage may also result in disorientation upon release which could potentially lead to problems with predation.

At the Edwards Dam (hydropower project) on the Kennebec River in Augusta, Maine, negotiations between the project owner and the resource agencies over how best to provide an economic means of safely passing American shad, alewife, and Atlantic salmon have been underway for some time. The intent was to use a pump to transport fish (mainly adult alewives) to a sorting and holding facility for trucking upstream. A fish pump[4] is being used as an interim measure, though it has not been as effective as hoped in passing fish upstream (41). In addition, there were initial difficulties with injury and mortality.

The State of Maine favors removal of the Edwards Dam in an effort to restore the river above the project as a spawning and rearing area for a variety of anadromous species which are not known to utilize conventional fish passage technologies.

EFFECTIVE FISHWAY DESIGN

An effective fish passage system must be "fish friendly." Fish use proximate cues from the physical environment to select a riverine space for migration. Increased understanding of these innate preferences could improve the ability of fish passage experts to create suitable environments that attract and pass fish (133). The design must accommodate the unique site conditions and target fish. Achieving such a standard is reliant on obtaining sufficient knowledge of the biology and behavior of the target fish population, and collecting the appropriate hydrological and environmental information.

The basic design requirements of standard upstream fish passage facilities are reasonably well understood, and some conventional fishway designs (e.g., ladders such as the Denil, Alaska steeppass, pool and weir, vertical slot; and lifts and locks) have been used long enough that the design specifications are almost generic. In other words, fishway practitioners understand form and function well enough to make predictions about how a particular fishway might function and accommodate a particular species under given conditions.

Information and data specific to the site must still be obtained. Site data are the physical description of the barrier, river channel, uplands, and hydrology associated with the barrier location, which includes geologic, hydrologic, and topographic descriptions. Stream gauge data is essential and aerial and ground photos are useful. Biological data are the fish passage design criteria which include species targeted for passage, physical size, run size, other species that might compete for space or that should be excluded, and timing of passage needs, including both the time of year and day when target fish are present (i.e., seasonal and diurnal characteristics). In addition, information related to swimming ability (speed and endurance) and preference for flow (orifices, streaming or plunging flow, surface or bottom), and an understanding of what behaviors can be accommodated to enhance passage success are all important to design and success.

[4] The pump in question is a Wemco-Hidrostal screw impeller pump. This is the most commonly employed fish pump at fish hatcheries and thermal power plants.

Understanding and maintaining hydrology and design flows is critical, although there are few situations in which fish passage can be maintained during all possible flow regimes (15). It is important to determine the highest and lowest flows at which the fish passage criteria are satisfied as well as the "normal" operational flows. Different species may or may not be able to adapt to higher flows when hydraulic conditions in the fishway diverge from design criteria (15). Finally, keeping the fishway debris free and regularly checking operation are critical to optimizing and maintaining proper hydraulic conditions.

Without the appropriate information, an ineffective fishway will likely result. Practitioners should do their homework and hydraulic modeling can assist the practitioner in developing the appropriate design. The design should allow for any potential changes in hydrologic and environmental conditions that might occur up- or downstream of the facility. These changes may occur naturally or may be human-induced and can negatively influence fishway operation. For example, inadequate or excess flow in the fishway due to alterations in instream flows could result in a submerged or elevated entrance that is inaccessible to the target fish (186).

However, because river systems are dynamic and variable, each site presents the possibility of new challenges that must be addressed and resolved through the cooperative efforts of the project owner, the resource agencies, and consultants (220). In some cases, the full involvement of agency personnel with the experience and expertise necessary for designing effective fish passage systems may not be possible, due to lack of sufficient staff and/or their time constraints. There may be a lack of necessary information at the state and local levels, and as a result, fishways may be inappropriately designed. A lack of expert staff and/or information needed for the design of fish passage typically results in the use of those technologies that are better known and generally accepted by the resource agencies.

A relatively small group of people from resource agencies, and some experienced consultants, is recognized regionally and/or nationally to posses significant experience and expertise in fish passage problem solving, and in the determination of design criteria. These experts have generally provided written standards and guidelines for their regions of the country, and are in general agreement over what data and information are needed to build a successful and effective fish passage system. In the last several years, the FWS, as well as a couple of state resource agencies, have hosted courses on fish passage design and implementation for those involved in fishway application, in an effort to increase working knowledge and create an open forum for discussion and information exchange between practitioners and regulators. It is the hope of these agencies that this type of effort will help enhance fish passage results and reduce the incidence of costly mistakes by encouraging communication, dissemination of information, and cooperation.

Effective design of a fishway system must address the three basic components of all fishways: entrance, fishway, and exit. Key design elements for each component are described below.

Fishway Entrance

The fishway entrance, the critical link to fishway effectiveness, must be designed to attract fish in a timely manner: "No fish in = No fish out" (13,14,132). Adequate attraction flow is the most important element of a successful passage system because it provides the means of getting fish to the entrance and providing them access to the fishway.

Entrances should be located where fish will have good access. Considering which riverbank most of the fish orient to during upstream migration, how instream and tailwater conditions may affect fish movement and detection of attraction flow are all critical to success.[5] If fish are to be attracted, the entrance cannot be located too far

[5] In wide channel sites, fishway entrances are often required for both river banks and should be operational at all flows.

downstream from the dam or powerhouse, or too far from the main streamflow, or in a back eddy (220).

The depth of the entrance is an important consideration, and is influenced by flows in the river channel upstream of the fishway. If flows in the system are erratic, the entrance should be situated low enough in the river to eliminate the risk of its being exposed (i.e., elevated) and therefore inaccessible to fish. Some sites may require that fishways have multiple entrances. In these situations, tailrace flow conditions must be considered and understood (15). Should the entrance become inaccessible, auxiliary water is needed.

The auxiliary water system is the source, control, and supply of supplementary water to the lower end of the fishway (15). Auxiliary water provides additional flow for attraction, especially when the entrance is in competition with high river flows, and helps maintain the desired flow characteristics in the fishway and in transportation channels. This water can be introduced to the fishway through diffusers (e.g., bar grating, perforated plate, or wood racks) in the walls or floors of the fishway. In general, diffusers must introduce water at a relative velocity (perhaps as low as 0.25 feet per second) that will not cause delays by attracting fish (15). To mitigate against this possibility, a steady stream of flow from the fishway can be directed along the face of the diffuser (15).

Fishway

Designing an effective fishway requires availability of the appropriate pre-design data including physical site and hydrologic data, and biologic data (85). These data form the basis for the technical design of the fishway which should accommodate the weakest individual (in terms of swimming performance) of the target fish population.

Excess flow in the fishway due to changes in upstream conditions and flow characteristics may be problematic, and mechanisms for controlling flow are essential. Such conditions typically require retrofitting to accommodate or control the flow. Considerations of flow patterns and hydraulics at all flows within the prescribed fish passage design flow range must be given. Extreme flows within the design flow range are often not observable during the design process and conditions should therefore be predicted by hydraulic experts or physical modeling. Extra baffling or other flow control methods may help to alleviate this problem. Increased flows can wash out the desired flow characteristics the fishway was designed to create, in the entrance, fishway, and exit.

Fishway Exit

Fish tend to delay when exiting a fishway into a forebay mainly due to disorientation and the need to adjust to the new environment and flow conditions (15). Proper placement of the fishway exit can reduce this delay time but requires understanding of a site’s forebay current. Exits should be located away from spillways or powerhouses and placed in areas where there is a consistent downstream flow (15). Fish tend to orient to the shoreline and into a consistent current during upstream migration. Exits may be extended upstream of the facility in order to achieve correct current conditions. Accumulation of debris around the fishway exit can be prevented by placement of trash racks; however, regular maintenance is required to assure proper operation. A rack or a boom may be placed to guide debris away from the fishway exit to the spillway or sluiceway.

WHY FISHWAYS FAIL

There are three major reasons why fishways do not always work as expected: inadequate or unclear goals, poor design, and inadequate operation and maintenance.

Inadequate or Unclear Goals

The question of whether or not a fishway works or how well it works can be answered in narrow scope (Are fish using it? How many fish are using it?) or in broad scope (What impact is the movement of fish via the fishway having on the larger population and ecosystem?) (189). Determining which approach to take is dictated by the goal. Goals for establishing fishways vary from site to site. Goals may be short or long term, they may be directly measurable or more broad in nature. If no goal is set, there can be no real measure of effectiveness.

If the goal of the fishway is protection, i.e., to pass fish as a mitigative measure for whatever blockage might be in place, then evaluating passage (through counts, telemetry, tag/mark and recapture studies) will serve to determine how well the fishway is functioning. However, if the goal of establishing the fishway is much broader than that, for example, to assist in the restoration of a threatened species or the restoration of a species which has ceased to exist in the waterway, then measurement of achievement and success becomes more complex. This type of measurement would require knowledge of past conditions and population information as well as management and population goals for the future.

Poor Design

Upstream fish passage technologies, though relatively well understood, can still fail to pass fish effectively. Some of the reasons include lack of attraction flow, poorly designed entrances, unsuitable hydraulic conditions within the fishway, ill-placed exits, improper operation, or inadequate maintenance. Fish ladders are highly flow- and velocity-dependent, not only to attract but to move fish. Successful operation of fish lifts is also dependent on attraction flow. Transportation operations are less dependent on flow.

Attraction flow can make the difference between fish passage success and failure. Optimum attraction flow often requires multiple fishway entrances. In these situations, however, tailrace and/or flow conditions can vary considerably. A lack of good attraction flow, or the inability to maintain the appropriate flow, can result in delays in migration as fish become confused or fatigued. The proper location and position of the fishway entrance will help move fish past the obstruction more quickly.

Similarly, increased volume and velocity of flow in the fishway over baffles and around weirs could negate the roughness factor they create, and a submerged fishway entrance could increase "delay time" for fish looking for a means to move upstream (120). Current velocities that exceed the swimming capabilities of the fish create a barrier to fish movement (14,133). The capacity to add additional baffles helps to mitigate increased flow by adding roughness. Decreases in flow in the fishway can negate the fishway hydraulics and expose the entrance, making it inaccessible to fish. Also, decreased flow in the fishway can significantly raise temperatures in turning pools and resting areas, causing fish to hold up (i.e., school or delay) in the fishway. The addition of auxiliary flow can help avoid these situations. In fact, improper flow inside the fishway can negate any positive elements associated with the attraction flow and fishway entrance.

In addition to hydraulic conditions and temperature, some species are also sensitive to light, and in a lesser way to odor. Lighting conditions in the fishway can discourage or encourage movement (133). For example, adult American shad tend to avoid shade, while adult alewives avoid intense mid-day illumination during migration (133). Light intensity affects the orientation ability of some fish. As light intensity decreases below a threshold level, fish cannot orient; this behavior is exacerbated in fast flow (133). For example, adult American shad may actively seek passage in high-flow tailraces during the daylight hours but tend to move more slowly at night in those areas. In addition, some fish may be caused to delay movement in response to certain odors introduced via surface runoff.

Good fishway design cannot occur without consideration of fish behavior and swimming ability. Understanding the behavior of target fish species is necessary to optimally design, locate, and operate upstream passage facilities (133). Delays in migration can result if the hydraulic conditions within the fishway itself are inappropriate for the species to be passed. Design must accommodate species preference for different swimming behavior (e.g., surface, bottom, middle of water column), flow regimes (such as plunging or streaming), and willingness to swim through slots, orifices, etc. Appropriate flow conditions must be maintained under all river flow conditions. The resting and turning pools and baffle and weir configurations of the fishway must be matched to biology, behavior, and swimming ability.

Inadequate Operation and Maintenance

Consistent performance of any well-designed fishway is largely based on maintenance and regular observation of operation. If a fishway becomes clogged or blocked with debris, hydraulic conditions will be altered and the fishway may be rendered ineffective. Some styles of fishways tend more easily to be blocked with debris. The susceptibility to debris blockage often regulates minimum dimension of orifices and weirs and fishway flow. In addition, physical changes in the waterway that alter hydraulics above and below the fishway can adversely impact fishway performance. Debris loading and blockage within the fishway can alter flow conditions and slow or prohibit fish movement. Without proper maintenance even perfectly designed fishways can be rendered useless.

CONCLUSIONS

Upstream fish passages are necessary to move fish around hydropower facilities so they can reach necessary habitat and spawning grounds. Most conventional fishways are accepted and approved for use by the resource agencies. Fish ladders (e.g., pool and weir, Denil, Alaska steeppass, vertical slot), and fish lifts are in use at a number of FERC hydropower projects.[6] Although few have been evaluated, these technologies are considered well developed and understood for certain anadromous species, including salmonids, American shad, alewives, blueback herring, and eels; and somewhat for riverine (so-called *resident* species) including trout, walleye, bass, and lamprey. Site- and species-specific criteria, as well as economics, help to determine which method is most appropriate.

Fish passage success is highly dependent on creating a "fish friendly" environment. Some fish ladders perform better than others because they better accommodate fish behavior and responses to particular hydraulic conditions. Attention to ichthyomechanics is essential to fish passage success. Although it is difficult to pinpoint the range of responses that the target fish might exhibit under natural conditions, available data on fish behavior can be applied to fishway design. An understanding of whether the target fish(es) are bottom, surface, or orifice swimmers, or whether plunging or streaming flow is preferred, helps to assure successful passage.

Attraction flow can make the difference between fish passage success and failure. This is true for fish ladders and lifts. A lack of good attraction flow, or the inability to maintain the appropriate flow, can result in delays in migration. Conversely, good attraction flow and a properly located fishway entrance will help enhance fishway effectiveness. This is true for fish ladders and fish lifts.

The design of fishways must also accommodate a range of flow conditions up- and downstream of the structure and be self-regulating, to the extent that it is possible. They should be properly maintained and kept debris free, or even the best designed structures will fail. Inadequate operations and maintenance, inadequate coordination between design of fishway and hydropower generation, inadequate attraction flow (e.g., difficulty or delay in finding entrance), ill-maintained flow regime in the fishway, or excessive fishway length (e.g., fish become fatigued or hold up in resting areas) are all potential contributors to fishway failure.

The use of trucks to move adult migrants upstream is somewhat controversial, and some

[6] Resource agencies have many concerns about the use of fish pumps for upstream passage.

practitioners have concerns regarding the effect that handling and transport might have on fish behavior and health. On the other hand, trap and truck operations have been successful in moving adults upstream of long reservoirs where they might become lost or disoriented on their way to habitat and spawning grounds. In some cases, where hydropower plants occur in series and fishway installation occurs as a staged process, trucking is critical to species survival. At sites where fishways are feasible, resource agencies prefer the use of transport only as an interim measure.

Because river systems are dynamic and variable, each project site has unique characteristics and can present new challenges in fishway design. They can be addressed through the cooperative efforts of the project owner, the resource agencies, and consultants. The full involvement of agency personnel with the experience and expertise necessary for designing effective fish passage systems is critical. The FWS and some state resource agencies have provided courses on fish passage design and implementation in an effort to increase working knowledge of practitioners, and to promote an open forum for discussion and information exchange between practitioners, FERC, and project operators. This type of effort could help enhance fishway performance and reduce the incidence of costly mistakes by encouraging communication, cooperation, and commitment to doing good work.

Downstream Fish Passage Technologies: How Well Do They Work? 4

The implementation of downstream mitigation for fish passage at hydropower facilities has three distinct goals: to transport fish downstream; to prevent fish from entrainment in turbine intakes; and to move fish, in a timely and safe manner, through a reservoir.[1]

A range of mitigation methods for downstream passage and for prevention of turbine entrainment exist, and some have been applied with more success than others. The so-called "standard" or "conventional" technologies are mainly structures meant to physically exclude or "guide" fish to a sluiceway or bypass around the project and away from turbine intakes by means of manipulating hydraulic conditions. Other "alternative" technologies attempt to "guide" fish by either attracting or repelling them by means of applying a stimulus (i.e., light, sound, electric current). Many theories have been applied to the design of downstream passage systems and further experimentation is underway in some cases (see box 4-1).

For downstream migrating species, including the juveniles of anadromous upstream spawners, it is important that a safe route past hydropower facilities be made available. For these fish, a means of preventing turbine entrainment, via a diversion and bypass system, is often needed (242,243) (see box 4-2). For some resident fish, downstream movement may not be critical or desirable. Philosophies of protection vary across the country depending on target fish, magnitude of the river system, and complexity of the hydropower facility. For example, practitioners in the Northwest tend to prefer exclusion devices that physically prevent entrainment, while those in the Northeast tend to recommend structural devices that may alter flow and rely on fish behavior for exclusion.[2] Much of the variance in protection philosophy may be linked to differences in target fish in these regions. The Northwest hosts a number of endangered or threatened species (mainly salmonids), while the Northeast does not have quite the same history of concern. In the Northwest, fish protection is mainly focused on salmonids. Downstream migrants

[1] The main difference between up- and downstream passage is that upstream moving fish may keep trying until they find a means of passage (i.e., a fishway). A downstream migrating juvenile has one chance to find the proper passage route, otherwise it becomes entrained.

[2] The mechanism that causes fish to be guided by angled bar racks is not well understood.

BOX 4-1: Chapter Findings—Downstream Technologies

- There is no single solution for designing downstream fish passage. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.
- Physical barrier screens are often the only resource agency-approved technology to protect fish from turbine intake channels, yet they are perceived to be very expensive.
- The ultimate goal of 100 percent passage effectiveness is most likely to be achieved with the use of physical barrier technologies, however site, technological, and biological constraints to passing fish around or through hydropower projects may limit performance.
- Structural guidance devices have shown to have a high level of performance at a few studied sites in the Northeast. The mechanism by which they work is not well understood.
- Alternative behavioral guidance devices have potential to elicit avoidance responses from some species of fish. However, it has not yet been demonstrated that these responses can be directed reliably; behavioral guidance devices are site- and species-specific; it appears unlikely that behavioral methods will perform as well as conventional barriers over a range of hydraulic conditions and for a variety of species.

SOURCE: Office of Technology Assessment, 1995.

tend to be small and have limited swimming ability. In the Northeast, fish protection is focused on a variety of species. In some cases downstream migrants are of fairly good size and possess fairly good swimming ability (e.g., American shad).

Physical barriers are the most widely used technology for fish protection. These technologies include many kinds of screens (positioned across entrances to power canals or turbine intakes) providing physical exclusion and protection from entrainment. In some parts of the country, *behavioral guidance devices* such as angled bar racks (modified versions of conventional trashracks) are used to protect fish from turbine entrainment. For both categories of downstream passage technologies, careful attention to dimensions, configurations and orientations relative to flow is required to optimize fish guidance.[3]

In most cases, structural measures to exclude or guide fish are preferred by resource agencies. Screens and angled bar racks providing structural measures for physical guidance are preferred by resource agencies, however, the screens can be expensive to construct and maintain. As a result, the development of alternatives to these technologies, such as *alternative behavioral guidance devices* (e.g., light, sound), continues to be explored. These devices have not been proven to perform successfully under a wide range of conditions as well as properly designed and maintained structural barriers. Thus, the resource agencies consider them to be less reliable in the field than physical barriers. In addition, other methods for downstream passage are also being explored. New turbine designs that will be not only more efficient but more "friendly" to fish are under proposal. And in the Columbia River Basin, a surface collector system which intends to guide fish past hydropower facilities by better accommodating natural behavior is being experimented with at a number of sites.

DESIGN OF CONVENTIONAL STRUCTURAL MEASURES

Progress in developing effective downstream fish passage and protection mechanisms has occurred over the past 50 years (203,205,221). Physical barrier screens and bar racks and lou-

[3] Fish impingement on screens or trashracks can stress, descale and otherwise injure fish, particularly juveniles (168, 190).

BOX 4-2: Complements to Exclusion, Diversion, and Guidance Technologies

Once fish are diverted by physical screens, angled bar racks, or louvers, a means of passing them around hydropower projects is needed. This is achieved through the use of bypasses and sluiceways. These measures would also be required for any emerging behavioral guidance technologies.

Bypasses

Engineered bypass conduits are needed for downstream-migrating fish at hydropower facilities and are the key to transporting fish from above to below a hydropower project. Most early downstream mitigation efforts only marginally improved juvenile fish survival. Today, juvenile bypass structures are more efficient due to lessons learned and a better understanding of the interaction of hydraulics and fish behavior (190). In some instances bypasses must provide efficient and safe passage for both juvenile and adult life stages (175).

Despite efforts at designing mitigation systems for specific sites, efforts may fail due to inadequately designed fish bypasses (204). Bypass design should be based on the numbers, sizes, and behaviors of target species (204). The entrance to such channels may be their most important feature. Smooth interior surfaces and joints, adequate width, absence of bends and negative pressures, proper lighting, and appropriate hydraulic gradients should be considered when designing an effective bypass system (239). High-density polyethylene, PVC, or concrete cylinders are all appropriate bypass materials (175).

Bypass entrances and the velocity of the flow are critical to success. For example, fish may be less likely to enter a bypass if met with extremely high flows. Typically, bypass entrances consist of a sharp-crested weir configuration which causes an increase in velocity. The development of a new weir, which may be able to be retrofitted at some applications, will result in gradual velocity acceleration intended to be more attractive to fish.[a]

Bypass outfalls are also critical in achieving safe downstream passage of target fish. The potential for predation at bypass exits where fish are concentrated is a particular concern (204). Gulls, squawfish, otters, herons, and other predators often congregate at these outfalls. Submerged outfalls may allow for avoidance of strong currents, bottom injury, and predation by birds; but they may cause disorientation and have debris problems (175,190). Elevated outfalls may greatly subject fish to predation and disorientation, but avoid problems with debris. Injury and mortality associated with various bypass structures has rarely been studied, although in some cases it has been high.

Sluiceways

Sluiceways are typically used to bypass ice and debris at hydropower projects, but they can also provide an adequate and generally successful means of downstream passage provided fish are able to locate them. Small hydropower projects often rely on sluiceways for passage. This type of passage may work well for surface or near-surface oriented fish (i.e., clupeids, salmonids, and some riverine species) but may not work as well for fish distributed elsewhere in the water column.

Entrance location, adequate flow, and thorough maintenance and debris removal are critical factors to sluiceway success. The sluiceway should be located to one side of the powerhouse, generally at the most downstream end, with its outfall located so as not to interfere with the attraction flow of the upstream fishway. The greatest problem associated with sluiceways is the potential for predation at the entrance or exit.

[a]The NU-Alden Weir was developed by Alden Research Laboratory with funding from Northeast Utilities, Inc. Testing of the weir took place at the Conte Anadromous Fish Research Center during the spring of 1995. Results were promising.

SOURCE: Office of Technology Assessment, 1995.

vers have been used to exclude fishes from turbine intakes and are considered to be standard, conventional technologies.[4] In cases where there is a large forebay area, water velocities are high, or site specifications are limiting, these types of systems may not be feasible, or the costs may be exceedingly high. Physical barrier screens may provide nearly 100 percent protection for migrating (target) fish, but for the aforementioned reasons, the development of alternative behavioral guidance techniques (e.g., sound and light) has been, and continues to be, pursued in the public and private sector.

The design of effective structural measures for assisting in downstream passage of juvenile outmigrants and riverine species is dependent on behavioral criteria, and the knowledge of physical, hydraulic, and biological information which are critical to success (13,185). Lack of knowledge of fish behavior tends to lead to disagreement on what the best available method or technology for a particular site might be. This type of information is also necessary for the design of alternative behavioral guidance devices. For example, the limited swimming ability exhibited at the juvenile stage is a critical design concern. Flow data, species and population size, and where the target species tend to exist within the water column will help determine location and type of passage system necessary.

Downstream passage design must take into consideration the lack of or limited swimming ability of outmigrating (anadromous) juvenile and smolt fishes. Other catadromous and riverine species may have limited swimming ability as well, depending on age and size. Where larger catadromous fishes and anadromous adult repeat spawners are concerned, entrainment avoidance might be more related to behavior than to physical swimming ability. Where hydropower projects exist in series, a system of reservoirs may be created where velocities are low and water temperatures elevated. These conditions may alter fish behavior and slow outmigration of juveniles that are dependent on water flow to assist their movement. The series of four dams (McNary, The Dalles, John Day, Bonneville) on the lower Columbia River, for example, can add up to 20 to 30 days to the travel time for juvenile fish due to alteration in flow conditions (230).

Screens as well as bar racks generally are designed to work with site hydraulics to help or encourage fish in moving past or away from turbine intakes. Well-designed screen facilities may result in a guidance efficiency of over 95 percent (see appendix B) (236,236A). The effectiveness of bar racks is less conclusive. The size and cost of screen and bar racks systems depends on the site. However, water velocities in the forebay in general, and the approach velocity[5] in front of the system in specific, are of primary concern. The idea is to maintain approach velocities within the cruising speed of all target fishes to be screened in order to achieve protection (58).

Physical Barriers

Screens

Outmigrating juvenile salmonids depend a great deal on hydrology and hydraulics to guide their movement. These fish have limited swimming ability and orient themselves into the flow.[6] Therefore, downstream protection devices must take advantage of natural fish behavior. At many hydropower projects a physical barrier is used in conjunction with a bypass to facilitate passage. The flow characteristics that are generated by the particular placement of a screen and the physical parameters of the screen itself help to guide fish

[4] Bar racks and louvers are considered standard technologies for application in the Northeast, but not in the Northwest.

[5] "Approach velocity" is the velocity component of flow normal to and approximately three inches in front of the screen face. Fisheries agencies determine this value based on the swimming capabilities of the smallest and/or weakest fish present (239).

[6] Some salmonid pre-smolts have good swimming ability (i.e., sockeye, coho, steelhead), while others (i.e., pink and chum) smolt shortly after emergence and their swimming ability does not change significantly during smoltification. Not as much is known about how other migratory species (e.g., American shad, blueback herring) behave during outmigration (187).

to the bypass. The key to successful downstream passage is to employ the fish's behavior to guide them to a safe bypass. The hydraulics of the structure must be benign enough that the fish can be guided to safety before they fatigue or are injured.

Physical barrier screens can be made of various materials based on the application and type of screen (i.e., perforated plate, metal bars, wedgewire, or plastic mesh). Screens are designed to slow velocities and reduce entrainment and impingement (78). Smooth flow transitions, uniform velocities, and eddy-free currents just upstream of screens are desirable. Adequate screen area must be provided to create a low flow velocity that enables fish to swim away from the screen.

The positioning of the screening device is critical. It must be in appropriate relationship to the powerhouse to guide fish to the bypass by creating the appropriate hydraulic conditions. Fish then enter a bypass which either deposits them in a canal that eventually rejoins the main channel, releases them into the main flow downstream of the project via an outfall pipe or sluiceway, or leads them to a holding facility for later transport. Outfall pipes typically release fish above the water's surface to avoid creation of a hydraulic jump or debris trap within the closed pipe. Releasing fish above the water may also alleviate disorientation and help to prevent schooling. However, predation at the outfall can be a problem and there is no consensus on how to avoid this, though multiple outfalls might alleviate the situation in some cases (188).

