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

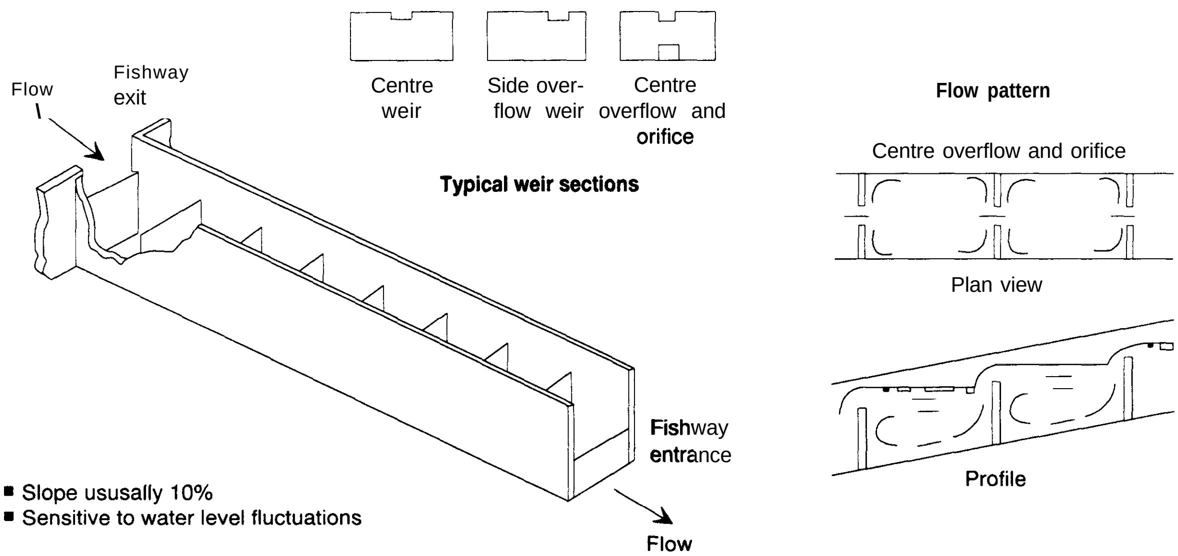
The pool and weir ladder has the longest history of use. Pool and weir fish ladders are designed primarily to provide plunging flow and ample resting areas that provide leaping fish with hydraulic assistance in moving upstream (15,120) (see figure 3-1). In these fishways, pools are arranged in a stepped 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).

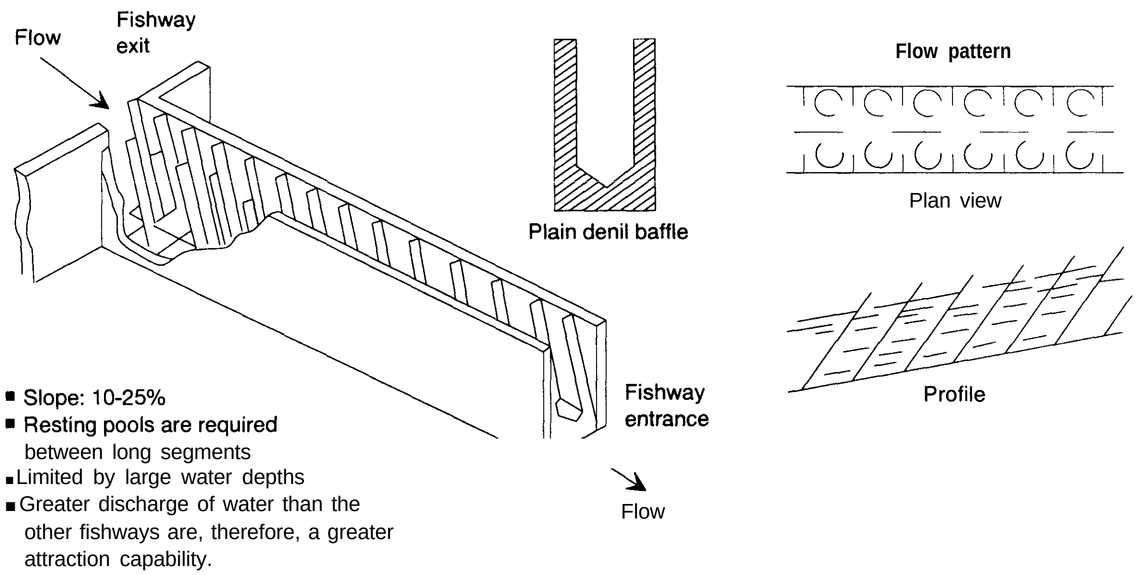
Some pool and weir fishways have submerged orifices that allow fish to pass upstream without cresting each weir (121). Weir and orifice/weir fishways have been used successfully by anadromous salmonids, but not readily by alewife, shad and other fish that rarely leap over obstacles or swim through submerged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

