FISHWAY GUIDELINES
FOR WASHINGTON STATE

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Washington Department of Fish and Wildlife

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GUIDELINES FOR SALMONID HABITAT PROTECTION AND RESTORATION

As part of Washington State's salmon recovery strategy, the Washington State Departments of Fish and Wildlife, Ecology, and Transportation, are currently developing guidelines for salmon habitat protection and restoration. The standards and guidelines are a series of manuals, workshops, and other tools addressing various activities of salmon habitat protection and restoration and are intended to [KB1]ensure compliance with requirements of the federal Endangered Species Act and state salmon restoration policies.

This document is one of a series of documents that will make up the guidelines. Additional subjects for which guidelines have been (as of April, 2000) or will be developed are:

Bank protection – Integrated Streambank Protection Guidelines is currently being developed.
Fish passage at road culverts – Fish Passage at Road Culverts is available.
Fishways guidelines are currently being developed.
Sand and gravel removal guidelines.
Estuary restoration guidelines.
Shoreline salmonids habitat restoration guidelines.
Freshwater habitat restoration guidelines.
Channel design guidelines.

The guidelines will be published on the web when complete. Parts of the guidelines will also be available on the web as "works in progress" while they are still draft. Workshop opportunities will also be posted on the web. These resources are located as technical assistance at http://www.wa.gov/wdfw/habitat.htm.

ACKNOWLEDGEMENTS

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FISHWAY DESIGN GUIDELINES - INTRODUCTION

A fishway is any structure or modification to a natural or artificial structure for the purpose of fish passage. Components of a fishway may include: attraction features, a barrier dam, entrances, auxiliary water systems, collection and transportation channels, a fish ladder, an exit, and operating and maintenance standards. It can be a formal concrete structure, pools blasted in the rock of a waterfall or log controls in the bed of a channel. The water and fish, of course, are necessary parts of the system. The design of key features of fishways is the subject of this guideline.

This publication describes guidelines for the design of fish passage facilities for upstream migrating fish and are the result of both formal studies and practical experience. Though applying specifically to Pacific salmon and steelhead, the guidelines are also applicable to other anadromous and resident fish species. They also apply to a wide range of potential project sites encountered; from mainstem rivers such as the Columbia, to small culverts under country roads.

These guidelines do not discuss swimming ability of fish other than as it directly relates to fishway design nor do the guidelines discuss the analysis and determination of fish passage barriers.

This document is a guideline only. It is intended to describe how to comply with specific design criteria or other fish protection requirements. Design criteria generally accepted by Washington Department of Fish and Wildlife (WDFW) are included as a guide. Design criteria and requirements for a specific site or facility should be verified directly with WDFW and National Marine Fisheries Service (NMFS) and/or United States Fish and Wildlife Service (USFWS). Contacts are provided in Appendix X Fish Passage Contacts in Washington State. These guidelines cover common situations where fish screens are required; different or additional requirements may be stipulated for specific installations.

PRE-DESIGN REQUIREMENTS

A variety of physical, hydrologic, and biologic considerations determine whether a given obstruction is passable to fish. For this reason, information gathered prior to initiating a design, provides a foundation for the technical analysis. Collecting and understanding these data, developing a consensus on the relevant design criteria should be completed prior to investing in technical design.

Biological Data

Fish passage design is based on biological criteria. Often that criteria specifies providing for the weakest species requiring passage and accommodating the weakest individual within that species. Management objectives may, however, direct passage of certain species or age classes. Biological information critical at the pre-design stage includes the identification of the following:

- What species are targeted for passage ?
- When are they present ?
- What are their swimming abilities ?
- What behaviors can be used to enhance their passage success ?

<u>Design criteria considerations</u>
The development of criteria for adult upstream passage and juvenile downstream passage differ. Upstream passage criteria tend to optimize passage conditions based on selecting the best known technology and optimum conditions. Downstream passage criteria often requires a specific efficiency or performance. The difference is because inadequacies in upstream passage cause delay whereas, in downstream passage, they result in fish mortality. For this reason, upstream passage conditions tend to be more difficult to evaluate quantitatively than downstream passage.

The following biological variables should be considered in designing passage improvements.

<u>Species</u>
Species of fish are the most basic variable in passage design. The swimming and leaping capabilities of species determine design criteria though the design criteria among species of salmon and steelhead vary little. However, other fish species, though not the primary intended target of a fish passage design, should also be considered. Fishways on the Columbia River were not originally intended for commercially insignificant shad. Passage research instead focused on salmon and steelhead. Fishways were initially a blockage or at least a hindrance to shad passage; they accumulated within the Bonneville fishway, at times, to the extent that they blocked the passage of salmon. Later, modifications to the fishways allowing shad passage resulted in American Shad populations in the Columbia River expanding from about two hundred thousand in the early 1960s to as many as four million passing the Dalles dam in 1990.