The screen must be kept clean and clear of debris or it will not function properly. Debris is commonly the biggest problem at any screen and bypass facility. Debris loading can disrupt flow and create high-velocity hot spots, or cause injury to fish (238). In addition, a partially blocked bypass entrance can reduce the efficiency of fish passage and cause injury or mortality (190) (see box 4-2). Installation and operation of a screen cleaning system and regular inspections to ensure proper operation of screens may be the most important activities to increase effectiveness. Mechanical cleaning systems are preferable over manual ones and often more reliable, provided they are functioning properly. Very frequent cleaning may be needed where there is a lot of debris. California screen criteria require cleaning every five minutes. Ideally, screens should be cleaned while in place, and temporary removal of a screen for cleaning is usually not acceptable (12).

A variety of physical barrier screens has been developed to divert downstream migrants away from turbine intakes.[7] Years of design, experimentation, evaluation, and improvement have alleviated some problems but others still remain, and no physical barrier is 100 percent effective in protecting juveniles. Few studies have been able to demonstrate conclusively a guidance efficiency exceeding 90 percent; and although the effectiveness of these facilities is probably close to 100 percent at many sites, losses of fish may occur due to predation or leakage of fish past faulty or worn screen seals (59). However, improvements in screen components have been made and designs have begun to reflect new knowledge about hydraulics. Some specifics of design and function of a variety of low-velocity[8] physical barrier screens are highlighted below.

The *drum screen* is often found to provide the best fish protection at sites with high debris loads. Comprehensive evaluation of large drum screen facilities has demonstrated nearly 100

[7] Between 1985 and 1989, a series of evaluation reports on the performance of diversion screens in use at irrigation and hydroelectric diversions in the Yakima River Basin, Washington, were jointly produced by the U.S. Department of Energy, Bonneville Power Administration, and Batelle PNW Laboratory. The reports evaluate flow characteristics of the screening facilities. A discussion of these sites is not included in OTA's report; however, they were used by resource agencies in developing screen criteria in the Northwest and therefore the reports deserve mention (244, 245, 246, 247, 248, 249, 250).

[8] The physical barrier screens discussed in this section are considered to be low-velocity screens, meaning that they can function at velocities (perpendicular to the screen) between 0.33 to 0.5 feet per second (59).

percent overall efficiency and survival (12). The drum rotates within a frame and is operated continuously for cleaning. Debris is carried over the drum and passed down a channel or into a bypass (175). Drum screens can be expensive to construct and install, but relatively economical to operate; however, application criteria are site specific. These screens have been proven to be reliable at sites in California and the Pacific Northwest (204). Relatively constant water levels in the forebay are necessary for operation, and maintenance and repairs to seals can be problematic and costly.

Simple fixed screens can be an economical method of preventing fish entry into water intakes at sites where suspended debris is minimal; however, costs are site specific. Though fixed panel screens can and have been built in areas with substantial debris, automatic screen cleaners are required. These screens have demonstrated greater than 95 percent overall efficiency and survival at sites in the Columbia River Basin (12). Several types of simple fixed screen are available. The stationary panel screen is a vertical or nearly vertical wall of mesh panels installed in a straight line or "V" configuration. Fish-tight seals are easily maintained around this fixed screen, and the design accommodates a range of flows and forebay water elevations (175).

Inclined plane screens are also stationary, but are tilted from the vertical to divert fish up or down in the water column to a bypass. A conceivable problem with this design is the potential for dewatering of the fish and debris bypass route if water levels should fall below either end of the tilted screen. Also, cleaning is a primary concern for both stationary panel and inclined plane screens (175). Manual brushing is usually required to keep surfaces debris-free. The design is practical for water intakes drawing up to 38 cubic meters per second (175,204); however, application depends more on the site than on the flow.

Submersible traveling screens (STSs) are expensive to construct and install, and subject to mechanical failures, although in some cases they have been considered by the U.S. Army Corps of Engineers to be the best available technology for diverting downstream migrating fish in the Columbia River Basin (204). STS configurations operate continuously during the four- to nine-month salmonid migration period in the Columbia River; they are capable of screening extremely large flows in confined intakes but do not screen the entire powerhouse flow (175,204). At hydropower facilities where the fish are concentrated in the upper levels of the water column, good recoveries have been achieved (65). However, intakes at projects in the Basin tend to be very deep (i.e., greater than 90 feet) and flows are high. Under these conditions, fish have been seen to try to move away from STSs, especially if they are deeper in the intake. Also, the potential for impingement is greater due to high through-screen flow velocities (175). These screens seem to work better for some species than others.

Vertical traveling screens were originally designed to exclude debris from water intakes but were found to be effective at guiding or lifting fish past turbine intakes. The screen may consist of a continuous belt of flexible screen mesh or separate framed screen panels (baskets). Vertical traveling screens are most effective for sites where the intake channel is relatively deep. If approach velocities are kept within the cruising speed of the target fish, impingement can be greatly reduced (175,204). However, traveling screens that lift fish are not recommended for fish that are easily injured, such as smolting salmonids.

Structural Guidance Devices

Fish passage devices designed with the goal of guiding fish by eliciting a response to specific hydraulic conditions are described below.

Angled Bar or Trash Racks and Louvers

Angled bar racks and louvers are used to direct juvenile fish toward bypasses and sluiceways at hydropower plants. These structural guidance systems are devices that do not physically exclude fish from intakes, but instead create hydraulic conditions in front of the structures. Theoretically, fish respond to this condition by moving along the turbulence toward a bypass system. The success of these systems is dependent on fish response to hydraulic conditions, which means their performance can be poor under changing hydraulic conditions and for different fishes of non-target sizes and species (12,65).

Angled bar and trash racks have become one of the most frequently prescribed fish protection systems for hydropower projects, particularly in the northeastern United States (59,243), to prevent turbine entrainment of down-migrating juvenile anadromous species (e.g., alosids and salmonids) (194,242). Most of the angled bar racks installed to date consist of a single bank of racks placed in front of the turbine intake at a 45-degree angle to flow. Although design can vary from site to site, most racks consist of 1-inch spaced metal bars with a maximum approach velocity of two feet per second (15,59).

The angled bar rack is set at an acute angle to flow and with more closely spaced bars than conventional trashracks. It can divert small downstream migrating fish, and larger fish cannot typically pass through the bars. However, the use of close-spaced bar racks creates the potential for impingement of fish. This is of greatest concern for species with weak swimming ability and/or compressed body shapes (59). Most of the angled bar racks have been installed at small hydropower projects, the majority of which have not been evaluated for their performance in effectively diverting fish.

Proper cleaning and maintenance of the bar and trash rack systems on a regular basis is a critical element of operational success. Racks can be equipped with mechanical cleaning systems or can be pulled out of the water for manual cleaning; trash booms can also be helpful in mitigating debris loading. The ideal trash boom is designed to carry debris past the fishway exit to the spillway or falls and out of the forebay area (15).

A louver system consists of an array of evenly spaced, vertical (hard plastic) slats aligned across a channel at a specified angle and leading to a bypass (59). The louver system, like the angled bar rack, attempts to take advantage of the fact that fish rely mainly on senses other than sight to guide them around obstacles. Theoretically, as fish approach louvers, the turbulence that is created by the system causes them to move laterally away from it toward a bypass (59).

Louvers have been installed at a small number of locations, but are not generally acceptable as a mitigation technology for protecting fish from turbine entrainment. If approach velocities do not exceed their swimming ability, fish generally assume a tail-first position and move parallel to the line of louvers guided by streamflow and hydraulics toward a bypass (204). However, louvers may be considered for sites with relatively high approach velocities, large uniform flow and relatively shallow depths (204), and for some sites with species requiring lesser levels of protection. Louver efficiency in fish diversion, although high for some species, is relatively low on average compared to true physical barriers.

Passage of Atlantic salmon smolts at the Vernon and Bellows Falls hydropower projects on the Connecticut River was evaluated during the spring outmigration in 1995. A newly designed angled louver system at the Vernon site, which was based on hydraulic modeling, is in place to guide fish to a primary bypass chute in the middle of the powerhouse. Smolts are spilled into the tailwater of the project. Preliminary data indicate that about half the smolts are being guided to the primary bypass, while the remainder are either sounding beneath the louvers and passing through the turbines, or going through the secondary bypass, or are never making it into the forebay due to downmigration behavior (94).

The system may not be as successful as hoped due to the fact that the actual hydraulic conditions in the forebay of the project are not consistent with the modeling. This is mainly a result of not replacing certain turbine units adjacent to the primary bypass. This decision, which was made based on economics, has led to a less than adequate flow regime in the forebay of the project. Data and evaluation have yet to be finalized.

Despite efforts to monitor performance at any of these hydropower sites on the Connecticut River, information regarding effects of the angled bar rack and louvers on the overall salmon population in the Connecticut River has yet to be generated. Though angled bar and trash racks are frequently used to prevent turbine entrainment, evaluations of performance and effectiveness are rare. As of the writing of this report, 36 trash racks have been installed at projects in the Northeast (U.S. Fish and Wildlife Service (FWS)–Region 5); however, few had been evaluated prior to the spring of 1995.[9]

Louvers operate most efficiently when they are designed for larger fish of a specific size (175). Tests of a louver system at the J.E. Skinner Fish Protective Facility in Tracey, California, showed good guidance for larger juveniles (i.e., greater than 70 percent) (100). However, this same system operated poorly under high debris conditions. Floating louver systems have shown excellent promise for protecting fish which migrate downstream near the water surface (204). However, excessive entrainment on louvers of smaller, weaker fish, including juveniles, has caused louvers to be rejected as a design concept at most new hydropower installations (190).

There is a great deal of variation in opinion regarding how well, or why, louvers work. A better understanding of fish behavior could lead to improved designs for these structural guidance devices. Currently, they are recommended for use by the FWS in the northeastern part of the country. They are not in use in the Pacific Northwest because they have not been found to provide a high enough degree of effectiveness. The degree of protection granted by a louver system is directly related to the target fish, the degree of protection being sought, the approach velocity, and the extent that debris is present or is a problem.

OTHER METHODS FOR PROVIDING DOWNSTREAM PASSAGE

Other methods for providing downstream fish passage include pumps, spilling, turbine passage, and transportation.

Pumps

The hydropower industry is currently examining the application of fish collection systems, or *pumps*, to collect and divert fish at intakes (220). There are air-lift, screw impeller, jet, and volute pumping systems. These pumps could be used to force fish into bypass pipes for downstream passage at hydropower projects. Pump size and speed, however, may affect fish survival (223).

Fish pumps are not widely used because they can lead to injury and de-scaling as a result of crowding in the bypass pipe and to disorientation once released back into the river environment, and do not allow the fish to move on their own (196). Historically, the conventional wisdom of the resource agencies is to use bypass methods which allow fish to move of their own volition. However, a major research effort spearheaded by the Bureau of Reclamation is underway at Red Bluff Diversion Dam on the Sacramento River. Tests are being done to evaluate the usefulness of pumps to pass juvenile salmonids. Both the Archimedes screw and the Hydrostal-Volute pumps are being tested for the effective and safe passage of fish.

Spilling

Spill flows, or water releases independent of power generation, are the simplest means of transporting juvenile fish past (over) a hydropower project and away from turbines (36). Increased spill to flush fish over a dam can be especially cost-effective when the downstream migration period of the target species is short, when migration occurs during high river flows,

[9] The trash rack at the Wadhams Project on the Boquet River in northeastern New York, in place to guide down-migrating Atlantic salmon smolts, has been evaluated. Others include Cabot Station and the Holyoke Canal Louver on the Connecticut River in Massachusetts, and the Pine Valley Project on the Souhegan River in New Hampshire (195).

or where spill flows are needed for other reasons (e.g., to increase dissolved oxygen levels to maintain minimal instream flows).

Care should be taken to ensure that spillway mortality does not exceed turbine passage mortality (36,243). Consideration of forebay flow patterns, location of spillway relative to turbine intake, and positive flow to attract fish to spillways are all features of effective spillway passage (175).

Spilling is a particularly controversial issue in the Columbia River Basin (see box 4-3). The U.S. Army Corps of Engineers (COE) maintains that spilling water to pass juvenile fish has been demonstrated to be the safest, most effective, and one of the lowest-mortality means of getting juvenile anadromous fish past hydropower projects in the Columbia River Basin. In addition, it is viewed as the only means of enhancing survival without additional flow augmentation or drawdown (229). However, spilling water to assist fish in downstream passage means lost revenue for the hydropower operator. The COE recognizes that spill has its own associated risks (231) and has modified some spillways and operations to reduce problems in the Columbia River Basin (49). Passing juvenile fish by spilling water can result in "gas bubble trauma," or cause pressure-induced injury. According to at least one study, juvenile anadromous fish that pass a hydropower project by means of spill have a significantly higher rate of survival (98 percent estimated) than do fish that pass through the turbines (85 percent estimated) (229). However, this 85 percent turbine survival is through low-head dams with Kaplan turbines; survival is much lower for high-head dams with Francis turbines (12).

Gas Bubble Trauma

As spill water plunges below the dam the hydrostatic pressure causes air, mostly nitrogen gas, to be entrained in the flows. The pressure at the bottom of the stilling basins forces the gases into solution, creating a supersaturated condition. The slack water and low flow velocities below the dam slow the escape of the gas back into the atmosphere (23).[10] When fish absorb this gas, bubbles can form in the bloodstream. This effect, coupled with the pressure changes experienced when fish plunge with the flow and then return to the surface, can cause traumatic effects and even death. This situation is referred to as *gas bubble trauma.*

Since the late 1960s, tests on exposure of adult salmonids to supersaturated water have been conducted to determine the effects of exposure. The impact that dissolved gas may have on fish at any given time cannot be simply determined from gas saturation measurements. Thus, monitoring of migrants for signs of gas bubble trauma is an important management tool for determining if dissolved gas levels are having an impact on populations (229).

In June of 1994 the National Marine Fisheries Service (NMFS) Northwest regional office convened a panel of experts to review the biological data concerning dissolved gas effects on fish. Their findings indicate that a dissolved gas level of 110 percent can protect fish on purely biological grounds, whereas levels above 110 percent have the potential to be damaging (231,234). COE policy calls for keeping gas supersaturation levels at less than 110 percent in the Columbia River Basin, the level set by Oregon and Washington State water quality standards (231). Some laboratory research indicates that total dissolved gas levels above 110 percent in shallow water increases mortality observed in laboratory animals. Yet, field responses may be very different, making it difficult to base in-river management criteria on laboratory results.[11] The NMFS Northwest office and the Intertribal Fish Commission, which represents tribes in the Columbia

[10] In the Columbia River Basin dams were built so that the reservoir of one project backs up on the tailwater of the next project upstream, exacerbating the supersaturation problem.

[11] For example, juveniles may dive to greater depths to avoid areas of high dissolved gas concentration.

BOX 4-3: Spilling to Facilitate Fish Passage: Debate Over the Effects on Juvenile Salmonids

Spilling water to pass downmigrating fish is being used as an alternative method for protecting juveniles and enhancing survival at mainstem dams in the Columbia River Basin.[a] Spilling would occur during high flow periods when juvenile salmonids are in the midst of their downstream migration. However, there is still debate over whether this method might do more harm than good.

A 1995 Spill and Risk Management report prepared for the Columbia River Basin notes that spill passage and associated damage caused by dissolved gases should not generate greater mortality than that caused by turbine passage. The report goes on to say that there is little doubt that increasing the total dissolved gas levels in laboratory studies results in increasing the levels of mortality observed in laboratory animals in shallow water. By the same token, the report recognizes that mortality levels experienced in the lab are in conflict with those that would be observed in the natural environment where fish can sound to a safer depth to avoid injury.

The incidence of Gas Bubble Trauma (GBT) has been observed in juvenile anadromous fish during periods of high flow and spill during the spring out-migration in the Columbia River Basin.[b] GBT occurs when gas bubbles or emboli develop in the circulatory systems and tissues of fishes as a result of supersaturated gaseous conditions in the tailrace waters of hydropower projects. GBT is considered a physical, not a pathological, response to an environmental condition (117). The occurrence of GBT has been shown to be dependent, in part, on water temperature, species, genetic composition, and physiological condition of fish, as well as proximity and length of exposure to the total gas pressure (3,117).

The data which have been collected in situ as well as in the laboratory are in conflict with some observations that have been made in the natural environment. Laboratory experiments have indicated that fish exhibit a high level of mortality when exposed to constant supersaturated conditions, but in contrast, observations made in the wild actually indicate that higher survival rates occur in populations migrating under higher spill/flow/TDG conditions. In some of the laboratory situations fish were held at a constant depth and exposed to a constant level of TDG. In the natural environment, fish would be sounding to different depths and therefore would probably exhibit a different response. As a result, the usefulness of these tests in the development of a spill management plan may be questionable.

The effect of supersaturated conditions on fish is dependent on the depths (i.e., spatial and temporal distribution) at which they swim and are present in the water column. Therefore, completing depth distribution studies would generate helpful information. According to scientists, each meter of depth affords adults a 10-percent reduction in adverse impacts of gas supersaturation. In addition, the length of time it takes for a fish to travel through a reach of the river, where nitrogen concentrations might be a concern, influences exposure to high levels of dissolved gas. This is the major factor in determining the impacts a high-level exposure might have on the fish (44a).

These concerns, and mounting political pressure, have led the federal and state governments to set standards for limits on the allowable levels of gas supersaturation in the tailraces of mainstem dams in the Columbia River Basin. Washington and Idaho have set water quality standards with maximum levels at 110 percent for the Columbia and Snake Rivers, while Oregon has adopted a 105-percent standard. Some have contested that these standards were set without adequate biological research and information regarding the effects of supersaturation on fish. In addition, there is concern over the lack of information regarding fish response to the combination of supersaturated conditions and reaction with other gases, varying water temperatures, exposure time, and swimming depth.[c] In general, a 110-percent standard is considered conservative because this level is typically observed, if not exceeded, in the Columbia River Basin with no discernible impacts on fish. Therefore, scientists and resource managers argue that the impacts that supersaturated conditions have on fish can only be determined by monitoring migrants for signs of trauma, and monitoring natural environmental conditions.

(continued)

BOX 4-3: Spilling to Facilitate Fish Passage:
Debate Over the Effects on Juvenile Salmonids (Cont'd.)

It is difficult to monitor the response of fish to supersaturated conditions because mortality may occur before any physical characteristics are evident. After death, the external signs of GBT (i.e., large body blisters) may disappear within 24 hours, leaving dissection the only option by which to make determinations regarding cause of mortality (52). However, swimming performance, physical growth, and blood chemistry can be adversely affected, leaving weaker fish more susceptible to predation, disease, and migration delay (47).

The National Biological Survey's research lab in the Columbia River Basin has instituted a Smolt Monitoring Program (SMP) to be implemented in 1995. The SMP will monitor biological parameters in both the tailwater and the reservoir of a number of dams on the Lower Snake and Lower- and Mid-Columbia. Ideally, data resulting from the SMP will give managers a sense of what the existing levels of supersaturation are so that an appropriate spill management plan can be developed.

Recently, a study of hatchery Chinook test fish (juvenile fall Chinook salmon) being in net-pens below Ice Harbor Dam on the Snake River resulted in mortality during a study of the effects of high quantities of dissolved nitrogen. While the exact cause of mortality was not known, an uncontrolled spill of heavy spring runoff was occurring at the dam and all the dead fish had signs of GBT.

Events such as these have kept the debate over spilling to facilitate passage of juvenile outmigrants at a premium. And despite all past studies, there is still great disagreement and many unanswered questions that remain regarding the level of dissolved gases that can be safely tolerated by juvenile salmonids.

[a]Juvenile salmon passed via spill as opposed to going through the turbines have a higher survival rate (98 percent) than those exposed to turbine passage (85 percent) (Scientific Rationale for Implementing a Summer Program to Increase Juvenile Salmonid Survival in the Snake and Columbia Rivers, by: Columbia Inter-Tribal Fish Commission, ID Dept. of F&G, OR Dept. of F&W, USFWS, WA Dept. F&W).

[b] Spilling has been implemented at mainstem COE dams since 1989 under 1989 MOA (protection of juveniles until functional bypasses are installed) and at Mid-Columbia PUD dams since 1983 under the Mid-Columbia FERC Proceedings. Studies have shown mortality from turbine passage to be 8 to 32 percent compared to 0 to 4 percent for spillway passage.

[c] Some research has indicated that swimming stamina is affected at concentrations of 110 percent, growth is affected at 105 to 115 percent, and blood chemistry is affected at 115 percent.

SOURCE: Office of Technology Assessment, 1995.

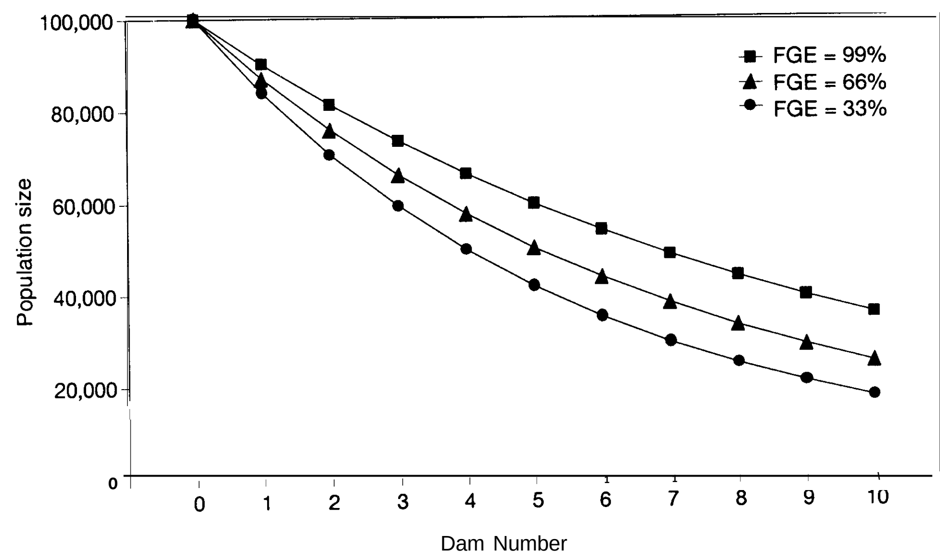
River Basin, recently recommended that spilling should be implemented on a broader scale to support juvenile downstream migration.

Turbine Passage

An explicit assumption behind the design of downstream bypass systems at hydropower facilities is that fish mortality associated with the bypass will be significantly less than turbine mortality (see figure 4-1; see chapter 2 for an in-depth discussion of turbine entrainment and mortality). This assumption is reasonable for many small-scale facilities, but is not always borne out at hydropower plants with large, efficient turbines (243). For example, studies at Bonneville Dam on the Columbia River indicate that subyearling Chinook salmon suffered more short-term mortality in screen/bypass systems than when passed through turbines, perhaps due to predation at outfalls (242). In a review of studies at 64 turbine installations, fish mortality ranged from zero to more than 50 percent (204). Turbine-induced fish mortality may be greatly overestimated or underestimated (206), and can vary considerably from site to site.

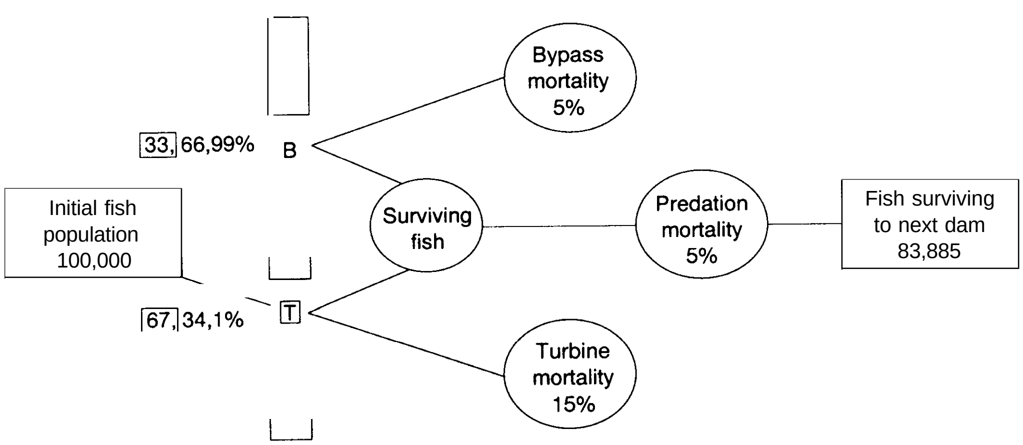
Turbine passage exposes outmigrating juveniles to blades, which can either de-scale or kill them, and distinct pressure changes, which can cause physical injury and/or death. Turbine mortality increases with fish size, suggesting that physical impact is also important (51,87). At the

FIGURE 4-1: Simulated Effects of Fish Guiding Efficiency (FGE) on a Group of Anadromous Fish Passing 10 Dams



Simulation Assumption: Initial population size = 100,000
Turbine Mortality = 15 percent
Bypass Mortality = 5 percent per dam
Predation Mortality = 5 percent per dam

Turbine mortality is only assessed to that part of the group that does not use the bypass. Bypass mortality is only assessed to that part of the group that uses the bypass. Predation mortality is assessed to all surviving individuals that pass through turbines and bypass.



SOURCE: Office of Technology Assessment, 1995.

edge of the turbine blade are areas of negative pressure that can be strong enough to pull molecules of metal from the turbine blades and likewise can cause damage to fish in the same vicinity.

Various turbine designs have been found to be linked to varying mortality rates for naturally and experimentally entrained fish.[12] Francis turbines are designed with "fixed" blades to accommodate a given head, flow, and speed. Kaplan turbines have "adjustable" blades which are better for low-head operations and seem to be better for fish survivability (i.e., are more "fish friendly"). To evaluate turbine mortality, fish must be tagged and released in the intake and then captured in the tailrace. The mark, release, and recapture technique has been found to be the most effective method of evaluating resultant turbine mortality for salmonid species; however, it has not been proven to be as useful for alosids (51) (see also chapter 2).

Operational factors can also affect turbine mortality rates. Running turbines at maximum overload during high power demands can result in higher losses of juveniles (23). In 1967, Milo Bell, a hydraulics engineer at the University of Washington, suggested that the best way to reduce mortality of smolts passing through the turbines was to operate the turbines at maximum efficiency. COE estimates that in most cases in the Columbia River Basin the expectation for turbine survival is 85 to 90 percent (230).

At Conowingo Dam (hydropower project) on the Susquehanna River, two old, damaged turbines were replaced with new Kaplan-type (mixed-flow) turbines.[13] This technology has been marked as more "fish friendly." The passage of American shad juveniles through the turbines was evaluated to determine survival rate. The new turbine design is based on a number of concepts: it allows for shallow intakes, and a smaller number of blades; it is capable of increasing dissolved oxygen in the tailwater; it has a wide flow range and is non-cavitating;[14] it also is greaseless and oil-free. These design considerations aim to increase survivability. Other factors are equally important to successful passage, such as where the fish exist in the turbine, what the blade strike range is, and what effect the pressure gradient that occurs in the vortexes between blades (gap flows) has on the juveniles. Principals in the turbine industry predict that technology is moving toward the use of these variable speed units.