FIGURE 3-1: Weir Fishway



SOURCE: C. Katopodis, 1992.

FIGURE 3-2: Plain Denil Fishway



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.

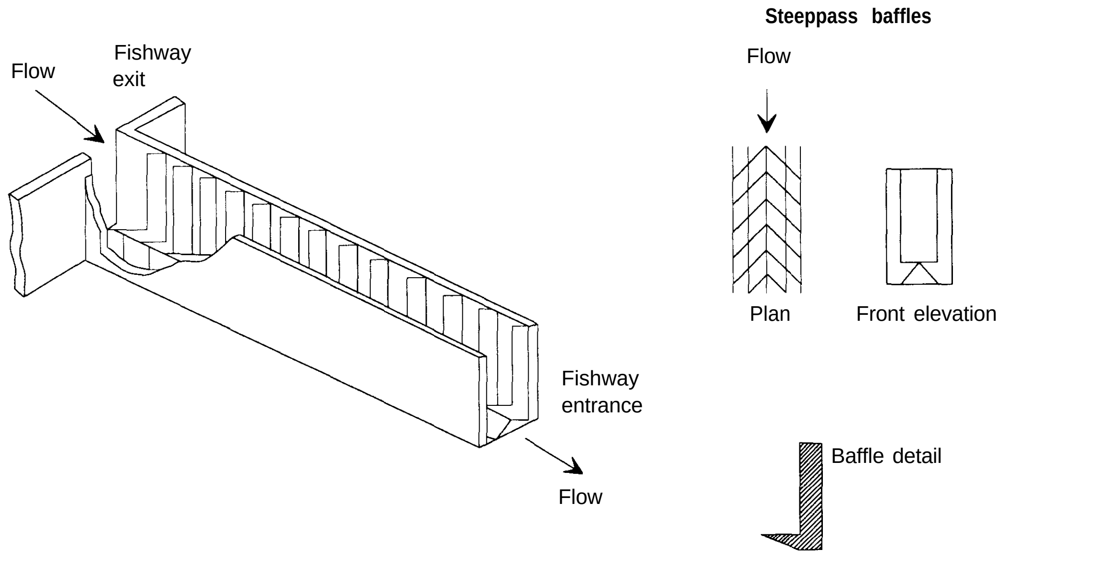
The steeppass has a more complex configuration of baffles than the standard Denil, is more efficient in controlling water velocity, and is operable at steeper slopes (up to about 33 percent for salmon and steelhead). The maximum slope, and therefore the water velocity within the fishway, is a design 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).