Design of fish passage for resident species in North America is often difficult. Migrations for adfluvial spawning, feeding, redistribution due to density and water quality are common among resident fish. Resident species often migrate at younger life stages with their migration timing and motivation largely unknown. Resident species tend to be swimmers rather than leapers. To their benefit, they may move at lower stream flows and delay may not be as significant as it is for anadromous fish.

Species such as chum salmon, that may have a stream residency of only a few days, may be more impacted by a minor delay than other species. The impact associated with chum delay is unsuccessful spawning. For coho, a delay can result in a poor distribution of spawners through a watershed. Delay of any salmon species can result in a loss of production. All obstructions, whether mitigated with fishways or not, cause migration delay. A well designed culvert will cause minor delay; changes in hydraulics and light conditions are enough to cause fish to hesitate. The larger the river, the greater the likely delay. It is not uncommon to experience delays up to a day at fishways in large rivers. The fish passage design criteria and the design hydrology described below are conservative in an attempt to mitigate the inevitable delay.

Behavior

Behavior of fish is critical to fish passage design and is often a function of species. Shoreline and depth orientation during migration, where they hold, their response to hydraulic, light, and enclosure conditions are important factors to be considered. Though chum salmon (and pink) are powerful swimmers, they refuse to leap; while a minor plunging drop of less than a foot can be a barrier, a steep chute, four feet high, is easily swum through.

In addition, the condition of the fish may influence design criteria. For instance, the swimming capabilities of anadromous fish generally decline as fish migrate upstream.

Timing

Understanding the seasonal, as well as diurnal, behavior of the target fish is important in setting the period of operation and the range of flows the fishway will eventually operate. Understanding the migration timing of the target species helps to define the impact of a migration delay.

Most adult salmon migrate during daylight hours. **Figure x** shows the timing of steelhead passage at Lower Granite Dam in 1992 and is typical of timing seen elsewhere. As at Lower Granite, there is often a peak of migration in the early daylight hours followed by a continuous rate of movement during the day. Passage declines to a low level at night. This migration timing is typical for salmon, though it can vary considerably. For instance, sockeye salmon passage at Zosel Dam (Okanogan River, Washington) for the same year was concentrated at night; 94.9% of the fish moved through the ladder between the hours of 8:00 PM to 4:00 AM with 12% of the run passing in a single day. However, the timing of passage may have been influenced by water temperature. Sockeye, that year, had been blocked for possibly more than a month downstream by a thermal barrier at the river's mouth.

Age

Fish passage programs tend to concentrate on upstream improvements for adult fish typically ignoring the need for juvenile passage. The ability of juvenile fish to redistribute, both upstream and downstream, into favorable rearing habitats, has been found important to the continued viability of many stocks. Juvenile anadromous fish that remain in fresh water substantial periods of time before migrating downstream are particularly vulnerable to blockages in small streams.

Size

Fish passage is designed for the smallest fish of the species requiring passage. The minimum and maximum sizes of fish of each species may determine maximum velocities, drops, and minimum depths in the fishway design. Swimming capabilities are a function of fish size and are an important consideration in the design of culverts and modifications to falls.

Run size

The peak magnitude of a fish run may control the size of a fishway or its collection pools. Hell's Gate (Fraser River, British Columbia, Canada) are examples where the size of the fishway was regulated by the size of the run expected. This is rarely the case, however, hydraulic considerations within the fishway pools normally control the design.

Site Data

At the pre-design stage, relevant site data should include a physical description of the barrier, the river channel, and uplands in proximity to the site. In addition, conceive a working description of potential designs of the fish passage resolution and its potential operation. Getting a good site description is most essential for small projects where extra field trips can become a substantial burden to the project.

Valuable information collected at initial site visits includes:

Topography

Describe the site topography by a stadia survey or a series of cross-sections (if dealing with a length of channel).

Hydraulics

Determine bathymetry of plunge pools. Identify channel and bar configurations to help understand high-flow hydraulics. Ordinary and high water marks should be recorded. Sufficient channel cross-sections should be surveyed to develop a hydraulic model and a tailwater rating curve. Aerial and ground photos are very valuable for larger sites.

Geology

Characterize site soil conditions. Soils relate primarily to construction and structural design considerations but they may dictate the basic fishway concept selected.

Access

Identify site access locations giving particular consideration to equipment access for construction. Be aware of utilities that must be relocated, road detours required, bank slopes and soil conditions. Operation and maintenance considerations should begin with predesign; safe access during bad weather conditions is essential for good operation.

Flood Protection

Record flood information including forebay and tailwater high water marks, bed load information and debris quantity and character.

Check lists

Maintain check lists to keep track of the many details of information needed. These details are especially important on small projects.