Transportation

Transportation as a means of providing downstream passage of juvenile fish encompasses both trap and truck operations and barging. Transporting fish around hydropower facilities is used for a variety of reasons: to mitigate the loss of fish in long reservoirs behind dams; to avoid the impacts of nitrogen supersaturation that may be associated with spilling water; to decrease the possibility of turbine entrainment; and to help avoid predation problems associated with locating bypass entrances to downstream fish passageways and diversion systems.

The use of transportation to move juvenile salmonids downstream in the Columbia River Basin is to decrease the time it takes for outmigrants to move through the system.[15] However, transportation in the Basin is controversial. During high flow periods, the need for transport is diminished, while during low flows the need for

[12] Design changes to reduce turbine mortality include smoothing of conduit surfaces, increasing clearance spaces, decreasing speed of rotation of turbine blades, reducing the height of the turbine above the tailwater, increasing the depth of the entrance to the penstock, and decreasing turbine diameter (145).

[13] Entrainment survival increased from about 80 percent with the old turbines, to 95 to 98 percent with the new turbines. There are plans to replace the remaining turbines at some point in the future.

[14] Cavitation occurs when vapor masses collapse on or behind small localized areas of the turbine blade, creating intense negative pressure. This results in the loss of metal from the blade. This situation can result in injury to fish and/or oxygen depletion, nitrogen supersaturation, other physical stresses, and ultimately mortality.

[15] Trucking requires approximately six to eight hours and barging, from the Lower Granite Dam to below Bonneville Dam, about a day and a half (176).

transportation is favored, in part due to the length of time required for the juveniles to move through reservoirs (176). During high flows juveniles may be bypassed by spilling and may be able to pass relatively quickly through reservoirs. However, during times when flows range somewhere in the middle, the use of transportation becomes controversial.

In the Columbia River System, juvenile salmonids are screened from turbine intakes, then loaded onto trucks or barges. After being transported downstream, the fish are discharged below the lowest dam, thereby avoiding turbine entrainment and exposure to predators at intervening dams. However, juveniles may experience delay in their migration schedule as a result of transportation, depending on flow rates, points of collection, holding time, and points of release. Delay may have a negative impact on physiological development (i.e., smolting) critical to the survival of juvenile salmonids. Fish may also be exposed to diseases, stress, and disorientation. However, the effects of transportation on fish development and behavior are virtually unknown and little study has been done.

There is strong regional fish agency and tribal support for trap and truck operations to move juvenile fish in the Columbia River Basin, especially during low flow periods. Much work is needed to improve facilities and operations further to reduce stress and injury (7).

Barging juvenile fish downstream has drawn mixed reviews although it continues to be supported and promoted by the Army Corps of Engineers (230). More barges are scheduled for use during 1997 in the Columbia River Basin. Barging juveniles has generated support over the use of trucks by virtue of the fact that fish are left in the water when barges are utilized. However, some controversy remains.

In the Columbia River Basin the focus of the transportation effort is on increasing smolt survival and improving the numbers of returning adults in future years. Research results are not conclusive regarding the link between transportation and adult returns to spawning grounds (251). There is some evidence that transportation from rearing to release site does affect salmon homing, but the extent of the effect is dependent on the status of the salmon (smolt, hatchery resident, or in-river migrant), the method of transportation, and the physical distance between rearing and release sites (251). However, it has been shown that salmon trucked long distances do tend to return to their release site (i.e., below lowest obstruction on the river), as opposed to their rearing site (251). Juvenile salmon learn the odors of their home stream, or hatchery, prior to seaward migration and this olfactory memory is essential for the freshwater stages of homing (98). Salmon transplanted prior to smolt stage tend to return to their release site, not their natal (i.e., native) site. Smolts are more likely to return to the reach of river where they were released (251). Homing patterns may differ depending on whether fish are transported by truck or barge.

The COE supports the transportation of fish in the Columbia River Basin. However, due to the lifecycle of salmonids, the length of time spent at sea, and the various obstacles to survival any given fish encounters, it is difficult to pinpoint cause and effect relationships between the impacts of either of these methods on population. Although the desirability of transport is controversial, there is some agreement that barges are preferable to trucks; that the release site should not be an estuarine or marine one, but the river itself; and that fish should be captured after some period of migration rather than transported from the point of origin; and finally, transportation should be regarded as experimental (251).

EVOLVING DOWNSTREAM PASSAGE TECHNOLOGIES

A number of methods for providing downstream fish passage are currently under development or being experimented with.

■ Advanced Hydropower Turbine System (AHTS)

The heritage of current hydropower turbine designs dates from the late 19th and early 20th centuries, when little was known about environmental conditions and requirements. DOE has taken a new look at the "turbine system" in an effort to identify innovative solutions to problems associated with the operation of turbines at hydropower projects. DOE and the hydropower industry have co-funded the AHTS program. DOE has the lead role in developing and implementing the program (26). The hydropower industry created a non-profit organization, the Hydropower Research Foundation, Inc. (HRFI), which includes 10 utilities that have contributed funds for the conceptual design phase. HRFI will represent and administer industry funds for the program. Steering and technical committees consisting of representatives for industry, utilities, and other federal agencies are in place to provide program direction and technical evaluations.

The purpose of the program is to stimulate and challenge the hydropower industry to design, develop, build, and test one or more environmentally friendly advanced turbine(s). This would involve the development of new concepts, application of cutting-edge technology, and exploration of innovative solutions (26). Also, the AHTS program will function to develop, conduct, and coordinate research and development with industry and other federal agencies in order to improve the technical, societal, and environmental benefits of hydropower.

The first phase involves conceptual engineering designs submitted by the industry to a technical review committee. The second phase involves building and testing fully engineered models of the most promising designs. The third phase will consist of building and testing prototypes of the most promising models in actual operating hydropower plants. Each phase will be independent of the others and will follow in succession as the previous phase is completed. The program will be subject to ongoing evaluation by HRFI and DOE.

The AHTS Program completed Phase I during 1995. Two firms, Voith Hydro, Inc., and Alden Research Laboratory, Inc., have been selected for negotiations toward possible contracts. Phase II is scheduled to be initiated in the latter part of 1995.

The U.S. Army Corps of Engineers (COE) is also working to develop an advanced turbine design that would be more "fish-friendly" by determining the mechanisms which affected fish survival. Like the DOE effort, the COE is attempting to come up with new turbine designs to increase survival of downstream migrants (34). The COE program is more oriented toward relatively minor modifications of existing turbines in the Columbia River Basin; the DOE program is focused on developing new designs that would be applicable across the United States.

Eicher Screen

The Eicher Screen was developed in the late 1970s by biologist George Eicher in an effort to develop a better means of bypassing fish safely around a turbine. The elliptical screen design fits inside the penstock at an angle and can function in flow velocities up to 8 feet per second (fps) (262).[16] Non-penstock designs are also possible (54). The screen's ability to function at relatively high velocities is what distinguishes it from conventional screens, which tend to operate at channel velocities of about 1-2 fps (262).

Eicher Screens are relatively less expensive and have smaller space requirements than most barrier screens (175). The system is about 50 percent cheaper to install than conventional, low-velocity screening systems, and involves a screened area about one-tenth that of conventional systems. The other benefits of employing this screen are that it takes up no space in the forebay area, has low operating costs, no risk of icing, and is not dependent on forebay water levels. In addition, because the screen operates at high velocities, there is less chance that it will harbor predators (262)

The approach velocity into the screen violates most state and federal screening criteria. EPRI

[16] Both the Eicher Screen and the modular inclined screen are considered to be high-velocity screens. This type of screen is supposed to function (i.e., safely pass fish) at 8 to 10 feet per second or up to 3 feet per second perpendicular to the screen (59).

supported the University of Washington test of the screen's efficiency. The studies were performed under the assumption that the swimming ability and stamina of the fish were inconsequential to the functionality of the screen.[17] Tests performed in the laboratory as well as in two prototypes in the field have produced data to support this assumption. Prototype testing has been performed at two hydroprojects, the Elwha Hydropower Project near Port Angeles, Washington, and the Puntledge Project at B.C. Hydro on Vancouver Island.

EPRI tested a refined screen design at the Elwha Project with promising results. The Elwha tests evaluated screen performance under a range of velocity conditions. EPRI's tests used hatchery-raised smolts which were marked and then released into the forebay. After traveling into the penstock and being guided by the screen, the fish were bypassed to a collection tank where they were measured, counted, and classified by amount of de-scaling or injury they had suffered. According to EPRI, the screen had nearly perfect diversion efficiency (99 percent) for some species and life stages, indicating its potential for protecting downstream migrating fish (263).

Diversion efficiency was lower and mortality higher for fry of some species and the statistical validity of this non-peer reviewed study has been questioned (12). If the screen can pass different sizes and species of fish it could have wide application in the hydropower industry. Additionally, EPRI funded a series of hydraulic model tests during 1992 to evaluate the applicability of hydraulic data from Elwha to other sites and to evaluate potential for further improvement of the flow distribution via porosity control. To complete these tests, a model of the intake, penstock, and Eicher Screen was constructed at Alden Research Laboratory. The tests evaluated 1) the possibility that hydraulic conditions at Elwha were influenced by the bend in the penstock leading up to the screen; and 2) the potential for creating a more uniform velocity distribution over the length of the screen (263).

The hydraulic model studies indicated that the velocity distribution at Elwha was not significantly influenced by the upstream bend in the penstock (263). The other tests showed that passage survival rates exceeding 95 percent can be achieved for fish in the 1.5 to 2.0 inch range at velocities up to 7 fps, while smaller fish can be protected using lower design velocities and closer bar spacing (263). At the Puntledge, British Columbia project, evaluations indicate 99.2 percent successful guidance of coho yearlings through the new Eicher Screen (211).

In general, the Eicher Screen has multiple positive operating characteristics. For instance, it is biologically effective for target fish; the total costs of installation are usually less than for other types of screen; it is unaffected by changes in the forebay elevations; it takes up no critical space; operation and maintenance costs are negligible; the relatively high velocities at which it can be used make it adaptable to almost all penstock situations (53).

Research and evaluation of the Eicher Screen has led to approval at specific sites from agency personnel who were not otherwise convinced in the early stages. Agency approval of use at other sites will depend on documentation that the design performs well for target fish at velocities present at the site.

Modular Inclined Screen (MIS)

EPRI has developed and completed a biological (laboratory) evaluation of a type of high velocity fish diversion screen known as the Modular Inclined Screen (MIS). This screen is designed to operate at any type of water intake with water velocities up to 10 fps (221). The MIS consists of an entrance with trash rack, stop log slots, an inclined wedgewire screen set at a 10- to 20-

[17] These criteria are not applicable to this type of pressure screen, because the relative flat slope coupled with the high transportation velocity over the smooth surface funneling into the bypass means that the fish are involuntarily swept into the bypass seconds after passing over the screen (53).

degree angle to flow, and a bypass for directing diverted fish to a transport pipe.

This modular screening device is intended to provide flexibility of application at any type of water intake and under any type of flow conditions (221). Installation of multiple units at a specific site should provide fish protection at any flow rate (220) Currently, no fish protection technology has proven to be highly effective at all types of water intakes, for all species, and at all times (i.e., seasonal variability (65)).

To determine viability of the MIS, a testing program to evaluate biological effectiveness was undertaken by EPRI at the Alden Research Laboratory (ARL) in Holden, Massachusetts. Evaluations at ARL have focused on the design configuration which yields the best hydraulic conditions for safe passage and shows biologic effectiveness for diverting selected species to the bypass (58).

Mark, release, and recapture tests were undertaken with 11 species including walleye, trout, alosid, and salmon smolts. These species were chosen because they are representative of those fish that are of greatest concern at water intakes across the country, based on a review of turbine entrainment and mortality studies that have been conducted in recent years (62). The tests were conducted with two screen conditions: clean screen (i.e., no debris) and incremental levels of debris accumulation. Three replicates were conducted at each of the five test velocities and control groups were used to determine mortality and injury associated with testing procedures. Control fish were released directly into the net pen and recovered simultaneously with the test fish.

To assess effectiveness, four passage parameters were calculated for each combination of species, module water velocity, and test condition (i.e., clean screen and debris accumulation) that was tested. Success was measured by determining percent of fish diverted live, adjusted latent mortality, adjusted injury rate, and net passage survival (221).

According to the 1992 EPRI report, the results of the tests "clearly demonstrate that the MIS has excellent potential to effectively and safely divert a wide range of fish species at water intakes." The results showed that nearly 100 percent of the test fish were diverted live and that the adjusted latent mortality was less than 1 percent, although this was variable depending on species and velocity (58). Fish were safely diverted over a range of velocities (e.g., 2 to 10 fps) with minimal impingement, injury, and latent mortality; and debris accumulation did not appear to affect fish passage up to certain levels of debris-induced head loss (221). Also, EPRI noted that it was possible that the testing procedures (i.e., transport, marking, fin clipping, netting from pen or bypass) may have contributed to the observed mortality.

ARL has developed a prototype of the MIS which will be field evaluated in the spillway sluicegate at Niagara Mohawk's Green Island facility on the Hudson River in September of 1995. The prototype MIS test is important in the development and acceptance of the technology. However, resource agencies will be unlikely to approve full-scale applications of the MIS without additional testing (12). Resource agencies are particularly troubled by operational aspects of high-velocity turbine screening. These screens only collect fish when water is flowing over them. Hydropower operational changes may be necessary to ensure adequate flow to the screens, especially during periods when many hydropower projects are filling reservoirs and not producing much power (12).

Hydrocombine

A hydrocombine design of a hydropower facility is one where the spillway is situated over the turbine intakes. This design was employed at Douglas County PUD's Wells Dam (hydropower project) on the Columbia River as a result of the wide success of ice and trash (debris) sluiceways in passing juvenile fish. Evaluations of the hydrocombine design showed that it too was effective in providing passage for juvenile salmonids. As a result, Wells Dam became the model for research on the "attraction flow" or "surface collection" concept of downstream fish passage and sparked investigation into the potential for use elsewhere.

The theory was that this combination system could improve salmon survival by taking advantage of natural behavior and accommodating the majority of juveniles that moved downstream in the upper portion of the water column. Providing a means of passage over a surface-level spillway as opposed to forcing juvenile fish to dive to turbine intakes is more in line with natural behavior of outmigrating juveniles. A bypass with vertical slot barrier is placed in the spill intakes, which creates an attraction flow for outmigrating juveniles. Once the fish are entrained in the flow, they enter the bypass and are diverted past the dam instead of passing through the turbines (242). The hydrocombine was shown to produce a 90 percent success rate for juvenile fish passing through the Wells project (42).

The success of such a system might decrease the need for spilling, as well as the possibility of electricity rate increases. However, the results at Wells Dam were not easily explained. As is the case for many evolving fish passage technologies, there is often a lack of information regarding *why* they work. As a result, a prototype was installed at Chelan County PUD's Rocky Reach Dam and Grant County's Wanapum Dam. The configurations of the Wells, Rocky Reach, and Wanapum projects are significantly different; however, the surface collection concept is the same. Results are not yet available on either of these evaluations, but this research has sparked the development of the COE's Surface Collection Program.

Surface Collector

Surface-oriented bypasses could prove to be effective in improving juvenile salmon survival in the Columbia River Basin (232).[18] There is a major effort underway in the Pacific Northwest spearheaded by the COE to develop a surface collector design (39,77). The thrust of the research is to better understand the biological and physical principles that are at work at the Wells Dam, where a hydrocombine design is in use, and apply them to the surface collector design to provide a safer means of passage for juveniles. This "attraction flow" concept may provide downstream-migrating juveniles with an alternate, more passive route through hydropower facilities than is possible with other methods (42).

Surface collector prototypes are being evaluated at The Dalles and Ice Harbor Dams by the Portland and Walla Walla Districts of the COE, respectively. Various configurations of the design are being tested. The attraction flow prototype consists of a 12-foot-wide by 60-foot-high steel channel attached to the forebay face of the powerhouse (42) perpendicular to flow in the forebay. The goal is to guide fish hydraulically directly into the collectors, and then pump them to a bypass which moves them around the dam.

Hydroacoustics will be used to monitor fish movement and behavior in and near the collector. An adaptation of the new surface collector design is in operation at Bangor Hydro's West Enfield project on the Penobscot River and Ellsworth project on the Union River, although debris blockage has been a problem at both sites. The results of the 1995 testing at Wanapum Dam could potentially add much to what is known about downstream fish passage and design at hydropower facilities. Also, results of the prototype tests would hopefully be transferable to other powerhouses at projects on the Columbia and Snake Rivers (42).

Barrier Nets

Most technologies proven to be effective in downstream mitigation at hydropower intakes rely on large screening structures designed to provide a very low approach velocity. For many projects, such technologies are not financially feasible. For others, screens are inappropriate for other reasons. In these cases, the use of barrier nets may provide a cost-effective means of protecting fish from entrainment. In general, barrier nets have not been utilized in situations where

[18] For a more indepth discussion of the surface collector see appendix A.

both downstream passage and protection from entrainment are desirable.

Barrier nets of nylon mesh can provide fish protection at various types of water intake, including hydropower facilities and pumped storage projects. Nets generally provide protection at a tenth the cost of most alternatives; however, they are not suitable for many sites. Their success in excluding fish from water intakes depends on local hydraulic conditions, fish size and the type of mesh used. Barrier nets are not considered to be appropriate at sites where the concern is for entrainment of very small fish, where passage is considered necessary, and/or where there are problems with keeping the net clear of ice and debris (213). It may not be practical to operate nets in winter due to icing and other maintenance problems. Thus nets may not offer entrainment protection in winter at some sites.

Nets tend to be most effective in areas with low approach velocities, minimal wave action and light debris loads. Biofouling can reduce performance, but manual brushing and special coatings can help alleviate this problem. An evaluation was underway during the spring of 1995 at the Northfield Pump Storage Project on the Connecticut River in Massachusetts. The study has yet to be completed. There have been problems with debris loading and net inversion when flow in the river is reversed due to pump-back at the project.

The Ludington Pumped Storage Plant, one of the world's largest pumped storage facilities, located on the eastern shore of Lake Michigan, has had a 13,000-foot-long barrier net installed around the intake since 1989. Barrier net effectiveness, described as the percentage of fish prohibited from entering the barrier net enclosure, was estimated at about 35 percent in 1989, but substantially increased to about 84 percent in 1994 after significant improvements were made (90). This seasonal barrier appears to be effective for target fish (90).

ALTERNATIVE BEHAVIORAL GUIDANCE DEVICES[19]

Behavioral guidance technologies include any of the various methods that employ sensory stimuli to elicit behaviors that will result in down-migrating fish avoiding, or moving away from, areas that potentially impair fish survival. In all cases, the purpose is to get fish to leave a particular area (e.g., a turbine intake) and move somewhere else. The nature of the response may be long-term swimming in response to a continuous stimulus where the fish has to move some distance (e.g., a sound that is detected for an extended period of time and from which the fish continues to swim), or it may be a "startle response" that gets a fish to turn away and then continue in a different direction without further stimulation. Any stimulus that produces a startle response or frightens a fish from a particular place (essentially exclusion) is not a suitable deterrent unless there is a component to the response that moves the fish in a specific direction that leads to safety as opposed to swimming away from the stimulus in a random direction (202).

Fishes, as well as other vertebrates, are capable of detecting a wide range of stimuli in the external environment (76). The modalities most often detected include sound, light, chemicals, temperature, and pressure. Some fishes can detect electric currents and possibly other stimuli that fall outside of human detection capabilities.

For the most part, behavioral barriers have not been approved of and accepted for use by the resource agencies because they have not been shown to achieve a high enough level of protection (220). In some cases, progress has been made in developing technologies that can guide fish, possibly at a lower cost than physical barriers. Some in the industry would like to see sub-

[19] This section is drawn largely from A.N. Popper, "Fish Sensory Responses: Prospects for Developing Behavioral Guidance Technologies," an unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, June 1995.

stantial investment in developing these technologies for use at sites where complete protection is not required, or as a means of improving the effectiveness of an existing physical protection device (220).

Behavior-based technologies are touted as being less expensive than physical screening devices and easier to install than more conventional methods. Another presumed benefit is that these technologies can be used with little disturbance to the physical plant or project operation. Lastly, developers of these technologies claim that although they have not yet achieved 100 percent effectiveness, they have shown that various behavioral methods do guide fish, and that guidance can be improved upon with research and experimental application.

Lights

Many species of fish have well-developed visual systems. Light has a high rate of transmission in water and is not masked by noise. At the same time, the usefulness of light depends upon the clarity of the water as well as upon the contrast between the artificial and ambient light.

The visual system of fishes is highly adapted to enable different species to see in environments that range from shallow waters of streams to great ocean depths (142). These adaptations include, for example, the shape of the lens, the distance between lens and the photoreceptor layer, the ability to adjust the eye to see objects at different distances ("accommodate"), and other aspects of the optics of the eye. As one example, diurnal fish living in shallow waters often have yellow corneas (and sometimes yellow lenses). This serves as an optical filter to screen out some of the shortwave light which is found in such waters, and which can scatter around the eye and decrease visual acuity. Special adaptations may also be found in the setup of the photoreceptors.

While most fish see reasonably well, problems with use of light include transmission characteristics being very dependent on water turbidity, and variable attenuation of different wavelengths. Also, the effectiveness of light is likely to vary between day and night when the ratio between the stimulus light (e.g., strobe) and background illumination (e.g., daylight) differs (152).

Two types of lighting are the most widely used in experiments—mercury and strobe. Of the two, experimental results suggest that strobe lights (pulsing light) are the more successful in affecting fish movements, although mercury illumination was useful in a number of instances (61,101,163), including attracting and holding blueback herring at the Richard B. Russell Dam to keep them from entering undesirable areas (165,178). At the same time, light may attract some species and repel others living in the same habitat (25,76).

One of the earliest studies on use of lights (sealed beams) was by Brett and MacKinnon who provided data on a limited number of animals moving down a canal away from a light source (25). The fish were restrained in a particular region of the canal with nets. The results were not extensive, but two findings are of interest. First, some species swam away from the light while others did not, suggesting different behaviors by different species. Second, flashing lights were more effective at eliciting a response than continuous light, a harbinger for the use of strobe lights. Response differences to the same light source between species have been documented by others and are not surprising. These differences raise the issue, germane to all stimuli and not just light, that the stimulus has to be closely fit to the species being studied.

Strobe light has been extensively evaluated as a fish deterrent in both laboratory and field situations (59). Deterrence has been shown with a number of species, but the lights have worked most extensively and effectively with American shad juveniles (220). Successful fish deterrence with strobe lights has often been site specific, which indicates that hydraulic and environmental conditions and project design and operation have influence on the effect the lights have on species (59). The lack of conclusive results may also be attributed to inadequate sampling methodology and design.

Field tests conducted at the York Haven project on the Susquehanna River demonstrated a strong avoidance response to strobe lights by juvenile American shad (62,63). The system was designed to repel fish away from the turbine intakes and through the sluiceway. The system proved to be effective (94 percent). However, the study pointed out the need for establishing relationships between behavioral fish bypass systems and site-specific hydraulics in an effort to maximize bypass efficiency (59). Hydraulic and environmental factors had primary influence over the occurrence, distribution, and behavior of shad (152). The influence of these factors has definite bearing on the success of the system. As a result, it was concluded that the proper combination of physical and hydraulic conditions must exist in the area of the lights and the bypass system in order to achieve the desired level of effectiveness (152). Additional work is underway to verify response of various species.

The use of mercury lights to attract or repel various species including salmonids and clupeids is reviewed by EPRI (57). The results suggest that such illumination can be used with a number of species to move fish away from intakes, although the results are quite variable between sites and species. Such illumination may be more effective at night than during the day (not an unreasonable situation considering the contrast between the stimulus and ambient illumination differs greatly at night). Incandescent illumination has been tried as a method to modify behavior (57), but with no clear success.

Studies conducted at the York Haven project on the Susquehanna River indicate that mercury lights can be highly effective in attracting gizzard shad, and several studies have successfully improved bypass rates of salmonid species using mercury or incandescent lighting (57). The relatively inexpensive nature of mercury lights is a driving force of research. However, additional research is necessary to determine the feasibility of using sound as part of a directional bypass system (57).

Acoustics (Sound)

Sound has many characteristics that make it suitable for use in the possible modification of fish movement, especially over longer distances or when visibility is marginal. Sound travels at a high rate of speed in water, attenuates slowly, is highly directional, and is not impeded by low light levels or water turbidity (201). Moreover, many species of fish are able to detect sounds (69). From the standpoint of directionality, attenuation characteristics (especially with depth), the lack of effect of turbidity, and suitability during the day and night, other potential signals are not as versatile as sound. At the same time, high noise levels, such as at turbine intakes, may prevent fish from hearing artificially generated sounds in such environments, while high-intensity sounds (produced by any source) might have deleterious effects on fish.

Many fish species are known to use sound as part of their behavioral repertoire for intra-specific communication. Sounds produced by fish for communication are generally low-frequency (usually below 500 Hz) and broad-band (159,181). More recently, it has become apparent that fish are also likely to use sound to get a general "sense" of their environment, much as do humans. These sounds may include those produced by surf, water moving against objects in the environment, or wind action on the surface of the water (207). In addition, there is some evidence that fishes may respond to sounds that are produced in association with human-made structures, such as bypass screens and other signals produced as a byproduct of hydropower projects (6,164), although little is known about the actual behavioral responses to these sounds.

It is important to understand that detection of vibrational signals (which includes sounds) by fishes involves two sensory systems, the ear and the lateral line. Together, these are often referred to as the octavolateralis system (182). Both systems use similar sensory hair cells as the transducing structure for signal detection and both respond to similar types of signals. However, from the perspective of modifying the behavior of fish with sound, it is probably unimportant which sensory system per se is involved with the response; however, the distance over which stimuli can affect each sensory system differs.

A variety of different studies have been conducted using sound in attempts to affect movement patterns of fish. For the most part, these studies have concentrated on various species of salmonids and clupeids, although work has been done with regard to a variety of other species. The range of techniques used has also varied quite widely, as have the sound sources and the frequencies employed. Results are also quite variable and range from totally unsuccessful in controlling behavior to demonstrating potential usefulness for a few species under certain conditions.

Various species of clupeids (herrings and their relatives) have been studied by a number of investigators. A major thrust of this work has been to modify the swimming behavior of alewives and American shad so that they are kept from entering turbine intakes at dams. Some investigations have proven unsuccessful, while others have achieved some success.