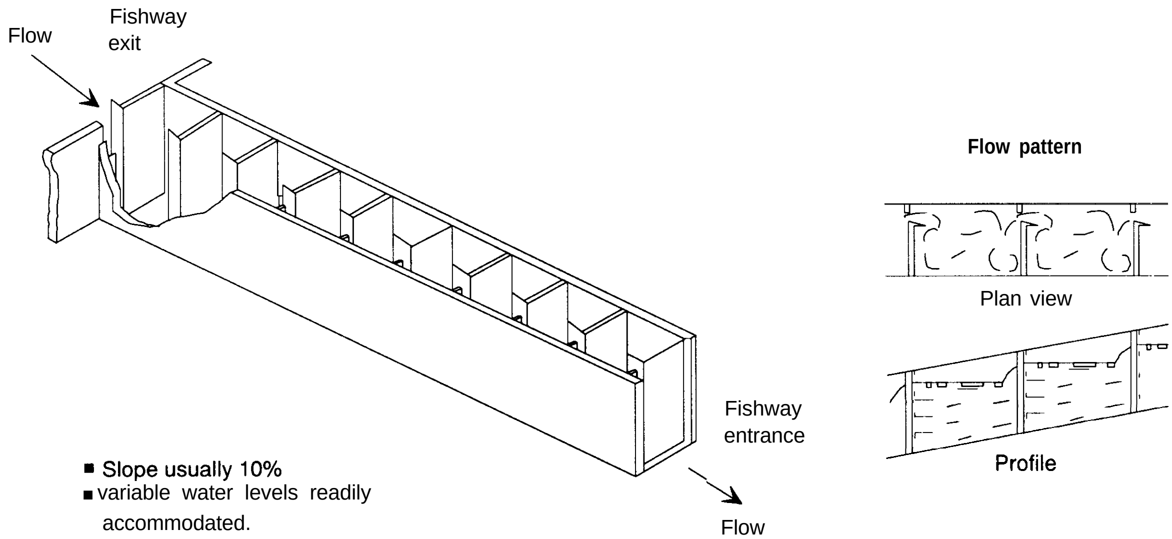
Fish are assumed to move from slot to slot in a nearly direct path (this has not, however, been verified) while swimming at their preferred depth (15). Fish use a "burst-rest" pattern to move up the fishway from pool to pool (121). Pools provide an opportunity to rest, but fish must exert a burst of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

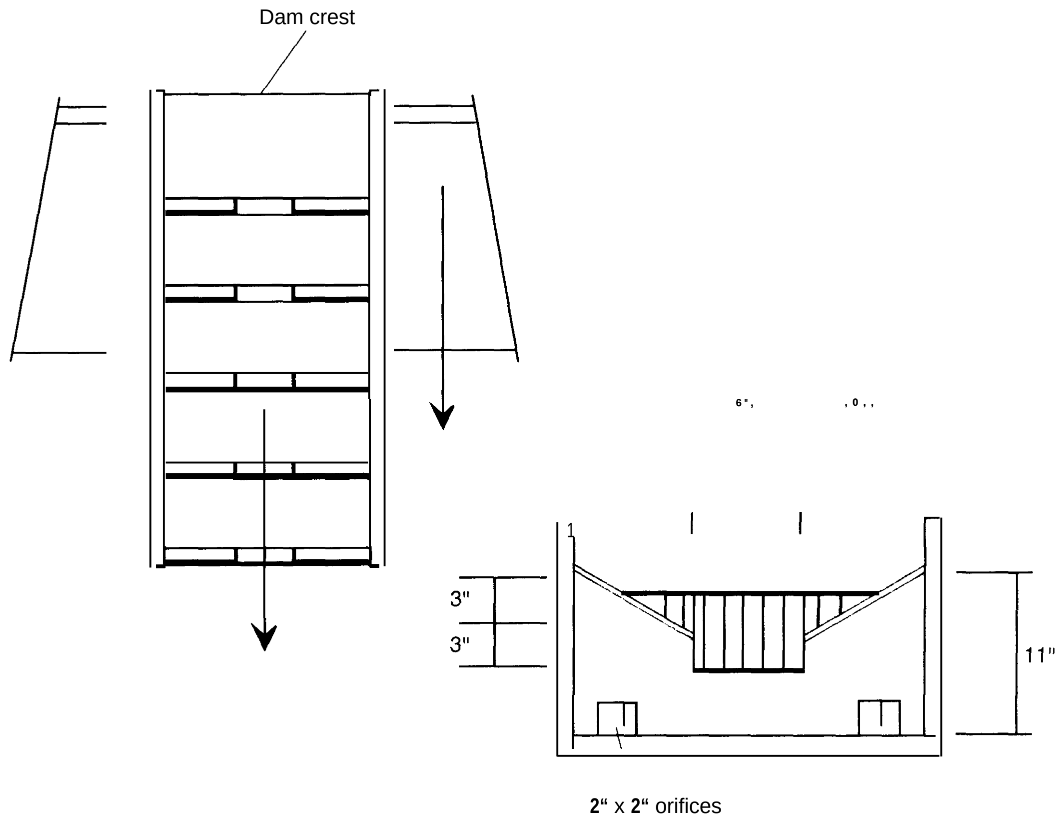
The design features of several types of ladders may also be combined in a single fishway design to accommodate variations in flows (186) or multiple target fish. Features of pool and weir, vertical slot and roughened channel (Denil) designs can be brought together (see figure 3-5).

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.