The most compelling studies to date on clupeids in the United States involve the use of ultrasound to modify the swimming behavior of American shad and other species at a variety of sites. These transducers produce high-frequency (approximately 120 kHz) signals that appear to produce an avoidance response in juvenile American shad, causing them to move away from the sound source. Field studies have demonstrated that the effectiveness of sound can be altered by environmental conditions such as water temperature or site hydrology. Moreover, sound may be more effective at certain times in the life cycle of clupeids than at other times, and at certain times of the day or night, possibly depending upon the particular species being studied.[20]

Early studies on controlling the migration of salmonids with sound across a range of frequencies generated mixed and somewhat unclear results (33,156,254). One study showed that animals in a lab setting would respond to certain wavelengths, but there was no apparent response in a river (254). In another study, attempting to guide trout into a channel using plates set into vibration at 270 Hz, there was some evidence of success. However, there was no statistical analysis, and the limited amount of data does not suggest that results were replicated or that other compounding factors were taken into consideration (254).

Hawkins and Johnstone found that Atlantic salmon would respond to sounds from 32 to 270 Hz with best sensitivity from about 100 to 200 Hz (99).[21] More recently, studies on Atlantic salmon by Knudsen et al. (128) support the findings of Hawkins and Johnstone (99) that this species only detects very low-frequency sounds. Using a behavioral paradigm, Knudsen and his colleagues (126,128) measured the responses of salmon to tones from 5-150 Hz. The best responses were in the 5-10 Hz range. They also determined that the juvenile salmon would show an avoidance response (in a pool of water) to 10 Hz signals but not to 150 Hz signals, although avoidance to the 10 Hz signal would only occur if the fish were within 2 m of the sound source.[22,23]

Knudsen et al. tested this hypothesis and demonstrated that low-frequency sounds could be used to modify salmonid movements in a field

[20] Blaxter and Batty (1987) show that the responses to sounds of clupeids changes in the light and in the dark (22).

[21] Hawkins and Johnstone (1978) trained fish using classical conditioning so that they would show a decrease in heart rate whenever a sound was presented (99).

[22] Unconditioned startle responses were also investigated by Stober (217) on the cutthroat trout (*Salmo clarki*). Stober found that a number of specimens (but not all) would show an unconditioned startle response to sounds up to 443 Hz, although no response was found below 50 Hz. He also showed rapid habituation, as reported by Knudsen et al. (128).

[23] While exact distances are different from those reported by VanDerwalker (254), the order of magnitude of the distance from the source at which salmonids will respond to sound is the same. These results strongly support the suggestion that the response of salmonids to signals is when they are close to the sound source and very far into the acoustic nearfield.

experiment (126). They were successful in getting salmon to change direction and swim away from a sound source. The stimulus was only effective when the fish were within a few meters of the source (within the acoustic nearfield). For such a system to be fully effective in rivers or by a dam, a large number of projectors would be needed to insure that fish were properly ensonified.

A similar study reported effective, statistically significant guidance (80-100 percent diversion from the entrance to an intake canal for downmigrating steelhead trout smolts and Pacific Chinook salmon smolts) for a patented sound system now available from the Energy Engineering Services Company (EESCO). Natural sounds of various salmonids were recorded, and modified forms of the recorded sounds were played back to affect fish movements (141). Results suggested that the fish could be as much as 70 feet from the projector and the sound would still elicit a response. These results have yet to be replicated and the study only provided minimal information as to the nature of the specific sounds used to modify fish movements.

Results from preliminary tests of the EESCO system on the Sacramento River in 1993 were inconclusive (46,94a), largely due to the preliminary nature of the study and problems in experimental design. Studies are continuing at the Georgiana Slough on the Sacramento (171). The results of testing that took place during the spring of 1994 at Georgiana Slough were encouraging (50 percent overall) and statistically significant (95 percent level) (100).

Infrasound testing is currently underway within the Columbia River Basin as part of the Columbia River Acoustic Program.[24] Two types of sources are being tested, both of which generate infrasound. They differ in one component of the sound field they generate. The infrasound source, patterned after that used in Norway, is referred to as an "acoustic cannon" because it generates a sound field with large particle motion. The acoustic cannon has a 19-cm-diameter piston with a displacement of 4 cm (39). Startle followed by avoidance has been shown under controlled laboratory and field conditions for Chinook and steelhead juveniles and smolt. The other sound source, EESCO technology, generates a sound field with little particle motion. This source has a moving coil with a diameter of approximately 8 cm with a displacement of approximately 0.08 cm (39). The Acoustic Program has not conducted nor do they know of any controlled laboratory behavioral tests of fish response to the EESCO technology source. Experience to date indicates that large particle motion is required to elicit avoidance responses by salmonids.

Few other fish groups have been tested in a systematic way to determine if they would avoid low-frequency sounds (69,181). There are, however, remarks in the literature regarding avoidance responses of a number of species, and lack of avoidance or any sort of responses by other species. The Empire State Energy Electric Research Corporation (ESEERCO) (65a) reported laboratory studies of behavioral responses to low frequencies by striped bass, white perch, Atlantic tomcod, golden shiner, and spottail shiner (51a, 201a, 201b). Despite some limitations, the studies demonstrate that white perch and striped bass would show an avoidance response to broad-band sounds of below 1,000 Hz at sound levels of 148 and 160 dB (re: 1 µPa) during the day, but they showed only a weak response at night to sounds as high as 191 dB (re: 1 µPa). The other species only showed a weak avoidance response during the day.

Considerable study and data are needed to elucidate the mechanisms through which certain fish receive sound. No matter what the actual stimulus, it is of considerable interest that sound can affect the behavior of certain species either by causing a startle response or actually causing

[24] Information on the Columbia River Acoustic Program taken from Tom Carlson, Pacific National Laboratory, comments to the Office of Technology Assessment, August 1995 (39).

fish to swim away from the source of the sound. It must be kept in mind that a startle response alone is not sufficient for controlling movement of a fish. Instead, whatever the stimulus, it must elicit sustained movement of the fish in a specific direction so the fish avoids the area of danger.

Electric Fields

There are several recent reports in the gray literature that describe the use of electric fields to guide fish behavior. To date, the results from these experiments are equivocal as to their success in controlling downstream migration of several different species (20,106).[25] A couple of significant points, however, arise from consideration of these studies. First, electric fields are potentially dangerous to other species that may enter the water in the area of electric field. Second, the electric fields are restricted to regions between electrodes. Thus, they are most effective in shallow streams and relatively narrow regions where sufficient field strength can be set up between opposing electrodes.[26]

In general, evidence supporting the effectiveness of electrical barriers at supporting the downstream passage of fish is not available (220). Effectiveness will vary depending on site-specific parameters and species/size-specific responses. Several problems have been identified with their application, including fish fatigue and the relationship between fish size and susceptibility to electrical fields (59).

A combination electric screen and infrasound system has been extensively tested by Simrad in Scotland over the last two years (39). It is novel in the sense that the electric portion of the behavioral barrier is used primarily to reinforce the response to infrasound by migrating salmonids. The infrasound sources used are large particle motion sources.

Bubble Curtains

Bubble barriers were used by Brett and MacKinnon in an attempt to guide fish, with no apparent success (25). Other researchers suggested that success with air bubbles may have been associated with the sound that they produce and not necessarily with the bubbles (107,131). Ruggles points out that air bubbles are effective for some saltwater species and possibly for some species in streams, but not in rivers. Patrick et al. report that air bubbles were effective in producing avoidance behavior in laboratory experiments with gizzard shad, alewife, and smelt (172). They also reported that avoidance increased when air bubbles were combined with strobes. However, these studies have apparently not been followed up with field experiments. Patrick et al. found that air bubbles were most effective when there was some illumination. They also pointed out that the basis for fish response was not known, but may have been visual or sound-associated, as suggested by Kuznetsov (131).

Air-bubble curtains have not proven to be effective in blocking or diverting fish in a variety of field applications, nor is there data available to indicate potential effectiveness (220). There are small-scale studies of water jet curtains in various field applications; however, mechanical and reliability questions have prevented further study. Hanging-chain curtains have shown some success in preventing fish passage under laboratory conditions. Lab results have not been duplicated in the field and research has ceased (220).

Hybrid Barriers

Some study has been done to evaluate the effectiveness of using behavioral barriers in various combinations to increase overall effectiveness, yet the results have been equivocal (220). Many of the field evaluations have been conducted for

[25] The results of testing done during the spring of 1995, of an electrical barrier, at RD 108 (Wilkens Slough) on the Sacramento River were inconclusive (100).

[26] There is literature from the manufacturer of electrical guidance systems, Smith-Root, Inc., that their devices can also be used to protect turbine intakes and in other environments than streams. However, this reviewer has seen no analysis, peer-reviewed or "gray" literature, that evaluates the success of these systems beyond those described in the cited references.

application at hydropower projects, including a test combining strobe lights and ultrasonics to guide down-migrating juvenile American shad at the York Haven Dam hydropower project on the Susquehanna River.

PERSPECTIVES ON TECHNOLOGIES

In an effort to minimize expenditures while still meeting protection goals, the hydropower industry is looking to implement low-cost fish protection. New behavioral guidance technologies may be less expensive than conventional fish protection methods (for downstream passage); however, the agencies approach application of behavioral technologies with caution and consider them to be "experimental." Therefore, the industry is reluctant to invest in these technologies for fear that they will simply have to replace them with more conventional technologies. This leads to frustration for the technology vendors.

Resource Agencies

National Marine Fisheries Service

The NMFS national office seeks a high level of effectiveness for new technologies before the agency will approve application in the field, and in some cases regional offices have released position statements regarding fishery protection and hydropower. These statements do not apply on a national level, but they do have the potential to be precedent-setting. The Northwest and Southwest offices have specific guidelines for developing, testing, and applying alternative fish protection technologies (see appendix B). NMFS regional offices in the Northwest and California strongly prefer physical barrier screens, which can completely exclude fish, for use at hydropower projects over other structural or behavioral guidance devices. In addition, the agency requires that experiments evaluating a new technology should parallel the development of a conventional (technology) solution.

NMFS maintains that it is critical to require technology developers and the hydropower industry to abide by this high standard in order to uphold the agency's primary charge to protect fish and because so many fish populations have reached a "crisis" status (257). It is this argument that forms the basis of NMFS support of the use of physical barrier screens for fish protection from turbine entrainment. The agency may be more comfortable with the use of these barriers because they physically block or physically divert fish, but also because the technologies have evolved over a fairly long period during which much was learned about how to optimize performance and make adjustments based on site criteria and biological considerations. In addition to NMFS's Southwest and Northwest regional offices, Washington State's Department of Fisheries and Wildlife and the California Department of Fish and Game have released statements regarding screening criteria for salmonids (237,238,239).

U.S. Fish and Wildlife Service

In the northeastern United States, FWS may be willing to consider the application of "experimental" devices as an interim or complementary measure, depending on the situation and the species. However, FWS has no formal policy or position statement regarding the acceptability of experimental fish passage technologies. The agency accepted the use of these technologies in certain limited circumstances, but these were site-specific decisions based on professional judgment, project specific characteristics, and the significance of the resource at risk (150).

Determinations are a reflection of expert opinion and best professional judgment about what might work best at a given site. The possibility of achieving 100 percent efficiency with a passage technology, or reducing entrainment to zero percent, is unlikely. However, given the status of an increasing number of threatened and endangered species, the agency may be willing to approve the application of a technology that fails to reach a 100 percent performance goal, but provides a good level of protection, in situations where the development of a physical barrier screen or structural guidance device may take years to achieve.

In the West, FWS is generally inactive on screening, but is involved to a degree in experimenting with alternative guidance devices. The agency has developed interim screen criteria for one species, and supports the use of technologies that provide the highest degree of protection possible for target fish at all intakes.

The agency prefers the use of physical barrier and structural guidance devices over alternative experimental guidance devices. However, there is some concern within the agency that constant pressure from vendors to utilize alternative devices has led to concession in certain cases. The agency is especially concerned that once an experimental measure is in place at a site it will remain as the long-term protection measure regardless of whether performance is less than what would be expected from a conventional technology. Many agencies view experimentation as a delaying tactic. Although experimentation can be very costly over time (possibly matching the cost of a conventional approach), yearly expenditures are often much lower than the capital outlay to install a conventional technology.

Hydropower Industry

The industry's goal is to provide effective fish protection and to minimize costs, which can be a challenge especially at large hydropower projects. The industry claims to be facing difficult economic times, which may be exacerbated by the possibility of deregulation. This mood has forced the industry to come out against expenditures for what they refer to as seemingly "unnecessary" items such as fish passage and protection mitigation technologies.

The possibility of deregulation has also caused the industry to reassess its role in the alternative energy market. NHA views hydropower to be the cleanest, most efficient, and most developed renewable energy source. As a result, some industry representatives balk at the federal research and development investment to advance and perpetuate other renewable energy sources (i.e., wind, geothermal, solar, etc.), as opposed to investing in the further improvement and efficiency of hydropower on a broad scale. The industry claims that it cannot afford to bear the costs associated with research and development of fish passage technologies and that this support should come from the federal government.

Technology Vendors

Vendors of new behavioral and guidance technologies are frustrated by the reluctance of resource agencies to approve their use despite what some consider convincing results in the field (27,50). Technology developers claim that these alternatives to conventional fish protection technologies will work for a fraction of the cost of conventional screening mechanisms. The agencies continue to question "how well" the technologies work, and NMFS requires that hydropower operators also pursue a parallel track with an accepted technology (e.g., design a physical barrier or other interim measure technology or method) while an alternative is being developed or tested at a site (174).

Though there is some discussion of allowing the use of behavioral technologies to enhance physical barriers or as interim protection devices, the agencies are unwilling to allow these technologies to be utilized as the sole line of defense in fish passage mitigation in the absence of scientifically rigorous demonstrations of effectiveness. This frustrates the vendors who argue that no such evaluation exists for physical barriers and that behavioral and alternative guidance devices are being held to a standard that other conventional technologies were not during previous years.

CONCLUSIONS

Physical structures, including barrier screens, angled bar racks, and louvers, that are designed to suit fish swimming ability and behavior, as well as site conditions, remain the primary downstream mitigation technologies at hydropower facilities. There is general consensus among practitioners that the conventional technologies effectively protect downmigrating fish. Barrier screens have an appeal in that they are perceived to be absolute in their operation. According to some resource agencies, under certain conditions they may be the only viable technology. However, the high costs associated with these technologies are often barriers to their use. As a result, much of the fish passage research presently being done is focused on further developing behavioral guidance devices. Some of this effort might be directed toward the installation of physical structures because the resource agencies have identified the need to provide protection *now* while research on behavioral and alternative guidance devices is taking place.

Extensive descriptions of downstream fish passage mitigation measures are available (16,59,65). Numerous and varied measures have been used to reduce turbine entrainment, including fixed and traveling screens, bar rack and louver arrays, spill flows, and barrier nets, and alternative behavioral devices. However no single fish protection system or device is universally effective, practical to install and operate, and widely acceptable to regulatory agencies (37).

With a few interesting exceptions, there is no behaviorally-based technology that is operationally successful in guiding fish. There is potential for use of strobe illumination with a number of species, as well as use of infrasound with salmonids (and possibly other species) and use of ultrasound with clupeids and cod. These investigations need to be continued and include both basic biology and investigation of field applications of these signals. Very little work is being done with electrical stimuli and bubble barriers, and these do not appear to have been broadly successful in earlier studies. There is some evidence (165,178) that combinations of sensory stimuli (e.g., light and sound) might be a productive possibility that needs further exploration.

There are major discrepancies in the views of resource agencies and technology vendors about the potential value and performance of alternative behavioral guidance devices. Part of the discrepancy in interpreting performance data has arisen from lack of a standard approach to testing and evaluation of the technologies. Vendors will work closely with clients and consultants but rarely involve the agencies in the early stages and the decisionmaking process. In addition, though some behavioral guidance devices have been shown to elicit an avoidance response in fish at certain sites, there are inconsistencies in subsequent years of testing. This type of result has caused the resource agencies to question the validity of the assumptions and criteria on which the studies, and the evaluation, are based. It is critical to keep in mind that results and methods developed for large western hydropower facilities may not be applicable to much smaller facilities in the Northeast and Midwest. At the same time, methods that do not work at the larger facility may be very useful and appropriate for much smaller facilities. In effect, it may be important to have research programs directed at different "classes" of sites—such as large hydropower projects, small hydropower projects, bypasses, etc.

Most of the research on fish exclusion systems has not been reported in the peer-reviewed scientific literature, but appears in progress reports for funded installations, and may be overly optimistic. Often research is not described in sufficient detail to allow thorough analysis of the results. Thus, it becomes difficult, if not impossible, to assess the effectiveness of many of the techniques described or the results reported. Some experimental results seem at odds with others, and care must be taken in interpreting this information (204). Conclusions reached should be viewed as tentative.

Many of the earlier studies are weak with regard to behavioral analysis. Methods of analyzing the behavioral responses of fish (e.g., methods of observation of fish in experimental pens) have often been poorly described. Also, inappropriate methods have been used in some cases. This has led some to believe that experimenters did not use appropriate observational techniques (e.g., "double-blind" experiments where the observers were unaware of the presence of a sound stimulus when reporting the behavior of a fish). Moreover, the applicability of techniques across species, or to the same species under different environmental or physical conditions (age and size), is not well understood. Researchers for the most part have failed to ask very basic questions about the general behavior of fishes under a variety of conditions and information which could be useful in developing bypass systems.

Statistical analyses of behavioral responses are often inadequate and thus it is hard to assess the effectiveness of a technique. An issue that often arises appears to be differences in ways that various investigators have used statistics to interpret data. What may appear to be a positive response in one statistical analysis may appear to be nonsignificant in another.

Additional studies, with very specific directions, are needed to advance behavioral guidance technologies. A key need is to develop a basic understanding of the mechanism(s) by which stimuli elicit responses. In particular, it is not known how very high-frequency sounds are detected by clupeids, and basic information to answer that (and other) questions could help markedly in the design of more suitable control systems. Knowledge of the mechanisms of signals detection, the normal behavioral responses to signals, and the range of signals to which a fish will respond are critically important in helping design appropriate control mechanisms.[27]

Even basic information on the general behavior of fish is often lacking. Thus, it becomes impossible to predict how a fish might alter its behavior when it encounters a hydropower facility or water bypass, how it might respond to various sensory stimuli (e.g., light or sound), including noxious stimuli, and whether certain sensory stimuli are within the reception capabilities of a particular species. Without such basic data it is very difficult to design a truly effective means for controlling fish behavior.

An interdisciplinary approach to investigating the potential for improving fish passage is needed. Studies should be designed with close collaboration between fisheries biologists having interest and expertise in the needs for fish passage and basic scientists knowledgeable in the behavior and sensory biology of fishes. Other important specialists would likely include hydraulic engineers and hydrologists, who would bring special knowledge of currents and other aspects of the problem to the discussion, and engineers involved in designing and maintaining barriers to fish movement. To date, there has been little interaction along these lines.

[27] An example of this is found in the work controlling the movement of Atlantic Salmon by Knudsen et al. (126,128). Their experimental design for their field work was clearly based upon their first studies on hearing capabilities (128), as well as the earlier studies of Hawkins and Johnstone (99).

The Federal Role in Fish Passage at Hydropower Facilities 5

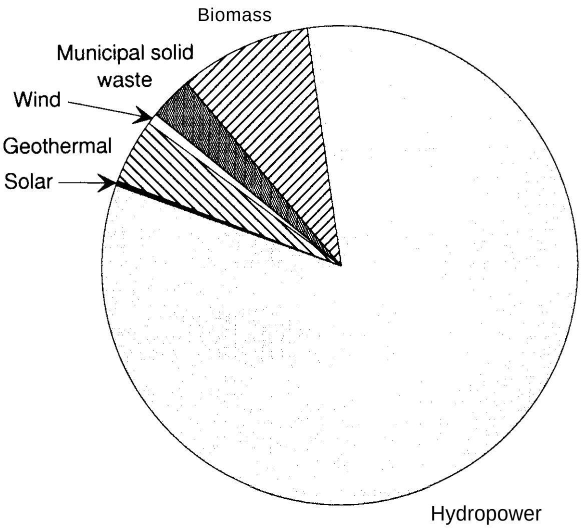
Hydroelectricity provides over 10 percent of the electricity in the United States and is by far the largest developed renewable energy resource in the nation (figure 5-1). At least 25 million Americans depend on hydropower for their electricity needs. Conventional hydropower plants total nearly 74,000 megawatts (MW) of capacity at roughly 2,400 plants. Pumped storage provides an additional 18,000 MW of capacity at about 40 plants. The undeveloped hydropower resource potential in this country is significant. The Federal Energy Regulatory Commission estimates that approximately 71,000 MW of conventional capacity remains undeveloped (81,82).

History has shown that hydropower development can, and generally does result in changes in the abundance and composition of migratory and riverine fish populations. Dams impede fish movements up and down rivers, delaying them, blocking them altogether and sometimes killing them directly (e.g., turbine mortality) or indirectly (e.g., predation at points of delay) (37). However, specific data on population changes attributable to hydropower development are difficult to come by and other factors also have had adverse impacts (e.g., habitat destruction, water pollution, over-harvest). To what degree each of these factors contributes to the overall decline of North American fisheries remains unclear.

This chapter examines the federal role in fish passage and protection at hydropower facilities (box 5-1). Federal involvement in managing nonfederal hydropower issues includes: licensing, monitoring, and enforcement; identifying mitigation plans for hydropower facilities; and conducting research on and development of fish protection technologies. The Federal Energy Regulatory Commission (FERC) is responsible for the licensing, monitoring, and enforcement of license conditions for nonfederal hydropower facilities. Explicit in FERC's authority is the responsibility for balancing the developmental and nondevelopmental values of hydropower development in the licensing process.

The National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (FWS), and, in certain cases, U.S. federal land management agencies prescribe mandatory fish passage conditions for inclusion in hydropower licenses. In addition, these agencies and state resource agencies also may make nonbinding recommendations for additional mitigation to promote fish protection.

FIGURE 5-1: Relative Contribution of Various Renewable Energy Sources



SOURCE: "Renewable Resources in the U.S. Electric Supply, " Table 4, February 1993,

Mitigation technologies to reduce the adverse effect of hydropower on the nation's fish resources exist and have been employed, although not uniformly, since the early part of this century. These techniques can be costly and their effectiveness is often poorly understood (242). Yet, in a review of 16 case studies, the majority demonstrated positive results stemming from technology implementation (242). The high cost of installing or retrofitting fish protection or passage facilities relative to the perceived benefit derived generates some tension between resource agencies and the hydropower industry. Yet, few studies have attempted to describe the full range of benefits and costs of fish passage mitigation over the long-term.[1]

LICENSING OF NONFEDERAL HYDROPOWER PLANTS

Federal licensing of nonfederal hydropower plants on navigable waterways is the responsibility of the Federal Energy Regulatory Commission (previously the Federal Power Commission (FPC) under the Federal Power Act of 1920).[2] In the 1930s, FPC's role was expanded to include rate regulation and other matters related to wholesale, interstate sales of electricity and natural gas (1935 FPA and 1938 Natural Gas Act). The 1977 Department of Energy Organization Act created the Federal Energy Regulatory Commission (FERC) and transferred FPC's energy jurisdiction to the agency as well as jurisdiction over oil pipeline transportation rates and practices. Today, FERC has exclusive authority to license nonfederal hydropower facilities on navigable waterways and federal lands (approximately 1,825 dams); regulate the electric utility and interstate natural gas pipeline industries at the wholesale level (including reviewing electric utility mergers and supervising/authorizing hydropower and gas pipeline construction); and regulate oil pipeline transportation (74).

The initial mandate of the agency was the regulation of energy production, distribution, and availability; and the promotion of hydropower, particularly for the Northeast and Northwest regions of the United States. Environmental concerns were largely addressed through a number of laws that were enacted to protect natural resources and the environment, including: the National Environmental Policy Act (NEPA), Fish and Wildlife Coordination Act, National Historic Preservation Act, Endangered Species Act, Federal Water Pollution Control Act (Clean Water Act), and the Wild and Scenic Rivers Act (box 5-2).

1 Hydroelectric licenses run from 30 to 50 years. Economic comparisions of the costs of installing or retrofitting facilities and the revenue flow from plant operation over the license period might clarify this debate, however, the information does not currently exist.

2 Under section 23(b) of the Federal Power Act, FERC has jurisdiction to license nonfederal hydroelectric projects that are on navigable U.S. waters; are on non-navigable U.S. waters over which Congress has "Commerce Clause" jurisdiction, were constructed after 1935, and affect interstate or foreign commerce; are on public lands or reservations; or use surplus water or water power from any federal dam (49).

BOX 5-1: Chapter Findings—Federal Role

- The Federal Energy Regulatory Commission (FERC) has exclusive authority to license nonfederal hydroelectric facilities on navigable waterways and federal lands, which includes conditioning of licenses to require operators' adoption of fish protection measures.
- Section 18 of the Federal Power Act (FPA) gives the federal resource agencies authority to prescribe mandatory fish passage conditions to be included in FERC license orders. Section 10(j) recommendations relate to additional mitigation for rehabilitating damages resulting from hydropower development or to address broader fish and wildlife needs (e.g., minimum flow requirements). Yet, these recommendations are subject to FERC approval.
- FERC's hydroelectric licensing process has been criticized as lengthy and can be costly for applicants and participating government agencies. In some cases, the cost of implementing fish protection mitigations from the utility perspective may render a project uneconomical.
- FERC uses benefit-cost analyses in its final hydroelectric licensing decisions; yet economic methods for valuing habitat and/or natural resources are not well established and many economists feel that they fit poorly in traditional benefit-cost analysis.
- There is no comprehensive system for monitoring and enforcing resource agency fish passage prescriptions. FERC's monitoring and enforcement authority has been used infrequently, and only recently, to fulfill its mandate to adequately and equitably protect, mitigate damages to, and enhance fish and wildlife (including related spawning grounds and habitat) affected by the development, operation, and management of hydroelectric projects.
- Parties must perceive a need to negotiate in the FERC hydropower licensing process, beyond the regulatory requirements of applicants and agencies, in order to achieve success. FERC must be seen as a neutral party to motivate participants to find mutually acceptable agreements in accommodating the need for power production and resource protection. If FERC is perceived to favor certain interests, the need to negotiate is diminished or eliminated.
- There are no clearly defined overall goals for North American fishery management and Congress has not clearly articulated goals for management of fishery resources and/or priorities for resource allocation.
- Fish protection and hydropower licensing issues return repeatedly to the congressional agenda. The 1920 FPA was designed to eliminate controversy between private hydropower developers and conservation groups opposed to unregulated use of the nation's waterways. Greater consideration of fisheries and other "nondevelopmental" values was called for in the Electric Consumers Protection Act of 1986 (ECPA) and oversight on these issues continued with the passage of the Energy Policy Act of 1992. In the 104th Congress, efforts continue to address power production (e.g., sale of PMA's; BPA debt restructuring) and developing sustainable fisheries (e.g., Magnuson Act amendments; Striped Bass Conservation Act).

SOURCE: Office of Technology Assessment, 1995.

In addition, section 18 of the FPA gave the Secretaries of Commerce and Interior authority to prescribe fishways at FERC-licensed hydropower projects. Section 4(e) allows federal land management agencies to issue mandatory conditions to protect the purposes for which their lands are held in trust. If the purposes of the lands include fish and wildlife, then section 4(e) may be used to issue mandatory fish protection conditions. Section 30 applies primarily to conduit exemptions: projects that use the hydroelectric potential of a conduit that is operated for the distribution of water for agricultural, municipal, or industrial consumption and not primarily hydropower. In these cases, FERC must include in the exemption the terms and conditions that NMFS, BOX 5-2: Environmental Laws Affecting the FERC Licensing Process

A number of laws beyond the FPA influence environmental protection in the FERC hydropower licensing process. These laws continue to affect the licensing process, although some of the intent contained in them has been reiterated and directly applied to FERC through ECPA.

- *National Environmental Policy Act*—requires preparation of an Environmental Assessment (EA) or an Environmental Impact Statement (EIS).
- *Fish and Wildlife Coordination Act*—requires FERC to give full consideration to the recommendations of the U.S. Fish and Wildlife Service (FWS), National Marine Fisheries Service (NMFS), and state resource agencies on the wildlife aspects of a project.
- *National Historic Preservation Act*—requires FERC to give the Advisory Council on Historic Preservation reasonable opportunity to comment on a license issuance involving an historic resource.
- *Endangered Species Act*—requires FERC to consult with FWS and NMFS to determine if action is likely to jeopardize the continued existence of any endangered or threatened species or adversely affect critical habitat.
- *Federal Water Pollution Control Act (Clean Water Act; CWA)*—requires applicants to confer with the "certifying agency" (U.S. Army Corps of Engineers (COE) or the Environmental Protection Agency (EPA)) and verify compliance with the CWA (National Pollutant Discharge Elimination System permit [NPDES], S401 water quality certificate, or S404 dredge and fill permit).
- *Wild and Scenic Rivers Act*—FERC is prohibited from licensing projects on or directly affecting a wild and scenic river as established by an act of Congress or State Legislatures.

SOURCE: Office of Technology Assessment, 1995.

FWS, and state resource agencies determine are appropriate to prevent loss or damage of the affected fish and wildlife resources. Under the broad scope of section 30 language, fish passage could be included, if appropriate. Sections 4(e), 18, and 30 have provided these specific authorities to protect fish and wildlife resources since the inception of the FPA in 1920 (123,150).

In 1986, Congress passed the Electric Consumers Protection Act (ECPA)(PL 99-495), a series of amendments to the FPA, which was designed to alter FERC's tendency to place power over fish in licensing decisions. The FPA, as amended by ECPA, establishes principles that guide FERC in the issuance of hydropower licenses. FERC is directed to give equal consideration[3] to the full range of purposes related to the potential value of a stream or river, to include: hydropower development; energy conservation; fish and wildlife resources, including spawning grounds and habitat; recreational opportunities; other aspects of environmental quality; irrigation; flood control; and water supply (1,74,123).

Although mandatory fish passage authority rested with the federal resource agencies since the early part of this century,[4] ECPA was instrumental in elevating the importance of nondevelopmental values in and increasing FERC's accountability for licensing decisions (1,240).

[3] *Equal consideration* does not mean treating all potential purposes equally or requiring that an equal amount of money be spent on each resource value, but it does mean that all values must be given the same level of reflection and thorough evaluation in determining that the project licensed is best adapted. In balancing developmental and nondevelopmental objectives, FERC will consider the relative value of the existing power generation, flood control, and other potential developmental objectives in relation to present and future needs for improved water quality, recreation, fish, wildlife, and other aspects of environmental quality (74).

[4] Since the early part of this century, the authority for issuing fishway prescriptions rested with the Department of Commerce and the Department of the Interior (DOI). Prior to the passage of the Federal Power Act in 1920, the Secretary of Commerce held primary responsibility for fish passage facilities at federally licensed projects (An Act to Regulate the Construction of Dams Across Navigable Waters, 1906) (P.L. 262). In 1939, DOI acquired concurrent authority. The Departments now share responsibility for developing fishway prescriptions (257).

Through the addition of section 10(j), federal and state resource agencies may recommend conditions to protect, enhance, or mitigate for damages to fish and wildlife resources under the FPA:

> Section 10(j) (U.S.C.§803(j)) stipulates that: in order to adequately and equitably protect, mitigate damages to, and enhance fish and wildlife (including related spawning grounds and habitat) affected by the development, operation, and management of the project, each license issued under this subchapter [16 U.S.C. §§ 792-828c] shall include conditions for such protection, mitigation, and enhancement....[S]uch conditions shall be based on recommendations received pursuant to the Fish and Wildlife Coordination Act (16 U.S.C. 661 et. seq.) from the National Marine Fisheries Service, the U.S. Fish and Wildlife Service, and State fish and wildlife agencies.
>
> Whenever the Commission believes that any recommendation referred to in paragraph (1) may be inconsistent with the purposes and requirements of this subchapter or other applicable law, the Commission and the agencies referred to in paragraph (1) shall attempt to resolve any such inconsistency, giving due weight to the recommendations, expertise, and statutory responsibilities of such agencies. If, after such attempt, the Commission does not adopt in whole or in part a recommendation of any such agency, the Commission shall publish each of the following findings (together with a statement of the basis for each of the findings): 1) a finding that adoption of such recommendation is inconsistent with the purposes and requirements of this Part or with other applicable provisions of the law, and 2) a finding that the conditions selected by the Commission comply with the requirements of paragraph (1).

The authority given to the resource agencies is a little more restricted than it may appear. Section 4(e), which allows federal land management agencies (e.g., Forest Service, Bureau of Land Management, etc.) to issue mandatory terms and conditions to protect the purposes for which their lands are held in trust, including fish passage where appropriate, applies to FERC-licensed hydropower plants on federal reservation lands.[5] Fish and wildlife recommendations made by federal and state resource agencies under section 10(j) are limited to those designed to protect, mitigate damages to, or enhance fish and wildlife, including related breeding or spawning grounds and habitats; but they are not mandatory.[6] FERC must meet with the pertinent agencies to discuss alternatives and new information or to demonstrate the recommendations' inconsistency with other applicable legislation in order to alter or decline section 10(j) recommendations. Nevertheless, this issue is at the core of one of the larger "balancing" debates. Section 18 fishway prescriptions developed by the federal resource agencies are mandatory, although of narrower scope than recommendations allowed under section 10(j).

FERC is not primarily an environmental agency, yet has the ability to enforce environmental requirements through conditioning authority, power to investigate, and penalty and revocation authority (43). FERC can specify conditions for a license approval, such as minimum flow, fishway requirements, etc. Once the conditioned license is accepted, the conditions become enforceable by FERC. Indeed, FERC is able to exact civil penalties of up to $10,000 per day in enforcement. In one case, a hydropower licensee that was found to have violated "run of the river" and minimum stream flow requirements was assessed a $19,000 civil penalty (43). Revocation authority—whereby the agency can halt a project found in non-compliance—is another important FERC enforcement tool. Yet, revocation also faces great constraints to use since it may not result in correcting the damage. In one such instance where revocation might have been

[5] Federal reservation lands include national forests, wilderness areas, Indian reservations, and other federal public lands reserved for specific purposes and withdrawn from private disposition.

[6] Additional recommendations related to broad-reaching efforts such as rehabilitation of damages, habitat, management considerations, and general enhancements for fish and wildife populations may be made under section 10(a); also subject to FERC approval.

employed, FERC chose not to revoke the license, but to examine possibilities for mitigation requirements and penalties instead (43).

Hydropower Licensing Procedure

The licensing (or re-licensing) procedure is a seven-step process occurring in three stages and culminating in a licensing decision (box 5-3) (74). Prospective licensees must notify FERC of the intent to relicense as early as five and a half years, but no later than five years, prior to license expiration. The application must be filed with FERC at least two years prior to expiration. Prior to application filing, prospective licensees must confer with the appropriate resource agencies. Pre-filing consultation stages include:

Stage 1: The applicant must provide the agencies with basic information about the project and any proposed changes. The agencies respond with recommendations for studies.

Stage 2: The applicant completes all reasonable and necessary studies, obtains all reasonable and necessary information required by resource agencies, and prepares the draft application.

Stage 3: The applicant provides the agencies with a copy of the application, including agency correspondence regarding the project, and copies of relevant certifications (e.g., section 401 CWA permit).

FERC staff conduct the environmental analysis required for the project by the National Environmental Protection Act and produce an Environmental Assessment or an Environmental Impact Statement, as appropriate. Finally, the Director of the Office of Hydropower Licensing (by delegated authority) or the Commission determines whether or not to issue the license and includes the conditions recommended by the agencies and found consistent by FERC, as well as conditions recommended by FERC staff in the environmental analysis.

A large number of FERC licenses have recently expired and many more are due for renewal by the year 2010. This situation provides a significant opportunity to consider the adequacy of fish passage at these sites. As of July 1995, FERC had relicensed 65 of the 167 projects in the "class of 1993." An additional 97 facilities will need relicensing between now and the year 2010 (49).

The Federal Resource Agencies

The Department of Commerce, acting through the National Marine Fisheries Service (NMFS), and the Department of the Interior, acting through the Fish and Wildlife Service (FWS), are the federal agencies primarily responsible for the conservation and management of the nation's fish and wildlife resources. Together, these agencies share a mandate to conserve, protect, enhance, and restore fish populations and habitat for commercial, recreational, and tribal fisheries.

FWS has broad-delegated responsibilities to protect and enhance fish and wildlife and related public resources and interests under authorities granted by the Fish and Wildlife Act of 1956; the Fish and Wildlife Coordination Act (FWCA); the National Environmental Policy Act (NEPA); the Migratory Bird Treaty Act; and the Endangered Species Act of 1973 (ESA). NMFS is entrusted with federal jurisdiction over marine, estuarine, and anadromous fishery resources under various laws, including the FWCA, NEPA, ESA, and the Magnuson Fishery Conservation and Management Act.

FWS and NMFS have expertise and responsibility for fishery resources which are germane to FERC's hydropower licensing decisions. Prior to licensing, FERC has an affirmative duty to consult with FWS and NMFS pursuant to the FWCA and the FPA to determine measures to protect, mitigate damages to, and enhance fishery resources, including related spawning grounds and habitat. FWS and NMFS recommend license conditions to achieve these goals and prescribe mandatory conditions for the construction, operation, and maintenance of fishways (150).

Consultation with prospective hydropower licensees and development of fish passage mitigation plans are the responsibility of these federal resource agencies and their state counterparts. NMFS and FWS develop fish passage prescriptions under section 18 of FPA for inclusion in the FERC license order. Broader mitigation recom-

BOX 5-3: Procedural Steps in Hydropower Licensing

- Applicant submits an application to FERC along with the background information on the project, economic, environmental, proposed benefits, etc. The background information may include as much as eight to nine volumes of information.
- FERC reviews the application and the supporting information and determines the need for additional studies or information. FERC sends Deficiency Statements to the applicant describing the types of information or studies that will be required to continue the application process.
- Additional information requests may be submitted by FERC after reviewing the new information submitted by the applicant in response to the Deficiency Statements.
- Upon receipt of all of the required information, FERC identifies the project as "Ready for Environmental Analysis." This is the starting point for the resource agencies, which have 45 days to develop and determine the need for fish protection mitigation under sections 10(j) and 18 of the Federal Power Act. The agencies may file for an extension if this cannot be completed within the 45-day period.
- Based on the information provided by the applicant and resource agencies, FERC develops Scoping Document I that investigates whether to undertake an Environmental Assessment (EA) or an Environmental Impact Statement (EIS) in compliance with the National Environmental Policy Act (NEPA).
- Scoping Document I is submitted for general public comment. Based on the review comments, FERC produces Scoping Document II, which is in essence a blueprint for the EA or EIS.
- The draft EA or EIS is produced and submitted for general public comment. Based on review, the final EA or EIS is produced.
- FERC develops a License Order for the project and submits this and the environmental document to the Commission for final determination for licensing.

SOURCE: Office of Technology Assessment, 1995.

mendations are made by the federal and state resource agencies under section 10(j) of the FPA.

Federal land management agencies (e.g., U.S. Forest Service, Bureau of Land Management, Bureau of Reclamation) have authority to issue section 4(e) conditions for hydropower facilities on public lands under their jurisdiction. Facilities on U.S. Forest Service lands represent nearly 15 percent of all FERC-licensed hydropower plants, or at least 240 facilities. The Forest Service (FS) currently is facing approximately 50 applications for relicensing and another 60 applications for new projects. In an effort to streamline its process and improve certainty for prospective licensees, the FS has recently outlined a proposed policy with regard to issuing section 4(e) conditions.[7]

Although the FERC licensing process is not integrated with the fishway prescription process, it drives the latter. Resource agency prescriptions and recommendations must be submitted when FERC rules that the project is ready to undertake the required environmental studies (EA or EIS). In some instances, FERC makes this decision before the resource agencies have the information they believe is needed to make meaningful fish and wildlife recommendations that can be supported by substantial evidence.

[7] In the proposed policy, it is stated that 4(e) recommendations would not try to achieve "preconstruction" conditions. This harmonizes with FERC's approach to environmental assessment documents. A second alteration involves the relinquishing of FS's unilateral "reopener" for special-use permits. At present, FS may revise special-use authorization conditions at specified intervals to reflect changing environmental conditions if the terms of the authorization exceed 30 years. This enables FS to re-open the permit to ameliorate negative impacts at a site without waiting up to 50 years for a license to expire.

Issues in Hydropower Licensing

The licensing and relicensing of hydropower projects under the jurisdiction of FERC provides a unique opportunity to restore, rehabilitate, and protect river systems for the license term, often a 30- to 50-year time frame. However, relicensing is a highly controversial issue among the many stakeholders involved in the process. State and federal resource agencies, the hydropower industry, special interest groups (e.g., environmental), Native Americans, individual owner/operators, and the public at large are all involved. Balancing of all of the competing interests in hydropower licensing is a complex process, generating much dispute among the participants (112). Key issues include: adequate balancing of developmental and nondevelopmental values; defining the baseline goal for mitigation; process timeliness; reopening license orders; and dam decommissioning.

Adequate Balancing

The need for balance of developmental and nondevelopmental values in hydropower licensing decisions was underscored by ECPA in 1986. Yet, resource agencies contend that despite existing authority identifying their role and expertise in the hydropower licensing process, insufficient weight is given to their recommendations in final balancing decisions. Some observers note that FERC's role in balancing competing interests in hydropower licensing has become increasingly difficult because of the many mandatory license conditions possible in the licensing process (e.g., resource agencies, states) (112). Others point to the need for this broad level of input to ensure all factors are considered in FERC's balancing role.

Federal and state resource agencies and environmental groups note that the nonbinding nature of the section 10(j) recommendations is a significant problem. If FERC finds that 10(j) recommendations are inconsistent with other applicable law, they may be altered or excluded. FERC must meet with relevant agencies to alter or decline section 10(j) recommendations and section 10(j)(2) requires that FERC give "due weight to the recommendations, expertise, and statutory responsibilities" of federal and state resource agencies. In some instances where disputes are settled on the basis of FERC professional judgment, the resource agencies feel that their views and expertise have not been adequately considered or have been supplanted by FERC expertise. Thus, FERC has been criticized for rejecting or modifying recommendations—in some cases nullifying the recommendations' impacts (91). On the other hand, GAO found that FERC accepts a higher proportion of environmental recommendations without modification now than it did before ECPA, i.e., three-fourths versus two-thirds in the cases studied (123,240,241). However, given the nature of balancing, recommendations that are unlikely to affect a hydropower project's economic viability may be more likely to be approved than those that directly affect power production.

States may also enter into the balancing process in other venues. Where FERC's jurisdiction is exclusive it may preempt state environmental requirements. For example, in *California* v. *FERC*, 495 U.S. 490 (1990), FERC successfully defeated a proposal by the California State Water Resources Control Board to increase minimum streamflow requirements for a previously licensed hydropower plant. The licensee demonstrated to FERC that this increase would adversely affect the economic viability of the project (43).

Yet, FERC's authority to preempt state requirements recently was limited by the U.S. Supreme Court in *Jefferson County* v. *Washington Dept. of Ecology*. The case clarified that states could require minimum instream flows as a condition of a federally issued permit, such as a FERC license. Under the Clean Water Act's section 401, all applications for a federally issued permit must include a certification from the state that the proposed permit is consistent with achieving the state's water quality goals. The State's Department of Ecology argued that minimum flows were necessary to maintain the quality of the riverine systems for fisheries management, and refused to grant a certification unless the permit required those flows. The Supreme Court found that a state's responsibility for achieving water quality goals gave it the authority to mandate release of flows by FERC-licensed projects and to enforce other standards (136).

Critics of the ruling in *Jefferson County* argue that the intent of the Clean Water Act is to restore and maintain water quality, not to interfere with water quantity issues (113). Proponents of the decision say the Supreme Court was correct in saying that water quantity was an integral part of the Clean Water Act's intent to "restore the chemical, physical and biological integrity of the nation's waters" (Clean Water Act §101(a), 33 U.S.C. §1251(a)). The *Jefferson County* decision has created substantial controversy within the hydropower sector and is likely to be a continuing point of contention. In the 104th Congress, legislation has been introduced that would alter the effect of the decision.

Defining Baseline for Mitigation

Defining the baseline to be used in determining the goal for mitigation is perhaps one of the more hotly disputed issues. This is particularly significant in re-licensing decisions since existing hydropower plants may not have been previously required to mitigate for environmental impacts. Further, lack of historical baseline environmental data hinders identification of pre-construction conditions.[8] The question also arises as to the potential for achieving pre-construction conditions, given that the alterations to the environment may have occurred decades ago.

Operators sometimes feel that they are being asked to mitigate for conditions not of their making. Many view relicensing as a continuation of the status quo, and thus, existing conditions become the starting point for environmental studies. On the other hand, critics state that relicensing is not just a continuation of the status quo but a federal recommitment of public resources for a lengthy period of time (30 to 50 years). The environmental community points to the relative time sequence of past and present decisionmaking criteria and the significant advances made in environmental law and mitigation measures since the mid 1900s. Thus, efforts to achieve pre-construction conditions in certain riverine systems might be considered properly managing the resource for the public interest. In any event, there clearly is a need for close collaboration among FERC staff (or their surrogates) and the state and federal resource agencies in the development of the Environmental Impact Statement (EIS) and Environmental Assessment (EA) for hydropower projects.

Process Timeliness

Relicensing has not been a timely process, creating uncertainty for prospective licensees and resource managers. Licensees are concerned about uncertainty and costs in increasingly competitive energy markets. Delays due to multiple processes at both the state and federal levels may expose licensees to the risks of duplicative study efforts and inefficiency. Resource managers are concerned about preserving and conserving resources at risk. Delays in the licensing process slow the implementation of mandatory fish passage prescriptions. In the current "class of '93" situation, the process has been especially prolonged. Some blame licensing delays on the lack of cooperation among stakeholders, resulting in revisiting issues over the course of the process to ensure that all sides are fairly heard.

Delay may also be perpetuated by the timetables set by FERC's licensing regulations. For some projects, especially those involving multiple developments, the timeframe may be unrealistically short. Resource agencies contend that one to two years is inadequate to complete the required studies to give decisionmakers reliable information (150). Similarly, linking multiple facilities in the licensing process may lead to delays in implementing resource protection mitigation at several facilities due to difficulties at a

[8] Preconstruction conditions refers to the environmental conditions that existed prior to the placement of the hydroelectric facility.

single site. For example, several Bangor Hydroelectric Company facilities on the Penobscot River in Maine are linked in the licensing process. A single, controversial new project proposal has delayed the licensing process, leaving the other existing projects operating under annual licenses and delaying decisions on the need for fish protection mitigation at these sites (21).

Decommissioning and Dam Removal

Decommissioning and/or removal of existing dam facilities as an alternative to relicensing has been raised more frequently since the "class of 1993" and as part of the movement toward greater scrutiny of the adverse impacts of hydropower plants on certain fish populations. Dam removal options are faced by a number of very real environmental, economic, and political constraints and, thus, are infrequently considered as alternatives to fish passage development.

A recent FERC policy statement (RM93-23) identifies the Commission's authority to order decommissioning of hydropower plants at licensee expense as an alternative to relicensing. FERC would hear the cases individually rather than developing a generic decommissioning program. If the policy is actively pursued, a need exists to incorporate planning and budgeting for decommissioning and dam removal in the licensing procedure so that applicants are aware from the start of the costs and possibilities.

The Bureau of Reclamation is examining possibilities for removal of Savage Rapids Dam on the Rogue River in Oregon; the operator asked for removal rather than fishway installation. Removal of the dam would eliminate salmon and steelhead passage problems although recreational value would be curtailed. Demolition of the dam and construction of the plants is estimated to take five years and cost $13.3 million. To retain the dam and install fish protection has been estimated to cost $21.3 million (115).

License Reopeners

Reopening of licenses prior to expiration has also been the subject of much debate. FERC can use reopeners to require projects to mitigate cumulative impacts in multi-project basins. Placeholder clauses allow revisiting of license conditions after a specified event occurs. For example, an upstream facility license could contain a placeholder clause that would require development of fish passage mitigation at such time as a facility downstream completed relicensing to include fish passage, e.g., when fish populations were physically able to proceed to the upstream facility.

Resource agencies and other participants in the process may request that FERC reopen a license for various causes. However, this is not a unilateral decision and must be accomplished through a hearing process. Understandably, industry may be less inclined to support reopening when the potential for additional mitigation costs may result from the activity and thus affect project economics. Consequently, the resource agencies have been criticized for attempting to solve larger fishery management problems through the prescription process. The agencies respond that the long license period and lack of reopening authority means that they must develop mitigation plans with a vision toward meeting future as well as present needs through their recommendations, terms and conditions, and prescriptions.

Improving Hydropower Licensing

Not surprisingly, the level of controversy generated by hydropower licensing has led to a number of efforts to improve the process and bring adversarial parties together. Some of these efforts show promise, although in certain cases they have been bogged down by the very debate they intended to address. Primarily, efforts have attempted to make the process transparent and improve discussion among the participants.

Settlement Agreements

The FERC licensing process requires that prospective licensees consult with resource agencies and others in the first stage of licensing. Yet, many licensees are learning that even earlier coordination and outreach is needed. Agreements between parties with opposing interests are commonly used in other resource protection venues, and now appear more often than before in FERC proceedings. For parties advocating fish protection, a settlement agreement involves negotiating with the licensing party to obtain the protective measures deemed necessary. Tradeoffs in the usual fixed positions of the two parties can be made to obtain better mitigation than is usually attainable through the FERC process. Holistic viewpoints can be developed and maintained, and decisions can be reached at a local rather than exclusively federal level.

Parties must perceive a need to negotiate in the FERC hydropower licensing process, beyond the regulatory requirements of applicants and agencies, in order to achieve success. FERC must be seen as a neutral party to motivate participants to find mutually acceptable agreements in accommodating the need for power production and resource protection. If FERC is perceived to favor certain interests, the need to negotiate is diminished or eliminated. Requirements for successful use of settlement agreements are: skilled negotiators, technical specialists and lawyers skilled in FERC issues; and a shared goal to resolve differences. Commitment to conflict resolution on the part of negotiating parties is essential for success. Necessary tradeoffs can then be made to resolve difficult negotiating points.

Conceptual agreements may be reached fairly early in the process without involvement of legal expertise, but this expertise may be essential when it comes to drafting the actual language of the agreement. Successful settlement agreements also depend on consensus on a single position among resource agencies outside the negotiating room. Since different agencies have their own agendas and missions, which sometimes clash, this can be problematic. Significant agency concessions may be needed to satisfy the interests/missions of each.

The Michigan Department of Natural Resources has realized many of its goals for fish protection through settlement agreements on relicensing projects with Consumers Power Company and a new license project with Wolverine Supply Cooperative. Issues resolved in these agreements were largely accepted by FERC and incorporated in the licenses for these projects.

NMFS/FWS Advanced Notice of Proposed Rulemaking (ANOPR)

Some licensees feel the licensing process is unpredictable because of the lack of universal standards to be used in the fish passage prescription process. Neither NMFS nor FWS has published standards and criteria that a licensee can use to judge if a fishway is likely to be prescribed, and if so, what sort. However, licensees can expect that passage will be an issue if their project has blocked or will block fish movement and access to historic habitat.

In an effort to address this concern, FWS and NMFS solicited comments on the benefits of a proposed rule to harmonize and codify their existing practices for prescribing fishways under section 18 of the FPA (233). An extensive review and comment period generated a number of issues to be resolved, one of which is the need for such a rule or if a policy statement is sufficient.

Hydropower Reform Coalition

The Hydropower Reform Coalition (HRC) is a coalition of conservation groups with an interest in river protection. In its review of the hydropower licensing process, HRC found FERC's existing hydropower regulatory structure to be better than any of the suggested alternatives.[9] However, HRC feels FERC regulation of hydropower's effects on nonpower values of river systems is inadequate and suggests several options to rectify the problem, including:

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[9] Some of the suggested alternatives included: 1) placing regulatory authority at the state level and 2) exempting small dams from FERC authority. The first alternative was criticized for increasing the fragmentation of the licensing process and the latter was for failing to recognize that adverse environmental impact is not necessarily proportionate to facility size.

- FERC should examine an entire river system when evaluating and mitigating adverse environmental effects from hydropower development;
- FERC should synchronize license expiration dates so projects in a basin can be reviewed simultaneously; and
- FERC should include headwater storage reservoirs more consistently within regulatory control.

HRC supports FERC deference to state CWA section 401 rulings and favors adopting resource agency section 10(j) recommendations.

HRC and National Hydropower Association (NHA) entered into negotiations to determine if it would be possible to collaborate in developing a proposal to resolve many of the difficulties in the licensing process. Issues included ensuring compensation for private use of public goods by setting up decommissioning funds, establishing mitigation and restoration funds, and requiring licensees to reimburse resource agencies for study of license recommendations (113). Negotiations broke off, however, and NHA developed its own proposal and requested a FERC rulemaking proceeding. HRC opposed the rulemaking as unnecessary and a distraction to the relicensing process.

MITIGATION COSTS AND BENEFITS[10]

Quantifying fish passage system capital costs is fairly simple and largely a question of accounting. Determining which costs are rightly attributable to fish protection or passage may pose the largest difficulty. For example, damaged turbines at the Conowingo Plants required replacement to continue generating power at the facility. These new turbines provided acceptable downstream passage for juvenile American Shad as well as reduced turbine mortality rates compared to the older models (177). What, if any, part of the new turbines and installation expenses should be counted as fish protection costs, given that the turbines were needed for power generation in any event?

Quantifying operating costs related to fish passage is more difficult since it frequently involves costs related to revenue loss from lost power generation potential due to spillflows or other water management practices that are required for proper fish passage operation. For example, the high annual cost of downstream protection at the Lower Monumental Plant (table 5-1) is largely costs for the power that will not be produced.

Determining the benefits of fish protection and passage is more difficult. As a first step, it is imperative to examine the multiple values assigned to the resource. Some of these values are difficult if not impossible to describe economically (e.g., cultural, ecological) and thus fit poorly into traditional benefit-cost analyses. Nevertheless, they must be weighed in decision-making.

Costs and benefits are not directly proportionate. For example, “X” dollars for constructing and operating a fish passage/protection system does not necessarily result in an “X” amount change in the number of fish passing a barrier. Other life-cycle factors that affect a species also affect passage rates. Availability and quantity of spawning habitat, downstream passage success, ocean catch levels, and drought may directly affect population success.

Mitigation costs vary considerably depending on the type and scale of the mitigation measure. Scale is driven by a site’s physical features (e.g., water flow, dam size, and configuration) and finding similarities between two plants can be difficult (table 5-2). For example, the Wadhams plant, with its 0.56 megawatt capacity and 214 cubic feet per second (cfs) average water flows,

[10] This section is drawn from J. Francfort, Idaho National Engineering Laboratory, “Synthesis of the Department of Energy’s Fish Passage and Protection Report, Vol.II,” unpublished contractor paper prepared for the Office of Technology Assessment, U.S. Congress, June 1995.

TABLE 5-1: Downstream Fish Passage/Protection Mitigation Benefits Over 20 Years
(Levelized Annual Costs in 1993 Dollars)

Plant	Mitigation type	Agency objective	Mitigation benefit	Annual cost[a] (20-year average)
Arbuckle Mountain	Cylindrical, wedgewire screens	Prevent fish entrainment (chinook salmon, steelhead, rainbow trout)	No anadromous fish present. Drought restricted monitoring.	$7,900
Brunswick	Steel bypass pipe	Reduce mortality for downstream migrating fish (American shad, alewife)	No established monitoring program.	46,500
Jim Boyd	Perforated steel screen	"No induced mortality" standard	Reportedly achieves agency standard. Visual observations performed.	51,000
Kern River No. 3	Fixed barrier screens	Protect "put-and-take" rainbow trout fishery	No established monitoring program.	7,700
Leaburg	"V" wire screens and bypass	"No net loss" standard	Meets agency standards.	381,200
Little Falls	Wire mesh screens and bypass	Protect downstream migrating blueback herring	Less than 1% turbine entrainment (>100,000 passed each season).	123,400
Lowell	Bypass sluice	Pass American shad and Atlantic salmon	No established monitoring program but existing sluice is considered ineffective.	52,850
Lower Monumental	Submerged, traveling screens	Prevent turbine entrainment (salmon and steelhead)	Not yet monitored.	4,812,000
T.W. Sullivan	Eicher screen and conduit	Decrease turbine entrainment	Bypass efficiency between 77 and 95%.	713,000
Twin Falls	Inclined wedgewire screens	"No induced turbine mortality" standard	Reportedly effective.	75,850
Wadhams	Angled trash racks and bypass sluice	Protect downstream-moving Atlantic salmon from turbine mortality	1987 study; 8% entrainment.	2,420
Wells	Hydrocombine bypass	Goal: "no induced mortality"; present agency criteria: (passage efficiency): spring – 80% efficiency summer – 70% efficiency	Passage efficiency exceeds agency criteria.	1,756,000
West Enfield	Steel bypass pipe	Protect downstream migrating Atlantic salmon and alewife	Efficiency: 1990—18% 1991—62% (with attraction lighting). Mortality in bypass greater than in turbines.	61,000

[a] Some of these annual costs include costs due to loss of power generation capacity resulting from spillflows and other water management practices.

SOURCE: U.S. Department of Energy, *Environmental Mitigation at Hydroelectric Projects, Volume II: Benefits and Costs of Fish Passage and Protection*, Idaho Field Office, DOE/ID-10360(V2), January 1994.

TABLE 5-2: Case Studies General Information

Plant name	Capacity (MW)	Annual energy production (MWh)	Diversion height (ft.)	Average site flow (cfs)	State	Upstream mitigation	Downstream mitigation	Mitigation cost (mils/kWh)[a]
Arbuckle Mountain	0.4	904	12	50	California	Y	Y	12.9
Brunswick	19.7	105,200	34	6,480	Maine	Y	Y	3.7
Buchanan	4.1	21,270	15	3,636	Michigan	Y	N	10.6
Conowingo	512	1,738,000	105	45,000	Maryland	Y	N	0.9
Jim Boyd	1.2	4,230	3.5	556	Oregon	Y	Y	21.1
Kern River No. 3	36.8	188,922	20	357	California	Y	Y	0.09
Leaburg	15	97,300	20	4,780	Oregon	Y	Y	5.2
Little Falls	13.6	49,400	6	n/a	New York	N[b]	Y	2.8
Lowell	15	84,500	15	6,450	Massachusetts	Y	Y	5.5
Lower Monumental	810	2,856,000	100	48,950	Washington	Y	Y	2.3
Potter Valley	9.2	57,700	63	331	California	Y	Y	n/a
T.W. Sullivan	16.6	122,832	45	23,810	Oregon	N[c]	Y	5.8
Twin Falls	24	80,000	10	325	Oregon	N	Y	0.9
Wadhams	0.56	2,000	7	214	New York	N	Y	1.2
Wells	840	4,097,851	185	80,000	Washington	Y	Y	1.0
West Enfield	13	96,000	45	12,000	Maine	Y	Y	3.9

[a]Costs are in 1993 dollars, per kilowatt-hour of generation, based on 20-year averages. All upstream and downstream mitigation-related costs are included.

[b]Upstream passage occurs through New York Department of Transportation Barge Lock Number 17.

[c]Upstream passage occurs through Oregon Department of Fish and Wildlife maintained fish ladder at Willamette Falls.

KEY: n/a = not available.

SOURCE: U.S. Department of Energy, *Environmental Mitigation at Hydroelectric Projects, Volume II: Benefits and Costs of Fish Passage and Protection*, Idaho Field Office, DOE/ID-10360(V2), January 1994.

has annual downstream mitigation costs of $2,420. The Lower Monumental plant, with 810 MW capacity and average flows of 48,950 cfs, has an average annual cost of $2.4 million (table 5-1). Although these are poor summaries of both plants' costs, it illustrates the disparity despite their identical objectives to safely pass downstream migrants. A summary based on averages for such diverse costs would be, if not erroneous, at least misleading.

Alternatively, costs could be summarized based on a factor such as fish ladder construction costs per foot of design head; the design head implies the vertical elevation that a ladder must pass adults. Yet, it can also be misleading to assume that the hydraulic design head is approximately the same as the required height for a fish ladder. For example, the Kern River No. 3 plant has an 880-foot head, but the ladder is used at an upstream diversion that is only 20 feet high.

In the same vein, quantifying the benefits of fish passage mitigation is plagued with problems stemming from the inadequacy of traditional economic analyses in resource valuation. The examination of the DOE case studies that have implemented fish passage measures reveals that several plants have been successful in increasing the passage rates or survival of anadromous fish (i.e., the Conowingo, Leaburg, Lower Monumental, Wells, Buchanan, and T. W. Sullivan plants). Six other plants show encouraging preliminary results; they have not been adequately studied to determine the long-term impacts on fish populations (i.e., Brunswick, Jim Boyd, Little Falls, Lowell, Twin Falls, and Wadhams). Only one of the case studies (West Enfield) appears to have failed in the attempt to enhance fish populations, but for some the benefits are unclear. In some cases, benefits could be expressed only in terms of the numbers of individual fish that were transported around the dam or protected from entrainment. Missing, however, is the assessment of the long-term effects of these mitigation measures on fish population levels.

"How much are additional fish worth?" In some cases, the fish are commercially caught and determining value may be simplified. It is slightly more difficult to determine the revenue stream from fish caught recreationally. It becomes even more difficult to attach a price tag to fish caught as part of a traditional cultural activity. For example, Native American fishing rights at usual and customary locations as guaranteed by U.S. treaty is recognized as a significant cultural event. If hydropower development depletes historic stocks to the point where this activity can no longer be pursued, then how much is a fish worth? Clearly, fish have a variety of values depending on their ultimate use and the role that fishing plays in human activities.

If price tags are not available, how can the value of fish be estimated? Resource economics has developed two types of methods for estimating the values of natural resources, including recreational fish. The *direct method* is to ask people their valuations of particular resources through surveys constructed to eliminate a number of potential biases. The *indirect method* relies on the fact that to consume part of a natural resource, which has no price tag, a fisherman must spend some of his or her money (and time) on goods which are sold in markets. Travel costs, including the value of time as well as out-of-pocket costs and any entry fees at restricted fishing sites, amount to the effective, or implicit, price which fishermen pay for their recreational fish. This information can be used to construct a demand curve to estimate the recreational value of fish at a specific site and time—the marginal value.

Use and nonuse values in natural resource valuation have become prominent in public, scientific debates in the past several years, however, they are subject to theoretical and methodological concerns. The *use value* is the value someone will pay to consume a natural resource, whether that consumption act is catching a fish and eating it, catching a fish and releasing it, or looking at a mountain in a national park. The consumer of the natural resource is actively involved in the act of consumption and somewhere in the act of consumption pays out some real resources—money, time, wear and tear on a vehicle—for that consumption.

Nonuse value is how much it is worth to a person simply to know that a natural resource exists, even though he or she has no intention of ever directly consuming it (e.g., hunting or catching it, walking through it, or even viewing it). Nonuse value is more difficult—if not impossible—to observe, and its measurement is restricted to the direct method survey.

The estimated marginal values of recreational fish vary considerably, even within a single state, primarily according to the accessibility of the site to a population of fishermen and, of course, according to species. Fish at sites which are accessible to larger numbers of fishermen will be valued by more people, which drives up their marginal values. Table 5-3, which shows marginal values for steelhead trout on 21 rivers in Oregon in 1977 (in 1993 prices), reveals this effect quite clearly. Table 5-4 shows marginal values of trout and salmon (1978 values at 1993 prices) in 11 counties along the Lake Michigan shoreline in Wisconsin, with a range of values from $10.56 to $87.37, an eight-fold difference. The values in these two tables clearly demonstrate variation in value between sites, and the transfer of fish value estimates from one site to another is a subject of active study. The principal rule of thumb emerging so far is that values are more transferable to nearby sites than to sites farther away, although measures of "near" and "far" are still rough.

This brief review of the various methods used in determining the value of a fish points out the

TABLE 5-3: Marginal Values of Steelhead Trout in Oregon Rivers, 1977 (in 1993 prices)

River	Marginal value (in $)	River	Marginal value (in $)
Alsea	$31.48	Rogue	$114.95
Chetco	30.11	Salmon	243.59
Clackamas	240.86	Sandy	157.38
Columbia	190.22	Santiam	253.17
Coquille	46.53	Siletz	87.58
Coos	24.63	Siuslaw	90.32
Descutes	109.48	Trask	184.75
Hood	168.33	Umpqua	134.11
John Day	56.11	Willamette	455.71
Nehalem	183.54	Wilson	172.43
Nestucca	143.69		

SOURCE: Loomis, 1989, table 1, in U.S. Department of Energy, *Environmental Mitigation at Hydroelectric Projects, Volume II: Benefits and Costs of Fish Passage and Protection*, Idaho Field Office, DOE/ID-10360(V2), January 1994.

complex and subjective nature of this issue. Determining the value of a natural resource such as a fish is not an exact science. Research and discussion continue in the attempt to develop a methodology to determine natural resource values that would be universally acceptable. How this ultimately will affect the development of new hydropower sites, the relicensing of developed sites, and any affiliated mitigation requirements is unknown.

RESEARCH AND DEVELOPMENT: FEDERAL INVOLVEMENT

Many federal agencies are involved in research and development efforts related to fish passage and protection technologies. Below is an overview of certain institutions and activities relevant to improving fish protection.

Northwest Fisheries Science Center

The NMFS Northwest Fisheries Science Center (NWFSC) is the research center serving the Northwest Regional NMFS Office and provides scientific and technical support for management, conservation, and development of fishery resources. Research is performed in conjunction with federal, state, and local resource agencies, universities, and other fishery groups. The mission of the NWFSC includes a focus on the following research areas:

- understanding and mitigating the impacts of hydropower dams on salmon and performing ecological and genetic research on salmon in support of the ESA;
- evaluating the effects of marine pollutants on coastal ecosystems in the United States;
- enhancing the quality, safety, and value of fishery products; and
- developing methodologies for marine aquaculture and salmon enhancement.

Coastal Zone and Estuarine Studies

The Coastal Zone and Estuarine Studies (CZES) Division of NMFS defines its scientific mission as to develop information leading to conservation, enhancement, and balanced use of marine and anadromous resources of the Pacific Northwest (235). Research of the CZES Division focuses on the Columbia River Basin and Puget Sound and the salmonid populations in these regions. Four research programs exist in CZES: Ecological Effects of Dams, Habitat Investigations, Fisheries Enhancement, and Conservation Biology. Projects within these programs are undertaken collaboratively with other appropriate agencies (e.g., COE, FWS). CZES maintains

TABLE 5–4: Marginal Values of Trout and Salmon in Eleven Wisconsin Counties Bordering Lake Michigan, 1978

County	1	2	3	4	5	6	7	8	9	10	11
Marginal value of fish in dollars	12.42	18.37	11.50	36.52	86.37	10.56	12.01	15.17	87.37	16.23	42.63

NOTE: Unweighted averages in 1993 dollars.

SOURCE: Samples and Bishop, 1985, Table 2, p. 69, pp. 70–71, in U.S. Department of Energy, *Environmental Mitigation at Hydroelectric Projects, Volume II: Benefits and Costs of Fish Passage and Protection*, Idaho Field Office, DOE/ID-10360(V2), January 1994.

two field stations for research on the Columbia River at Pasco, Washington, and Hammond, Oregon.

The Ecological Effects of Dams Program engages in applied research relating to the migration of anadromous fish. Studies include: 1) the adaptability of juvenile salmonids to changing environments created by dams, 2) collection and transportation of juvenile salmonids, 3) migrant passage at dams, and 4) enhancement and redistribution of stocks. Habitat Investigation Program projects focus on the Columbia River estuary and emphasize environmental background studies, impacts of dredging and dredge-disposal studies, impacts of discharged materials or heat studies, and estuarine salmonid studies. The Fisheries Enhancement Program provides regional leadership in research on improving the production of aquatic organisms for commercial and recreational use and conservation of endangered populations. The Conservation Biology Program has responsibility for providing scientific bases for decisions on listing anadromous Pacific salmonids under the Endangered Species Act.

Conte Anadromous Fish Research Center

The National Biological Survey (NBS) operates the Conte Anadromous Fish Research Center in Turner's Falls, Massachusetts, and conducts cooperative research with a number of federal agencies. Conte is the sole center for applied fish passage research in the country. The lab is relatively new, having opened its doors in 1991, and is staffed and funded by FWS and NBS. The facility's size, and financial and personnel resources, limits the number of projects that can be conducted at any one time, and often joint efforts are forged with private research organizations or utilities that can provide an area of expertise or funding. As a result, the Conte staff tends to select studies that have the potential for generic applicability in the field, as opposed to those that might be more site- or project-specific. Thus, research results have the potential to be broadly applicable to practitioners in the field.

Conte's laboratory resources are allocated to projects that address questions concerning fish passage from *hydraulic*, *biological*, and *behavioral* perspectives. Staff engage in a constant exchange of data and results to help support research in the complementary area. Below are sketches of research areas the lab is currently engaged in:

Hydraulic Lab: The Hydraulic Lab conducts hydraulic modeling to answer specific research questions. Current projects include evaluation of a new passage technology, gathering basic data on the operation of Denil and Alaska steeppass fishways at various slopes and flows, and development of a fish passage design for Little Falls Dam on the Potomac River. Some investigatory work at Cabot Station on the Connecticut River is also underway.

Fish Behavior Lab: The fish behavior lab at Conte addresses fish passage research questions from a biological perspective. The lab has developed cooperative relationships with universities who share graduate students and funding. This program is an extension of the Fish and Wildlife Research Units that came into existence in the 1960s to enable university-supported fisheries research. The lab has also established relationships with state resource agencies and hydro project operators interested in improving and developing fish passage technologies for application at specific sites.

Project Improvements for Endangered Species

Under the direction and supervision of the Secretary of the Army, through the Assistant Secretary of the Army (Civil Works), the Commander of the Army Corps of Engineers (COE) has responsibility for investigating, developing and maintaining the nation's water and related environmental resources; constructing and operating projects for navigation, flood control, major drainage, shore and beach restoration and protection, related hydropower development, water supply, water quality control, fish and wildlife conservation and enhancement, and outdoor recreation; responding to emergency relief activities directed by other federal agencies; and administering laws for the protection and preservation of navigable waters, for emergency flood control, and for shore protection.

The COE has coordinated with other agencies and other regional interests in establishing programs to lessen the impacts of those projects on fish. The Portland District has developed a program that covers 19 activities under one umbrella called Project Improvements for Endangered Species (PIES). PIES, and its mission to improve salmon passage, has been endorsed by NMFS. The projects cover a wide range of issues and costs and are financed through Operations and Maintenance funding to the tune of $14 million. The COE also has a regionally funded research program known as the Fish Passage Development and Evaluation Program (FPDEP) which has numerous studies underway on juvenile bypass and transportation, adult fish passage, and related issues such as spill effectiveness and dissolved gas effects.

Waterways Experiment Station

The Waterways Experiment Station (WES) in Vicksburg, Mississippi, is a COE research compound complete with six laboratories: Hydraulics, Coastal Engineering, Geotechnical, Structures, Environmental and Information Technology. At WES, working models of dams in the northwest are used to assist engineers and biologists in finding ways to increase anadromous fish survival rates. The facility was established in 1929 with the mission of developing flood control plans for the Mississippi River. Today, its mission is a bit different.

In the Hydraulics Lab, most of the work is focused on fish passage issues. Research techniques are used on models (built 1 ft to 80 ft, or 1 ft to 100 ft) of the Columbia and Snake River projects (231). The models are used to analyze flow conditions, and scientists can evaluate the hydraulic conditions that salmon may encounter as they pass various projects in an effort to determine the range of on-site tests that might be needed when investigating passage needs. There are also sectional models at WES which focus on specific portions of projects and are generally constructed at a larger scale (1 ft to 25 ft). The sectional models are used to answer more localized and specific fish passage questions.[11] The models also help answer questions about drawdown operations by tracking changing flow patterns. WES personnel are also involved in passage research to develop and evaluate alternative behavioral guidance methods. At the Richard B. Russell Pumped Storage Project, an ultrasonic and light system have been tested for many years (chapter 1).

System Configuration Study

The COE's System Configuration Study (SCS) is examining various alternatives for physically altering the lower Snake and Columbia River dams to improve salmon passage conditions. The focus is mainly on restoration of the Snake River.

[11] Sectional models currently being used include three-bay turbine intake sections of Lower Granite, the Lower Granite Spillway, McNary, Bonneville, and the Dalles.

Preliminary findings of the study indicate that passage would only improve if the Snake River were returned to its natural condition (232). Other options under consideration in the study include constructing bypasses to route the river around the dams, creating a controlled breach through each dam, or removing the four lower dams.[12] The study also concluded that a year-round river drawdown would adversely affect power production, navigation, irrigation and recreation benefits, and would result in short-term loss of fish and wildlife habitat during construction and re-establishment of habitat (232).

Fish Passage Research Center

The Bonneville Power Administration (BPA) has responsibility to mitigate for wildlife and wildlife habitat affected by federal hydropower dams and reservoirs in the Columbia River Basin under the 1980 Pacific Northwest Electric Power Planning and Conservation Act.[13] The Northwest Power Planning Council was established by the 1980 Act and was charged with developing a program to "protect, mitigate, and enhance fish and wildlife" and their habitats. Under section 4(h)(10)(A) of the Act, Congress directed BPA to use its funds and legal resources to implement the program and to fund many of the program measures to offset effects of development and operation of hydropower projects in the Columbia River Basin. Many of the recommendations for fish and wildlife protection, mitigation, and enhancement come from resource agencies and Tribes, utilities, and the public. The Fish Passage Research Center in Portland was established in large part to monitor the effectiveness of programs undertaken in response to the 1980 Act.

One of the Center's main responsibilities is to monitor smolt passage on the Snake and Columbia Rivers. Hydrologic and hydraulic data, as well as temperature and gas concentration data, are collected at all trap sites in the tailraces of the lower Columbia and Snake River projects.[14] The smolt monitoring program provides data on the passage of fish through the basin's dams and reservoirs and also provides data about the physiological status of the fish. This information can be helpful in making operational management decisions relative to flow and spill which correlates to determinations and recommendations regarding the status of the smolt passage program and what improvements might be made to increase its success.

Surface Collector

BPA and COE are jointly supporting the development of a surface collection system for transporting downmigrating salmonids around dams. The idea behind surface collection is to present a flow stimulus to downstream migrants that will take advantage of their natural outmigration behavior. Juvenile migrants, typically oriented in the upper levels of a reservoir water column, are drawn into the system by the attraction flow at the surface and are collected for transport or directed to a bypass around the dam (40). NMFS and the Northwest Power Planning Council have endorsed the research effort. Hydroacoustic techniques will be used to monitor and evaluate the effectiveness of the system.

Research at the Wells Dam in the Douglas County Public Utility District indicated that juvenile passage could be improved using surface collection techniques. Hydrocombine units used at Wells Dam are a unique design for hydropower where the spill bays are located directly over the turbine units. Between 1984 and 1993, modifications to the spill bays at Wells Dam along with operational changes achieved at least 90 percent passage of smolts. Wells Dam

[12] The four dams on the lower Snake River are Lower Granite, Little Goose, Lower Monumental, and Ice Harbor.

[13] COE owns and operates many of the dams in the Columbia River Basin, whereas BPA is responsible for generation and distribution of the power generated at those dams. COE engages in its own research efforts; BPA and COE jointly fund and support research and development of fish passage mitigation methods and managing techniques.

[14] Data are collected at trap sites at the four dams on the lower Columbia (Bonneville, The Dalles, John Day, McNary) and at two Snake River dams (Lower Granite, Little Goose); data are then downloaded to the Fish Passage Center for analysis.

has become a model for downstream migrant passage using the surface collection concept, and an adaptation of this design, which is suitable for conventional hydropower configuration, is in place at Rocky Reach Dam (40).

COE hopes that the four-year $90-million-dollar program will provide a new means of passing juvenile salmon and steelhead around hydro projects at lower cost, and with improved efficiency over conventional fish passage. COE has placed great emphasis on this effort, as it represents an attempt to link the sciences of fish behavior and engineering (77). Plans call for system prototypes to be installed at a number of dams on the Columbia over the next few years, beginning with Lower Granite Dam in 1997. Additional prototypes will be installed at The Dalles and Bonneville dams in 1998.

Bureau of Reclamation Research Facility

The Bureau of Reclamation (BuRec) has been the nation's pre-eminent western water resource development agency for decades. The agency has increasingly focused on environment and water resource management as the need for large construction projects decreased. Today, BuRec helps to fund and participates in research and development of fish passage technologies to protect anadromous species in California and the Pacific Northwest.

BuRec's research facility in Denver offers technical support on fish passage issues to the Northwest and California regional offices. The facility is used in part to experiment with hydraulic models of parts of the Columbia River hydropower system, and various projects on the Sacramento River in California. This capability gives scientists the opportunity to laboratory test fish passage technologies under a range of potential hydraulic conditions which reflect field possibilities. The facility also evaluates prototypes of fish passage technologies (e.g., various screening technologies, downstream surface collector system) and conducts research on monitoring downmigrating salmonids on the Sacramento River.

Central Valley Project

In 1992, the Central Valley Project Improvement Act (CVPIA) directed BuRec to improve the management practices of the Central Valley Project (CVP) to address fish protection concerns.[15] The CVP is a federally funded water project on the Sacramento and San Joaquin Rivers and Delta in California and is essential to the distribution of water in California. The CVPIA expands the purposes of the CVP to mandate the protection of fish, wildlife, and associated habitat, and to work toward achieving a balance among competing demands for water.

The streams and rivers of the Central Valley are host to a multitude of diverters—federal, state, and private—which range in size and flow. In all, there are 3,000 outlets, most of which serve agricultural uses. More than 2,000 of the CVP diversions are unscreened and implicated in the decline of species in the river system. Although part of the CVPIA budget is allocated for fish protection through a diversion screening program, BuRec is not required to install physical barrier screens at diversions along the rivers and Delta. Whether it should is a point of considerable debate because of the high cost of the screens.

The resource agencies, NMFS, FWS, and the California Department of Fish and Game, favor positive-exclusion devices over alternative behavioral techniques that rely on sound, light,

[15] The Central Valley Project Improvement Act was passed in 1992 as part of an extensive piece of legislation known as the Reclamation Projects Authorization and Adjustment Act of 1992. Some of the Act's titles authorized water projects; however, the CVPIA (title 34) took a step toward conservation in mandating fish and wildlife protection.

and electric barriers.[16,17] The presence of endangered and threatened species in the CVP has heightened the concern over experimentation and use of behavioral guidance technologies particularly at sites where positive-exclusion barriers are feasible and where fish that are entrained in irrigation diversions have no chance at survival.

CONCLUSIONS

The incomplete state of knowledge regarding fish population dynamics; the impacts of hydropower development on fish; the need for mitigation in various contexts; and the protection/passage effectiveness of available mitigation technologies exacerbate the already adversarial relationship between hydropower and environmental interests. This situation is unlikely to be alleviated unless a solid, science-based process for mutual understanding and rational decision-making can be developed (box 5-4).

A combination of academic, government, and industry expertise is needed in a concerted effort to focus science and technology resources on the question of hydropower development effects on fish population sustainability, and on the assessment of available and developing fish protection technologies at dams.

Technologies

Technologies for upstream passage are more advanced than for downstream passage but both need more work and evaluation. Upstream passage failure tends to result from less than optimal design criteria based on physical, hydrologic, and behavioral information, or lack of adequate attention to operation and maintenance of facilities. Downstream fish passage technology is complicated by the limited swimming ability of many downmigrating juvenile species and unfavorable hydrologic conditions. There is no single solution for designing up- and downstream passageways. Effective fish passage design for a specific site requires good communication between engineers and biologists and thorough understanding of site characteristics.

Downstream passage of fish and protective measures to reduce turbine mortality are probably the areas most in need of research. The most fundamental test of downstream mitigation effectiveness—that the measure should yield better survival than downstream passage through turbines—rarely has been rigorously examined. When research and demonstration is carried out, results can be dramatic.

Varied technical fish passage knowledge among participants in the debate results in unsubstantiated claims and arguments. Moreover, some experimental results contradict others. Ambiguous or equivocal results of many fish passage studies have caused concern as to whether certain technologies are effective or generally useful. The variability of results may reflect site variability; uncontrolled environmental conditions in field studies; or incomplete knowledge of fish behavior. Thus, certain proposed solutions to the problem may be based on incomplete assessments. Advocates on both sides of the fish/power issue can select from a diverse body of scientifically unproven information to substantiate their points of view. Care must be taken in interpreting much published information on fish protection, arguments drawn from it, and conclusions reached.

Hydropower Licensing

Controversy abounds in the FERC hydropower licensing process. In part, this may be a result of the lack of clearly identified *goals* to be achieved through mitigation. Although *objectives* exist in the legislative language of the FPA, as amended, these lend themselves more to a philosophy than to hard goals that describe numbers, timeframes,

[16] A positive exclusion device is a barrier that physically blocks fish from entering diversions or water intakes; its effectiveness is not dependent on the swimming ability of the fish.

[17] NMFS supports research efforts on behavioral guidance technologies but guards against implementation prior to performance criteria being met.

BOX 5-4: Development of Fish Passage Technologies: Research Needs

There are no "sure things" in the world of fish passage technology. The technologies themselves, which are based on hydraulic engineering and biological science, can be designed to accommodate a wide range of environmental conditions and behavioral concerns, but in the real riverine world *anything* can happen.

Upstream and downstream fish passage problems differ considerably and both present a range of obstacles and challenges for researchers and practitioners. Despite these differences, common considerations in design and application exist, including: hydraulics in the fishway, accommodating the biology and behavior of the target fish, and considering the potential range of hydrologic conditions in the waterway that the passage technology must accommodate. Engineers and biologists in the Northeast and Northwest are collaborating in a number of research programs designed to improve understanding of the swimming ability and behavior of target fish. Understanding how fish respond to different stimuli, and why, is critical to improving passage methods.

Using a scientific approach to explore as many scenarios as possible, and collecting data in a careful manner, can improve researchers' abilities to design improved technologies. In addition, producing information that all parties can acknowledge as credible is key to the successful advancement of fish passage technologies. A sound scientific approach to developing, executing, and evaluating a field study is critical to the successful advancement of fish passage technologies. The elements of a good test include the establishment of clear objectives, agreement among all parties to the study design, and a protocol that lends itself to repeatability. In addition, there must be a proper accounting of environmental variability, documentation of all assumptions, and sufficient replications to support findings. Regular communication among stakeholders and peer-reviewed research results are key requirements.

Employing a process of this type could increase the potential for information transfer between sites. That information might include data regarding the response of the device to hydraulic parameters (e.g., flow/acoustical response), fish response to stimuli under hydraulic parameters, and basic biological information within species. Agreement on performance criteria and standards prior to study will avoid lack of acceptance of data and recommendations in the long term.

SOURCE: Office of Technology Assessment, 1995.

and methods for achieving and measuring the stated goal. Clearly defined goals for protection and restoration of fish resources might refer to numbers or percentages of fish expected to successfully pass a barrier and/or projected population sizes. Since resource management goals are rarely articulated, mitigation and enhancement measures are judged on a case-by-case basis with no means for assessment or comparison.

The lack of clear goals is, in part, reflected in the disjunction between section 18 prescriptions and section 10(j) recommendations of the FPA. Section 18 fish passage prescriptions are mandatory; however, section 10(j) recommendations may be altered based on consistency with other applicable laws or the goals for the river (e.g., whitewater rafting/recreation, power production needs). Yet, the recommendations made under section 10(j) may be critical to maintaining habitat for fish populations or promoting timely migrations for certain species. FERC, as the final authority for balancing developmental and nondevelopmental values, is not specifically charged with sustaining fish populations. Without clear identification of the goal for mitigation, monitoring and evaluation become less meaningful and fail to become critical to the process.

Monitoring and evaluation conditions for hydropower licenses are infrequently enforced, resulting in little information on how effective available mitigation technologies are in improving fish passage and survival at hydropower plants. Operation and maintenance failures have been implicated in poor efficiency of fishways. Forty percent of nonfederal hydropower projects with upstream fish passage mitigation have no performance monitoring requirements (242). Those that do generally only quantify passage rates, without regard to how many fish arrive at and fail to pass hydropower facilities. Moreover, most monitoring has dealt with anadromous salmonids or clupeids; much less is known about the effectiveness of mitigation measures for "less-valued" or riverine fish. Research is needed to determine whether river blockage is even negatively affecting riverine species.

Relicensing decisions often are not based on river-wide planning and cumulative analysis. FERC is required to review existing river management plans to assure that the project will not interfere with the stated goals (pursuant to section 10(a) of the FPA). Yet, comprehensive river basin planning is fragmented. Synchronizing license terms on river basins could improve the relicensing process and promote cumulative impact analyses. Terms could be adjusted to meet the ecological needs of the basin and to provide timeliness and predictability for licensees. Under such a plan, multiple sites could be relicensed simultaneously, although operators may be unlikely to respond positively to undergoing the relicensing process "early." On the other hand, consolidation could yield benefits, allowing licensees to develop integrated management plans to maximize the energy and capacity values of their projects; making it easier for all involved parties to view the projects and their impacts in their totality; and facilitating understanding of cause and effect relationships.

There is a need for further research on cumulative fish passage impacts of multiple projects; and for consideration of fish needs at the watershed level. In several northeastern states, cooperative agreements between resource agencies and hydropower companies have generated successful approaches to basin-wide planning for fish protection. Carefully planned sequential construction and operation of fish passages could provide significant opportunities for restoring historic fish runs. In the western states, watersheds in National Forests provide about one-half of the remaining spawning and rearing habitat for anadromous fish in the United States. Ecosystem or watershed management in these areas could have immediate and long-term impacts on fish populations (e.g., PACFISH).

Appendix A: Overview of Fish Passage and Protection Technologies in the Columbia River Basin

A

ABSTRACT[1]

Commercial exploitation of Columbia River salmon and steelhead began in the mid-1800s. Concurrent with commercial exploitation of adult fish was modification and destruction of spawning and rearing habitat by various landuse practices. In addition, survivorship of downstream migrants was negatively affected by unscreened irrigation diversions and entrainment of smolt in irrigation water. By 1920, prior to construction of mainstem dams, it was clear that the salmonid stocks of the Columbia River had been reduced significantly.

Construction of mainstem dams created additional challenges to the migration of adult and juvenile fish in addition to causing additional habitat degradation. The single most significant impact to Columbia River salmon stocks was the construction of Grand Coulee Dam, which was built without fish ladders and eliminated all the stocks originating above the dam site.

Fish passage research began with the study of the Bonneville Dam fish ladders, which passed adult migrants very successfully. During the early stages of dam construction conventional wisdom was that juvenile fish were not injured during passage through hydro turbines so smolt passage through dams was not a topic of research. The U.S. Army Corps of Engineers (COE) built a research laboratory at Bonneville Dam that was used for 30 years to study the behavioral response of adult migrants to elements of fish ladder design. The research conducted at the laboratory made major contributions to the success of fish ladders at other Columbia River Dams. Although adult migration behavior research continues to the present, its focus is on broader ecological questions.

Research of juvenile fish passage began with development and evaluation of screens for irrigation diversions. Continued research in this area for over half a century has resulted in irrigation diversion screens that are effective in preventing juvenile migrants from being entrained in irriga-

[1] This appendix is derived from T.J. Carlson, "Overview of Aspects of the Development of Adult and Juvenile Migrating Fish Passage and Protection Technologies Within the Columbia River Basin," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, July 1995.

tion water. Current research efforts are focused on evaluation of behavioral barriers using infrasound that will reduce the movement of juveniles past the headworks of irrigation diversions.

Juvenile fish passage research at mainstem dams has been mostly concerned with prevention of juveniles from passing through turbines. Since the early 1960s turbine intake screens have been in development to divert juveniles from turbine intakes and into bypass facilities for return to the river or transport. Most of the mainstem dams have been equipped with intake screens, and a major portion of the juveniles passing down the Snake River are collected for transport.

Investigations conducted in the 1960s showed that surface oriented flows were effective under some conditions in attracting juvenile migrants to alternative bypass routes prior to turbine passage. Subsequent research has further developed surface collection of smolts. Surface collection has been successfully developed at Wells Dam on the upper Columbia River, where over 90 percent of smolts are passed by the dam through modified spill bays utilizing less than 5 percent of the hydraulic capacity of the dam's powerhouse. Major surface collection research programs were initiated in 1995 by private utilities and the COE. Preliminary results are very encouraging and surface collection has become a major focus for current smolt passage research.

INTRODUCTION

The Columbia River is the second largest river in the continental United States in terms of volume, with a total length of over 1,200 miles. Historically, flows in the lower Columbia often exceed 200,000 cubic feet per second, with wild fluctuations following snow melt and rains in the spring. The Columbia drains 258,000 square miles, an area larger than several states. The watershed extends into four Northwest states: Washington, Oregon, Montana, and Idaho.

Documented exploration of the Columbia River by Europeans began in the late 1700s with Capt. Robert Gray, who crossed the Columbia River bar, a treacherous area of strong currents and turbulent water, and explored parts of the lower Columbia in the spring of 1792. It was Capt. Gray who gave the river its European name. Several years later, in 1805, Lewis and Clark traveled down the Columbia, reaching the Pacific Coast in November. The reports of Lewis and Clark documented the many rapids and falls in the Columbia River that initially were simply hazards to navigation but later were exploited for hydropower production. They also documented the richness of the salmon and steelhead runs to the river and their use by the native population (21,43,45).

There has been considerable discussion of the historical size of salmon and steelhead runs to the Columbia River. Estimates range from highs around 35 million to lows in the region of 6 to 7 million. For planning purposes, the Northwest Power Planning Council (NPPC), created by act of Congress in 1980 to develop and oversee implementation of a program for restoration of Columbia River stocks, estimated that the historical run sizes ranged between 12.5 to 13 million fish (59). Current run sizes are on the order of 2.5 million fish, which amounts to a loss, on average, of approximately 10 million fish (43). Research continues to try to better understand the historical production of Columbia River Basin salmon and steelhead. Discussion of the historical carrying capacity of the Columbia River Basin is of more than academic interest as efforts to restore habitat and recover stocks begin to focus on identification of critical habitat for restoration and targets for stocking levels. Of particular interest are recent efforts at template analyses of the many habitat features and climatic trends that influence ecosystem carrying capacity and discussions of the recovery potential of discreet stocks (38).

Although certainly exploited through aboriginal times, intensive commercial exploitation of salmon and steelhead didn't begin until the mid-1800s. Early efforts at commercial exploitation of salmon by salting and shipping to eastern U.S. markets were unsuccessful because of poor product quality. However, the introduction of canning in 1866 provided the means to preserve salmon quality over the long periods required for shipping while delivering a desirable product at low cost. With this innovation the commercial exploitation of salmon and steelhead started in earnest. Unlike today, the large quantities of salmon available and low cost of production made salmon a cheap food for the working class (43).

Analysts partition the historical commercial exploitation of Columbia River salmon and steelhead into several phases. The period from 1866 to present may be divided into four phases: initial development of the fishery (1866-1888); a period of sustained harvest with an average annual catch of about 25 million pounds (1888-1922); resource decline with an average annual harvest of 15 million pounds (1923-1958); and maintenance at a depressed level of production of about 5 million pounds (1958 to present) (38). Additional declines recently may indicate a new lower level of production and a fifth phase of exploitation. Another, similar analysis utilizes essentially the same periods with the exception of dividing the period of decline (1923-1958) into two segments bracketing the years prior to and following mainstem dam construction (46).

Exploitation rates, the percentage of the total run caught, at the height of commercial exploitation are estimated to have been in excess of 80 percent compared to estimated aboriginal exploitation rates of approximately 15 percent (19). Beginning with commercial exploitation and continuing in some cases until the mid-1940s, a wide range of traps, nets, and other miscellaneous fishing gear were utilized to capture fish. As late as the 1940s, gear such as large seines were used to take up to 70,000 pounds of salmon on single days. Such gear was not outlawed by both Washington and Oregon until 1949 (21,43).

Coincident with commercial exploitation was widespread settlement of the Columbia River Basin with accompanying natural resource exploitation in the form of mining, logging, and agriculture. Use of the many tributaries to the Columbia and Snake Rivers by anadromous fish was very obvious to the early settlers, and the potential damage to fish stocks by inappropriate use of these rivers and streams was clear. As early as 1848 the Oregon Territory had laws prohibiting obstruction of access to spawning and rearing habitat by dams or other means. However, the laws were not rigorously enforced and many dams were constructed that were barriers to fish. By the early 1930s, prior to construction of mainstem dams, it was reported that dams on the Columbia River and its tributaries had eliminated access by fish to approximately 50 percent of the most valuable salmon production areas. In addition, because of the state of the art in design and operation of fish ladders, many early attempts at providing passage for adult migrants were failures. An example was Sunbeam Dam, constructed on a tributary to the Salmon River to provide electric power for gold dredges. While Idaho Fish and Game evaluated the dam’s fish ladder as useless, the dam was permitted to operate for 20 years until 1934, earning the reputation of perhaps being the primary reason for loss of Redfish Lake sockeye salmon, now listed as an endangered species (43).

Significant dangers also existed for downstream migrants beginning during the earliest stages of settlement of the Columbia River Basin. As early as the 1870s large losses of smolt to irrigation diversions were observed. There were hundreds of larger irrigation diversions and perhaps thousands of smaller ones as farmers withdrew water for crops. Most of these diversions were unscreened, and untold millions of smolt and other juvenile fish were annually drawn into the diversions, ultimately ending up with the water on crops. In the early 1900s, laws passed much earlier but not rigorously enforced were amended, ordering irrigators and others operating water diversions to comply with screening laws. While many wanted to comply with the law, screening devices to do the job were not available. It wasn’t until 1911 that a revolving drum screening device was invented and in evaluation (21). There were myriad other less obvious impacts to salmon populations from agricultural practice. An example is the loss of riparian vegetation by logging, the conduct of farming, or destruction by cattle. Loss of riparian cover probably caused heating of stream water, negatively impacting adult migration and degrading the rearing environment for juveniles.

Review of history shows that Columbia River Basin salmon and steelhead stocks had been very significantly reduced from historic levels prior to construction of mainstem dams. The losses resulted from a variety of land use practices common at the time. Nevertheless, the result was wide-scale habitat modification and destruction concurrent with dramatic reduction in adult returns through commercial exploitation, sport fishing, and high rates of juvenile mortality by agricultural practice.

The first dam on the mainstem Columbia River was Rock Island Dam, which was put into service in 1933. Rock Island was a private dam, constructed by the Washington Electric Company (21). The first federal dam on the Columbia was Bonneville Dam, completed in 1938. Bonneville was followed by Grand Coulee Dam in 1941. Considerable thought was put into the design of fish ladders for Bonneville Dam. It was realized at the time that their success would depend on their ability to attract adult migrants, so the ladder entrances were supplied with water in addition to that flowing through the ladders to provide attraction flow. The Bonneville design was successful and was studied and used as the basis for the design of many other fish ladders within the Columbia River Basin and elsewhere.

Grand Coulee Dam was another matter all together. A high reservoir elevation was needed to enable pumping of water for irrigation purposes, plus a high-head dam would have greater power production potential. Therefore, in spite of initial congressional intention for a low-head dam, Grand Coulee was eventually built as a high-head dam, almost 550 feet tall. The problem for salmon with a dam as high as Grand Coulee was that fish ladders were not considered feasible for dams over 100 feet high. As a result, fish ladders were not built as part of Grand Coulee Dam, and salmon runs to all of the upper Columbia River drainage, literally hundreds of miles of rivers and streams and thousands of square miles of habitat, were forever cut off from access.

During the three decades following construction of Grand Coulee, eight more large dams were constructed on the mainstem Columbia and four on the lower Snake River. All but four of these dams were built by the federal government. In 1937, near completion of construction of Bonneville Dam, the Bonneville Power Administration (BPA) was created to market the power of Bonneville Dam and was later responsible for marketing the power of the whole Columbia River federal hydropower system. The role of BPA was changed in a very marked way in 1980 when Congress, upon creation of the NPPC with passage of the Pacific Northwest Electric Power Planning and Conservation Act (Public Law 96-501), charged BPA with implementation of the Columbia River Basin Fish and Wildlife Program to be developed by NPPC for restoration of Columbia River salmon and steelhead stocks.

The design of mainstem dams was driven by several objectives: power production, irrigation, flood control, recreation, and navigation. Other uses were lower priority while the priority of the major objectives changed from time to time. The emphasis on power production for Bonneville and Grand Coulee Dams may have been a decisive factor in the United States winning the Second World War. The large amount of power available permitted high-volume production of aluminum for airplanes and diversion of large amounts of power to the Hanford Works, where nuclear materials for the first atomic bombs were manufactured. However, the sites selected and aspects of the designs of dams did have additional negative impacts for fish. In the Snake River, lobbying by the Inland Empire Waterways Association resulted in locating the lower Snake River dams on the mainstem Snake to enable barge transport all the way to Lewiston, Idaho. Mainstem sites were eventually selected even though the economic return from navigation was considerably lower than that from power production and the potential for power production was greater at tributary sites, which would have greatly reduced the impact to Columbia River Chinook salmon stocks (43,62).

From the earliest days of fish harvest and natural resource utilization within the Columbia River Basin, there were always advocates for fish and investigators working to find ways to lessen the impact of human activities on the fish. However, funding for fish passage research was very scarce in the early years, partially because state and federal agencies failed to appreciate the value of systematic fish passage research. Most progress in addressing fish passage issues was through trial and error experimentation by a small number of dedicated biologists. Fish passage research was also not given a higher priority because there was widespread belief that artificial propagation of salmon and steelhead could overcome habitat losses. It was common during the dam-building decades for habitat lost through dam construction to be mitigated by construction and operation of fish hatcheries. It would not be until the 1980s that the failings of this strategy were better understood.

OVERVIEW OF COLUMBIA RIVER BASIN FISH PASSAGE RESEARCH: PAST TO PRESENT

Well-funded fish passage research did not really begin in the Columbia River Basin prior to initiation of construction of large mainstem dams. This came about because of an increasing realization in the 1930s by the public that the Columbia River fish stocks were in serious trouble. Incentive for fish passage research came from The Fish and Wildlife Coordination Act which was passed in 1934 and amended in 1946 and 1958. Initially the act required the U.S. Army Corps of Engineers (COE) and other water development agencies to consult with the states and the U.S. Fish and Wildlife Service about damage to natural resources. The later amendments placed increasing emphasis on natural resources, with the 1958 amendment requiring water development agencies to give conservation and enhancement of fish and wildlife equal consideration with other project objectives. Later in the 1970s, further emphasis was placed on fish and wildlife by the National Environmental Policy Act and the Endangered Species Act. Federal legislation has been augmented up to the present by the results of litigation such as the Boldt decision and the *United States* v. *Oregon* (21, 43).

Adult Fish Passage

The early years of fish passage research were focused on assisting upstream migration by adults. The first products of this effort were the successful fish ladders at Bonneville Dam (75). A very important factor during the early years of fish passage research was the existence of a fish passage laboratory at Bonneville Dam. The initial focus of the laboratory was to understand the apparent success of the Bonneville fish ladders, their success being a surprise to almost everyone involved. At the time of construction of the Bonneville ladders and, for that matter, a significant period following, virtually nothing was known about the design of fish ladders at the scales required for large dams that migrants would react favorably to and use. To meet these research needs the COE built the Bonneville Fisheries Engineering Research Laboratory in 1955. Significant amounts of fish passage research were conducted at the laboratory until its demise in 1985. Almost all of this work was basic fish behavioral research. Typical questions addressed included: the rate at which fish ascend fishways; maximum swimming velocities of fish; the optimum physical dimensions for fish ladders and other facilities; etc. (20).

Work on aspects of the migration of adult fish has been continuous over the intervening years and continues to the present. There has been a gradual transition from focus on issues related to the design and operation of fish ladders to resolution of uncertainties existing within a broader ecological context. Issues being addressed at present at several locations within the Columbia River Basin include habitat use, delays in passage at irrigation diversions, migration rates, substock separation, spawner success and production, including causes of prespawning mortality, and response of adults to factors such as flow manipulation for irrigation or power production, increased turbidity, and general decreased water quality due to irrigation (17,18,33,34,69). Adult passage work has been greatly assisted by developments in radio telemetry and the global positioning system. Improved instrumentation and deployment methods now permit adult migrants to be tracked over long distances with high spatial and temporal resolution. This work is permitting identification of problems that are limiting recovery of stocks as well as proving essential in developing strategies for other aspects of stock restoration. For example, an element of restoration of specific stocks may be hatchery supplementation. However, facilities for capture and holding of adult migrants must be located so that the stock of interest can be segregated from others. Fish tracking studies permit identification of those places within a watershed where a particular stock might be isolated for such purposes.

A system where wide adult migrant radio tracking study is to be performed beginning in 1996. The study will be funded by the COE and performed primarily by the National Marine Fisheries Services with cooperation by various other state and federal agencies, universities, and private utilities. The primary objective of the study is to observe the migratory behavior of adult salmon as they move through the hydropower system and onto their spawning grounds (25). Of particular interest are the delay of migrants at dams, fallback, straying, and prespawning mortality. The scope of the study includes the hydropower system as a whole, a considerable expansion in scope over most previous studies which tended to be project-specific, thereby very localized in comparison.

Juvenile Fish Passage

Protection of juvenile fish during downstream migration has historically focused in several areas. The areas of major investment in juvenile fish passage research have been: 1) protection from entrainment in irrigation diversions, 2) diversion from turbine intakes, 3) reduction in mortality due to predation, 4) reduction in exposure to high levels of dissolved gas, and 5) reduction in delay during outmigration. While listed as discreet juvenile fish passage concerns, there are interdependencies in the basic biology and behavior of juvenile fish between these elements. These interdependencies make experimentation to isolate an individual element quite difficult and also have resulted in overlap between research programs targeted on specific elements. This overview will be restricted to elements 1) and 2), with emphasis on diversion from turbine passage by surface collection.

The volume of research conducted in these areas, and others, to improve downstream passage for smolt has been huge. Literally hundreds of studies, almost all field studies, have been conducted within the last 40 years throughout the Columbia River Basin. These studies have greatly increased the knowledge base of the behavior and factors influencing the survivorship of smolt. The following sections will provide a brief overview of this work. This is not intended to be a synoptic review but rather an abbreviated guide to provide context for discussion of research currently in progress or planned for the immediate future.

Irrigation Diversion Screening

As mentioned previously, it was apparent to all who looked back to as early as the mid- to late-1800s that juvenile migrants were being entrained in irrigation diversions and killed on farmers' fields. Early records also show tension between the states and the federal government during this time. Although the states of Washington and Oregon had irrigation diversion screening laws as early as 1894, the federal government was not required to comply with the laws. In 1911, Oregon petitioned the federal government for compliance with Oregon state irrigation diversion screening laws (21).

As an element of the Fish and Wildlife Program, NPPC has identified screening of irrigation diversions as a priority (58). Irrigation diversions range from small, a few cubic feet per second, to large, thousands of cubic feet per second. Irrigation diversion screens are typically located downstream from the headworks for the diversion, sometimes a considerable distance, e.g., several hundreds of meters. Screening facilities for midsize and larger diversions typically have capability at the screening facility for separation of smolt from irrigation water. Following separation, smolt are returned to the mainstream via a fish return conduit. The tolerances for the mechanical and hydrodynamic elements of screening facilities are quite tight and must be kept in tolerance if the facility is to function properly and protect migrants. Evaluations conducted to date indicate that screening facilities kept in tolerance do provide high levels of protection to migrants (1,23,35,47,48,49,50,51).

Present research of irrigation diversion screening includes development and evaluation of behavioral barriers to reduce the number of migrants passing through headworks and into diversion canals. The reason for wanting to reduce the number of smolt entering the diversion canal is to reduce handling of migrants. While screening facilities are effective, they do require that smolt be passed through facilities to separate them from irrigation flow, concentrated into a smaller volume of water, and returned to the mainstream. The effects on smolt behavior and health of these actions are not clear, but the general assessment is to avoid them if possible. The Bonneville Power Administration, in cooperation with COE, has funded research beginning in 1995 into behavioral barriers. An objective of this research is to evaluate the use of infrasound to divert smolt at the headworks of irrigation diversion canals (52). Initial laboratory experiments recently completed have demonstrated avoidance by juvenile Chinook salmon and steelhead of high-intensity, high-particle-displacement 10-Hz sound. In addition, limited observations at a small irrigation diversion on the Umatilla River during the 1995 smolt outmigration have shown repulsion of Chinook salmon smolt from entering the irrigation canal (68).

Turbine Intake Passage and Diversion

At the time of construction of Bonneville Dam, conventional wisdom was that there was little danger of juvenile fish being injured during passage through hydro turbines. By the 1940s it was clear that passage conditions for fish through turbines could range from good to awful. Initial experiments indicated that direct mortalities through turbines typical of the Columbia River hydropower system were in the range of 15 percent (43). Subsequently, considerable research of fish passage through turbines was conducted in Europe and the United States (2,24,44). As a consequence of this work, operating criteria for Columbia River hydrosystem turbines was developed, the most significant being the mandate for operation of turbines at peak efficiency during periods of smolt passage.

There is currently a renewed interest in the conditions fish face during passage through turbines. Both the federal government and private utilities are performing studies to reassess injuries to smolt during passage through turbines. Recent experiments indicate 90-96 percent survival of juvenile salmon during turbine passage and that the majority of injuries observed are due to mechanical strike (63,64,65). As a result of study findings, the owners of Rocky Reach Dam are having the runners of a turbine modified to reduce the gap between the runner and the hub. This gap has been identified as the probable source for many, perhaps the majority, of mechanic injuries to juvenile fish during passage (22). In a comparable effort, COE is in the planning stage of a program to develop turbines that minimize the mortality of juvenile fish (72). Interest in providing a safer passage environment for juvenile fish is due to the fact that turbine bypass measures have not been and are unlikely to prove 100 percent effective. This means that some percentage of smolt will always pass through turbines. Under some conditions and for some species more so than others, a considerable proportion of a species may pass through turbines even when turbine bypass measures are fully implemented because of variation in migratory behavior between species and behavioral responses to turbine bypass guidance mechanisms.

Upon discovery that hydro turbines could kill and injure juvenile fish, considerable effort was made to develop methods to divert fish from turbine intakes. Early studies of the vertical distribution of smolt entering turbine intakes showed that many juvenile fish were located in the upper third of turbine intakes (39), although it was clear that smaller fish of all species and one or two species in total tended to be more deeply distributed (30,37). Experience with irrigation diversion screens and other similar screens led to development of a screen to be deployed in turbine intakes. Development continued through the 1960s, resulting in testing in 1969 of a prototype turbine intake screen at Ice Harbor Dam (40). Studies of prototype screens demonstrated that large numbers of juvenile fish could be diverted by turbine intake screens. When it was found that juvenile fish could be diverted and concentrated into bypass facilities, studies were initiated to evaluate the feasibility of transporting the juveniles to below Bonneville Dam, thereby eliminating their exposure to downstream dams. Initial evaluations showed positive results, and in 1971 a prototype collection and transportation system was evaluated at Little Goose Dam (43). At the present time, collector dams on the Columbia and Snake Rivers collect a significant portion of the total outmigration for transportation by truck and barge to below Bonneville Dam.

Development and evaluation of turbine intake screens continues to the present as the operation of those already installed is optimized and the design of those to be installed is refined. While most appear to be operating satisfactorily, not all intake screens are as effective as the vertical distribution of juvenile fish would imply. In general, it appears that juvenile fish respond to the modification of flow resulting from the presence of the intake screens, which, in at least the case of Rocky Reach Dam, rendered intake screening ineffective as a turbine bypass option (31,32). Visual observations of the behavior of smolt upon encounter with turbine intake screens has led to the hypothesis that the screens may act as hydromechanical sources of infrasound, which is detectable by salmonids and may be the stimulus for avoidance response (53,54).

There is considerable contention about the desirability of handling and transporting juvenile fish. While development, evaluation, and installation of turbine intake screens continue, other bypass alternatives are also being evaluated and, in the case of spill, utilized on a wide scale. The injury to fish during spill is thought to be significantly less than turbine passage and potentially even less than for fish diverted by intake screens and placed into bypass channels or otherwise handled (67). However, comparisons of the direct injury to smolt passing through turbines, spillways, and bypass systems have not been made at most dams. Assessment of smolt injury passing through dams via these various routes is an element of Phase II of the COE System Configuration Study Program which is at startup in 1995 (25).

Also an element of Phase II of the COE System Configuration Study is assessment of surface collection as a means of passing juvenile migrants past dams. The idea behind surface collection is to present a flow stimulus to downstream migrants that will take advantage of their natural outmigration behavior and lead them into a bypass leading around the dam or into collection facilities for transport. Surface collection is not a new concept and has been extensively tested with mediocre to poor success at scales considerably smaller than those required at mainstem Columbia River dams (27,28,61,66,70,74,73).

The impetus for retaining surface collection as a viable fish passage measure for mainstem Columbia and Snake River dams has been observations over the years of the high effectiveness and efficiency of ice and trash sluiceways, present at many Columbia River dams, under certain conditions as a means for bypassing migrants. Early investigation of the ice and trash sluiceway at Bonneville Dam indicated that during the day a large portion of total migrant passage was through the sluiceway, even through sluiceway flows were less than 5 percent of project total flow (41). This study lead to the recommendation that the ice and trash sluiceways at other projects be evaluated for downstream fish passage. In subsequent years similar studies were performed at The Dalles and Ice Harbor Dams (5,42,55,60). The findings in all these studies were similar. The sluiceways were very effective in passing migrants during the day, with effectiveness decreasing very markedly at night. While up to 80 percent of migrants passing the dam during the day might pass in sluiceway flows, sluiceway passage would drop to 20 percent or less of total passage at night. It soon became apparent that there were changes in the vertical distribution of migrants day to night and that there were probably other aspects of smolt behavior as well that determined the proportion of fish passing through sluiceways.

During the 1980s, in parallel with federally funded research to evaluate ice and trash sluiceways, Douglas County Public Utility District was evaluating modifications to its hydrocombine units at Wells Dam that might serve as a means to bypass smolt without using turbine intake screens. A hydrocombine is a unique design for a hydropower dam where the spill bays are located directly over the turbine units. Early studies of the distribution and passage behavior of smolt at Wells Dam indicated that the fish might pass in modified spill flows (3,4,5). Over the years between 1984 and 1993, Douglas County was able to develop a design for modification of spill bays and operation of the modified bays to achieve in excess of 90 percent passage of smolt in modified spill using approximately 5 percent of powerhouse hydraulic capacity (8,9,10,11,12,13,14,15,16,36).

Wells Dam has become the model for downstream migrant passage using surface collection concepts. The characteristics of the modified hydrocombine spill bays have become the basis for other efforts. The combination that proved successful was a slot 16 feet wide and approximately 70 feet deep, located at the face of the dam upstream of the spill gate. The spill gate downstream of the slot is operated so that velocities through the slot average approximately 2 feet per second. As in the case of the successful Bonneville Dam fish ladder 50 years earlier, it is not understood why the Wells Dam smolt bypass system works. There are some clues, one of which is the vertical distribution of smolt relative to the depth of the bypass slots. It appears that during both day and night periods at least 80 percent of the smolt approaching Wells Dam are located at depths less than 70 feet (71).

During the smolt outmigration of 1995, Public Utility District No. 1 of Chelan County tested a surface collection prototype at its Rocky Reach Dam. Characteristics of the operation of the Rocky Reach prototype surface collector are modeled after the Wells Dam bypass but utilize a completely different approach since Rocky Reach is a classical hydropower dam with separate powerhouse and spill. The evaluation of this prototype is still underway at the writing of this report, but initial evaluation appears favorable. Preliminary data indicates that the surface collector prototype may have passed more than an order of magnitude more smolt than the prototype bypass based on turbine intake screens evaluated in previous years (over 1 million smolt compared to 75,000). Based on this favorable performance, Chelan County expects to expand the coverage of the powerhouse by the prototype for the 1996 outmigration and continue evaluation (22).

Also during the 1995 smolt outmigration, Public Utility District No. 2 of Grant County evaluated a surface collection prototype at Wanapum Dam on the mainstem Columbia River. The design of this surface collector is different from both the Wells Dam bypass and the Rocky Reach prototype but it still utilizes the water velocities at the entrance to the collector found effective for the Wells Dam bypass in addition to other elements of the Wells bypass. The evaluation of this prototype was just ending at the time of writing this report and no preliminary estimates of effectiveness are available. It is expected that Grant County will continue experimentation with surface collection next year since the benefits to both fish and hydropower generation are well worth the effort and cost if a successful design and operating criteria can be found.

The year 1995 is also the startup year for the COE Surface Collection Program. As elements of this program, surface collector prototypes are being evaluated at The Dalles and Ice Harbor Dams by the Portland and Walla Walla Districts of COE, respectively. A variety of slot configurations and operation criteria is in evaluation. Preliminary data about the effectiveness and efficiency of the various designs were not available at the writing of this report. The Corps' Surface Collection Program is scheduled to continue through fiscal year 1998 and to expand to include other mainstem dams. Advanced planning for engineering designs continues. Harza Northwest recently submitted a report of general concepts for surface bypass at Bonneville Dam (29).

The success of the Wells Dam bypass, the apparent success of the Rocky Reach surface collector prototype, and the history of the high effectiveness and efficiency of sluiceway bypass during the day assures that testing of surface collection will continue well into the future. Surface collection is a very attractive bypass option because of the possibility of passing a high proportion of smolt using a relatively small amount of water, leaving the rest for power production, and working with, not against, the natural behavior of smolt. Within the group of biologists and engineers working with surface collection in the Columbia River Basin there is a desire to conduct controlled experiments under larger-scale laboratory conditions, following the model of the Bonneville Fisheries Engineering Laboratory. In general, it is the feeling of most concerned that some laboratory testing is needed to understand why surface collection, or more precisely, flow attraction, works. The challenge at this time is that no facility exists within the Columbia River Basin suitable for such work. In lieu of such facilities, and the need to move forward aggressively with smolt passage improvements, the needed observations of fish behavior are being obtained at field scales using hydroacoustic, radio tracking, and video monitoring technologies.

For successful surface collection at least two things that depend upon the behavior of smolt must occur. One of these is that the smolt must be able to locate the collector, and the second is that the physical characteristics of the collector and the flow field its operations generate must attract, or at least not repel, smolt. Considerable effort has gone into review of available information about the behavior of smolt as they approach the various mainstem dams. Such information is critical to locating surface collectors so that the opportunity for discovery by smolt of the flow fields generated by their operation is maximized. However, review of information provided by previous studies of smolt behavior have been disappointing. Unambiguous models of smolt behavior on approach to a dam cannot be developed, and information about the behavior of smolt in accelerating flow fields is almost nonexistent (26). Large scale radio tracking studies are being considered to provide the necessary smolt behavior information.

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Appendix B: Experimental Guidance Devices: NMFS Position Statements

B

EXPERIMENTAL FISH GUIDANCE DEVICES: POSITION STATEMENT OF NATIONAL MARINE FISHERIES SERVICE NORTHWEST REGION JANUARY 1995

NMFS Northwest Region Position Paper on Experimental Technology for Managing Downstream Salmonid

Summary

NMFS believes that positive-exclusion barrier screens, as described below, are appropriate for utilization in the protection of downstream migrant salmon at all intakes. However, the process described herein delineates an approach whereby experimental behavioral guidance devices can be evaluated and (if comparable performance is confirmed to the satisfaction of NMFS) installed in lieu of screens.

Introduction

Numerous stocks of salmon and steelhead trout in Pacific Northwest streams are at low levels and many stocks continue to decline. Idaho sockeye salmon and Snake River spring, summer, and fall chinook are listed as "endangered" under the Endangered Species Act. Petitions for additional listings are pending. It is essential to provide maximum protection for all salmonid juveniles to halt and reverse overall population declines.

The death and injury of juvenile fish at water diversion intakes have long been identified as a major source of fish mortality [Spencer, 1928; Hatton, 1939; Hallock and Woert, 1959; Hallock, 1987]. Fish diverted into power turbines incur up to 40 percent immediate mortality, while also experiencing injury, disorientation and delay of migration that may increase predation related losses [Bell, 1991]. Fish entrained into agricultural and municipal water diversions experience 100 percent mortality. Diversion mortality is the major cause of decline in some fish populations. For the purposes of this document, diversion losses include turbine, irrigation, municipal, and all other potential fish losses related to the use of water by man.

Positive-exclusion barrier screens which screen the entire diversion flow have long been used to prevent or reduce entrainment of juvenile fish for diversions of up to 3,000 cfs. In recent decades, design improvements have been implemented to increase the biological effectiveness of positive-exclusion screen and bypass systems by taking advantage of known behavioral responses to hydraulic conditions. Recent evaluations have consistently demonstrated high success rates (typically greater than 98 percent) at moving juvenile salmonids past intakes with a minimum of delay, loss, or injury.

(For diversion flows over 3,000 cfs, such as at Columbia River main-stem turbine intakes, submerged traveling screens or bar screens are commonly used. These are not considered positive-exclusion screens in the context of this position statement.)

The past few decades have also seen considerable effort in developing "startle" systems to elicit a taxis (response) by the fish, with an ultimate goal of reducing entrainment. This paper addresses research performed to avoid losses at intakes and presents a position statement reviewing and implementing future fish protection measures.

Juveniles at Intakes

Entrainment, impingement, and delay/predation are the primary contributors to the mortality of juvenile migrating salmonids. Entrainment occurs when fish are drawn into the diversion canal or turbine intake. Impingement occurs when a fish is not able to avoid contact with a screen surface, trashrack, or debris at the intake. This can cause bruising, descaling, and other injuries. Impingement, if prolonged, repeated, or occurring at high velocities, also causes direct mortality. Predation (which is the leading cause of mortality at some diversion sites) occurs when fish are preyed upon by aquatic or avian animals. Delay at intakes increases predation by stressing or disorienting fish and/or by providing habitat for predators.

Positive-exclusion screen and bypass systems (PESBS)

Design criteria for PESBS have been developed, tested, and proven to minimize adverse impacts to fish at diversion sites. Screens with small openings and fish-tight seals are positioned at a slight angle to flow. This orientation allows fish to be guided to safety at the downstream end of the screen, while they resist being impinged on the screen face. These screens are effective at preventing entrainment [Pearce and Lee, 1991]. Carefully designed bypass systems minimize fish exposure to screens and provide hydraulic conditions that safely return fish to the river, thereby preventing impingement [Rainey, 1985]. The PESBS are designed to minimize entrainment, impingement, and delay/predation, from the point of diversion through the facility to the bypass outfall.

PESBS have been installed and evaluated at numerous facilities [Abernethy, et al., 1989; 1990; Rainey, 1990; Johnson, 1988]. A variety of screen types (e.g., fixed-vertical, drum, fixed-inclined) and screen materials (e.g., woven cloth [mesh], perforated plate, profile wire), have proven effective, when used in the context of a satisfactory design for the specific site. Facilities designed to previously referenced criteria consistently resulted in a guidance efficiency of over 98 percent [Hosey, 1990; Neitzel, 1985; 1986; 1990a; 1990b; 1990c; 1990d; 1991].

The main detriment of PESBS is cost. At diversions of several hundred cubic feet per second and greater, the low velocity requirement and structural complexity can drive the cost of fish passage to over $1 million. At the headworks, the need to clean the screen, remove trash, control sediment, and provide regular maintenance (e.g., seasonal installation, replacing seals, etc.) also increases costs.

Behavioral devices

Due to the high costs of PESBS, there has been considerable effort since 1960 to develop less expensive behavioral devices as a substitute for positive fish protection [EPRI, 1986]. A behavioral device, as opposed to a conventional screen, requires a volitional taxis on the part of the fish to avoid entrainment. Some devices were investigated with the hope of attracting fish to a desired area while others were designed to repel fish. Most studies focused on soliciting a behavioral response, usually noticeable agitation, from the fish.

Investigations of prototype startle-response devices document that fish guidance efficiencies are consistently much lower than for conventional screens. Experiments show that there may be a large behavioral variation between individual fish of the same size and species to startle responses. Therefore, it cannot be predicted that a fish will always move toward or away from that stimulus. Until shown conclusively in laboratory studies, it should not be assumed that fish can discern where a signal is coming from and what constitutes the clear path to safety.

If juvenile fish respond to a behavioral device, limited size and swimming ability may preclude small fish from avoiding entrainment (even if they have the understanding of where to go and have the desire to get there). Another concern is repeated exposure; fish may no longer react to a signal after an acclimation period. In addition to vagaries in the response of individual fish, behavioral variations due to species, life stage, and water quality conditions can be expected.

Another observation is that past field tests of behavioral devices have been deployed without consideration of how controlled ambient hydraulic conditions (i.e., the use of a training wall to create uniform flow conditions, while minimizing stagnant zones or eddies that can increase exposure to predation) can optimize fish guidance and safe passage away from the intake. Failure to consider that hydraulic conditions can play a big role in guiding fish away from the intake is either the result of the desire to minimize costs or the assumption that behavioral devices can overcome the tendency for poor guidance associated with marginal hydraulic conditions. The provision of satisfactory hydraulic conditions is a key element of PESBS designs.

The primary motivation for selection of behavioral devices relates to costs. However, much of the cost in PESBS is related to construction of physical structures to provide hydraulic conditions which are known to optimize fish guidance. Paradoxically, complementing the behavioral device with hydraulic control structures needed to optimize juvenile passage will compromise much of the cost advantage relative to PESBS.

Skepticism about behavioral devices, at this stage of their development, is supported by the fact that few are currently being used in the field and those that have been installed and evaluated seldom show consistent guidance efficiencies over 60 percent [Vogel, 1988; EPRI, 1986]. The louver system is an example of a behavioral device with a poor record. Entrainment rates were high, even with favorable hydraulic conditions, due to the presence of smaller fish. Entrainment can be high, particularly when operated over a wide range of hydraulic conditions [Vogel, 1988; Cramer, 1973; Bates, 1961]. Due to their poor performance, most of these systems were eventually replaced by PESBS.

Experimentation Process

However, there is potential for future development of new and acceptable screening and behavioral guidance devices that will safely pass fish at a rate comparable with PESBS. These new concepts are considered “experimental” until they have been through the process described herein and have been proven in a prototype evaluation validated by National Marine Fisheries Service (NMFS). These prototype evaluations should occur over the foreseeable range of adverse hydraulic and water quality conditions (e.g., temperature, dissolved oxygen). NMFS encourages research and development on experimental fish protection devices, and stipulates that the following elements should be addressed during the process of developing experimental juvenile passage protection concepts:

1) *Consider earlier research*. A thorough review of similar methods used in the past should be performed. Reasons for substandard performances should be clearly identified.
2) *Study plan*. A study plan should be developed and presented to NMFS for review and concurrence. It is essential that tests occur over a full range of possible hydraulic, biological, and ecological conditions that the device is expected to experience. Failure to receive

study plan endorsement from NMFS may result in disputable results and conclusions.

3) *Laboratory research.* Laboratory experiments under controlled conditions should be developed using species, size, and life stages intended to be protected. For behavioral devices, special attention must be directed at providing favorable hydraulic conditions and demonstrating that the device clearly induces the planned behavioral response. Studies should be repeated with the same test fish to examine any acclimation to the guidance device.
4) *Prototype units.* Once laboratory tests show high potential to equal or exceed success rates of state-of-the-art screening, it is appropriate to further examine the new device as a prototype under real field conditions. Field sites must be fully appropriate to (a) demonstrate performance at all expected operational and natural variables, (b) evaluate the species, or an acceptable surrogate, that would be exposed to the device under full operation, and (c) avoid unacceptable risk to depressed or listed stocks at the prototype locations.
5) *Study results.* Results of both laboratory tests and field prototype evaluations must demonstrate a level of performance equal to or exceeding that of PESBS before NMFS will support permanent installations.

Conclusions

During the course of the past few decades, we have seen an increase in the number of unscreened stream diversions, and this trend is likely to continue unless corrective measures are implemented. Concurrently, anadromous fish numbers have dwindled. Proven fish passage and protection facilities, which have demonstrated high guidance rates at other sites, can provide successful passage at most diversion intakes.

Periodically, major initiatives have been advanced to examine the feasibility of experimental guidance systems. Results were generally poor or inconclusive, with low guidance efficiencies attributable to the particular device used. Often results were based on a small sample size, or varied with operational conditions. In addition, unforeseen operational and maintenance problems (and safety hazards) were sometimes a byproduct.

Nevertheless, some of these experiments show potential. To further advance fish protection technology, NMFS will not oppose tests that proceed in accordance with the tiered process outlined above. To ensure no further detriment to any fish resource, including delays in implementation of acceptable passage facilities, experimental field testing should occur with the simultaneous design and development of a PESBS for that site. This conventional system should be scheduled for installation in a reasonable time frame, independent of the experimental efforts. In this manner, if the experimental guidance system once again does not prove to be as effective as a PESBS, a proven screen and bypass system can be implemented without additional delay and detriment to the resource.

Adopted January 6, 1995

WILLIAM STELLE, JR.

Regional Director

EXPERIMENTAL FISH GUIDANCE DEVICES: POSITION STATEMENT OF NATIONAL MARINE FISHERIES SERVICE SOUTHWEST REGION JANUARY 1994

NMFS Southwest Region Position Paper on Experimental Technology for Managing Downstream Salmonid Passage

Introduction

Numerous stocks of salmon and steelhead trout in California streams are at low levels and many stocks continue to decline. The Sacramento River winter-run chinook salmon is listed as “endangered” under the Federal Endangered Species Act. Petitions for additional listings are pending. It is essential to provide maximum protection for juveniles to halt and reverse these declines.

The injury or death of juvenile fish at water diversion intakes have long been identified as a major source of fish mortality [Spencer, 1928; Hatton, 1939; Hallock and Woert, 1959; Hallock, 1987]. Fish diverted into power turbines experience up to 40 percent mortality as well as injury, disorientation, and delay of migration [Bell, 1991], while those entrained into agricultural and municipal water diversions experience 100 percent mortality. Diversion mortality is the major cause of decline in some fish populations.

Positive barrier screens have long been tested and used to prevent or reduce the loss of fish. Recent decades have seen an increase in the use and effectiveness of these screens and bypass systems; they take advantage carefully designed hydraulic conditions and known fish behavior. These positive systems are successful at moving juvenile salmonids past intakes with a minimum of delay, loss, or injury.

The past few decades have also seen much effort in developing "startle" systems to elicit a taxis (response) by the fish with an ultimate goal of reducing entrainment. This Position Statement addresses research designed to prevent fish losses at diversions and presents a tiered process for studying, reviewing, and implementing future fish protection measures.

Juveniles at Intakes

The three main causes of delay, injury, and loss of fish at water intakes are entrainment, impingement, and predation. Entrainment occurs when the fish is pulled into the diversion and passes into a canal or turbine. Impingement is where a fish comes in contact with a screen, a trashrack, or debris at the intake. This causes bruising, descaling, and other injuries. Impingement, if prolonged, repeated, or occurs at high velocities, also causes direct mortality. Predation also occurs. Intakes increase predation by stressing or disorienting fish and/or by providing habitat for fish and bird predators.

Positive barriers

Positive barrier screen systems and criteria for their design have been developed, tested, and proved to minimize harm caused at diversions. Positive barriers do not rely on active fish behavior; they prevent physical entrainment with a physical barrier. Screens with small openings and good seals are designed to work with hydraulic conditions at the site, providing velocities normal to the screen face and sufficient sweeping velocities to move fish past the screen. These screens are effective at preventing entrainment [Pearce and Lee, 1991]. Carefully designed bypass systems minimize fish exposure to screens and provide hydraulic conditions that return fish to the river, preventing both entrainment and impingement [Rainey, 1985]. The positive screen and fish bypass systems are designed to minimize predation, and to reduce mortality, stress, and delay from the point of diversion, through the bypass facility, and back to the river.

Carefully designed positive barrier screen and bypass systems have been installed and evaluated at numerous facilities [Abernethy, et al., 1989; 1990; Rainey, 1990; Johnson, 1988]. A variety of screen types (e.g., flat plate, chevron, drum) and screen materials (e.g., woven cloth, perforated plate, profile wire), have proved effective, taking into consideration their appropriateness for each site. Well-designed facilities consistently result in a guidance efficiency of over 95 percent [Hosey, 1990; Neitzel, 1985; 1986; 1990a; 1990b; 1990c; 1990d; 1991].

The main drawback to positive barrier screens is cost. At diversions of several hundred cubic feet per second or greater, the low velocity requirements and structural complexity can drive the cost for fish protection and the associated civil works over a million dollars. At the headwork, the need to clean the screen, remove trash, and provide regular maintenance (e.g., seasonal installation, replacing seals, etc.) also increase costs.

Behavioral devices

Due to higher costs of positive barrier screens, there has been much experimentation since 1960 to develop behavioral devices as a substitute for barrier screens [EPRI, 1986]. A behavioral device, as opposed to a positive (physical) barrier, requires a volitional taxis on the part of the fish to avoid entrainment. Early efforts were designed to either attract or repel fish. These studies focus on soliciting a behavioral response from the fish, usually noticeable agitation. Using these startle investigations to develop effective fish guidance systems has not been effective.

Experiments show that there is a large response variation between individual fish of the same size and species. Therefore, it cannot be predicted that a fish will always move toward or away from a certain stimulus. Even when such a movement is desired by a fish, it often cannot discern the source or direction of the signal and choose a safe escape route.

Many behavioral devices do not incorporate and use a controlled set of hydraulic conditions to assure fish guidance, as does the positive screen/bypass system. The devices can actually encourage fish movement that contrasts with the expected rheotactic response. Thus, the fish gets mixed signals about what direction to move. Another concern is repeated exposure; a fish may no longer react to a signal that initially was an attractant or repellent. In addition to the vagaries in the response of an individual fish, behavior variations are expected due to size, species, life stage, and water quality conditions.

In strong or accelerating water velocity fields, the swimming ability of a fish may prevent it from responding to a stimulus even if it attempts to do so. Other environmental cures (e.g., pursuing prey, avoiding predators, or attractive habitat) may cause a fish to ignore the signal.

A main motivation for opting to install behavioral devices is cost-savings. However, much of the cost in conventional systems is for the physical structure needed to provide proper hydraulic conditions. Paradoxically, complementing a behavioral device with its own structural requirements may lessen much of its cost advantage.

Present skepticism over behavioral devices is supported by the fact that few are currently being used in the field and those that have been installed and evaluated seldom exhibit consistent guidance efficiencies above 60 percent [Vogel, 1988; EPRI, 1986]. The louver system is an example of a behavioral device with a poor success record. In this case, even with the use of favorable hydraulics, performance is poor especially for small fish. Entrainment can be high, particularly when operated over a wide range of hydraulic conditions [Vogel, 1988; Cramer, 12973; Bates, 1961]. Due to their poor performance, some of these systems are already replaced by positive barriers.

Experimentation Process

However, there is potential for developing new positive screens as well as behavioral guidance devices for the future. Nonetheless, experimental technology must achieve, over the foreseeable range of adverse conditions, a consistent level of success that equals or exceeds that of the best available technology. It should be a deliberate, logical process. NMFS will not discourage research and development on experimental fish protection devices if the following tiered study process is incorporated:

1) *Consider earlier research.* A thorough review should be performed of past methods similar to that proposed. Reasons for substandard performances of these earlier methods should be clearly identified.
2) *Study plan.* A study plan should be developed and presented to NMFS for review and concurrence. It is essential that tests occur over a full range of possible hydraulic, biological, and ecological conditions that the device is expected to experience.
3) *Laboratory research.* Controlled laboratory experiments should be developed using species, size, and life stages intended to be protected (or acceptable surrogate species). For behavioral devices, special attention must be directed at providing favorable hydraulic conditions and demonstrating that the device clearly causes the planned behavioral response. Studies should be repeated with the same test fish to examine and habituation to the stimulus.
4) *Prototype units.* Once laboratory tests show high potential to equal or exceed success rates of state-of-the-art screening, it is appropriate to further examine the new device as a proto-

type under real field conditions. Field sites must be fully appropriate to 1) demonstrate all operation and natural variables expected to influence the device performance, 2) evaluate the species, or an acceptable surrogate, that would be exposed to the device under full operation, and 3) avoid unacceptable risk to resources at the prototype locations.

5) *Study results*. Results of both laboratory tests and prototype devices examined in the field must demonstrate a level of performance equal to or exceeding that of conventional, established technology before NMFS will support further installations.

Conclusions

In the course of the past few decades, we have seen increased demand for water diversions. This trend is likely to continue. Accompanying this demand is a corresponding decline of fisheries. Therefore, prudence dictates that fish protection facilities be held to the highest practicable level of performance.

A major effort was made to examine experimental guidance systems over several decades by a variety of funding agencies. The results were generally poor or inconclusive, with low guidance efficiencies attributable to the particular device used. Often results were based on a small sample size or varied with operation conditions. In addition, unforeseen operational and maintenance problems, including safety hazards, sometimes developed.

Nevertheless, some of these experiments show potential. To further improve fish protection technology, NMFS will not oppose tests that proceed in the tiered process outlined above. Further, to ensure no further detriment to fish, experimental field testing should be done with the simultaneous design of a positive barrier and bypass system for that site. This conventional system should be scheduled for installation immediately, if the experimental guidance system, once again, does not prove to be as effective as a conventional system.

Adopted January 11, 1994
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Acting Regional Director

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