Hydrology: Fish Passage Design Flow

There are few situations in which fish passage can be maintained during all flood flows. It is expected that upstream migrants do not move during the highest river flows. Fishway observations have verified this in locations where fish were blocked or chose not to move during high flows in high gradient channels. Keep in mind, however, that adult migrations of many species are induced by **freshets**, therefore, fish passage during moderate flood events is critical.

A high passage design flow (Q_{hp}) must be selected before design of a fish passage correction. Q_{hp} is defined as the highest stream flow at which specified fish passage criteria are satisfied. Fish passage will still occur at higher flows but hydraulic conditions begin to diverge from the design criteria at Q_{hp}. Biological impacts of delaying fish can affect selection of the high passage design flow; different stocks of fish may require more or less strict criteria. (Also consider that the barrier itself may become passable at some high flow.)

A variety of design flow criteria have been suggested or used. Gebhards (1972) suggested an allowable migration delay of six consecutive days for salmon and trout. Dryden (1975) recommended that a seven day impassable period should not be exceeded more than once in the design period of 50 years, and that a three day impassable period should not be exceeded during the average annual flood. The States of California and Washington suggest that passage should be provided for 90% of the migration period for the target species (Kay, 1970; Bates, 1988). The Alaska design flow is a mean annual flood event with a two day duration. A design discharge equivalent to 30% of the average annual flood has been suggested as a general guide in British Columbia (Dane, 1978). All of these criteria may be valid considering regional hydrology and species of concern.

WDFW has design flow criteria for fish passage at in-stream stormwater detention basins. That criteria states that fish passage shall not be violated more than 100-hours during the migration season and for no longer than 24-hours at any one time (Bates, 1981). As discussed later in this paper, just because the fish passage criteria is violated, it doesn't necessarily block all fish. Generally as the passage criteria is slightly exceeded, weaker fish may be blocked. As the criteria are more greatly exceeded, the blockage becomes more severe and additional fish may be blocked. For culverts, Alaska Department of Fish and Game uses the mean annual two-day flood as the high passage design flow.

The selection of hydrologic design criteria should consider the type of runoff expected during fish passage. Storm and rainfall runoff is event-oriented and leads to event frequency analysis. Snow melt runoff peaks are, typically, not as high, but last longer and, therefore, lead to an event duration analysis.

These criteria require a hydrologic analysis of gauging records, correlation to other streams or other hydrologic models that are appropriate. To build a simple Q_{hp} model, WDFW performed multiple regression analyzes on streamflow data from 188 Washington streams (Powers, 1996). All of the basins included in the analysis had drainage areas less than 50 square miles and minimum gauging record of five years. Models for prediction of Q_{hp} (10% exceedance flow) were developed for three hydrologic provinces in Western Washington for winter (January) and spring (May) months. Two regions have prediction models for highland streams (gauge elevation above and below 1000 feet); a total of 10 models were developed. No valid correlation was found for the drier, eastern region (east of the Cascade Mountains) of Washington where the hydrology is determined more by snowmelt and groundwater discharge than by stormwater runoff, more characteristic of the state's western side.

The models are presented here only as an example of one analysis approach; they can not be used in other regions without first being verified for that region nor should they be used for watersheds with drainage areas exceeding those used in the regression analysis. The variability among the regression models demonstrate their potentially poor application for other regions. The models are of the form of **Equation x**.

The parameters are defined as:

A	Basin area in square miles (square miles)
P	Mean annual precipitation at the gauging station (inches)
I	Rainfall intensity; 2-year, 24-hour precipitation (inches)
a	Regression constant
b,c,d	Regression exponents for basin area, precipitation and rainfall intensity.

Mean annual precipitation and rainfall intensity were not always statistically significant, so their exponents, for some regions, are zero.

The standard statistical errors for the regression formulae vary from about 26% to 75%. Sound judgement should be used in adding standard error to the predicted Q_{hp} for a specific site. For an appropriate degree of conservatism, consideration should be given to specific hydrology of the basin, species of concern for fish passage, and cost implications. As a conservative approach it is recommended to add the standard error to the Q_{hp} determination. Summaries of the regression constants and the statistics of the basins for each region are provided in **Appendix x**.

The other end of the fish passage flow range is the low design flow (Q_{lp}). There are no specific agency requirements in the Pacific Northwest for the low passage design flow though they should be considered in the negotiation of instream flows. In-stream flow fish passage considerations include adequate flow for fish attraction and operation of screen bypasses.

A necessary tool for any major fish passage design work is a set of monthly flow exceedance curves for the extent of the migration season. For small projects and culverts, a single fish passage design flow is usually enough.

Hydraulics

Hydraulics is the study of the static and dynamic behavior of fluids through observation, analysis, and modeling. Hydraulic principles are applied to the river channel and passage barrier to locate the fishway entrance and exit, determine entrance flows, and to determine the required scale of the facility. Competent hydraulic analysis to provide for adequate flow at the fishway entrance and within the fishway are the basis of successful fish passage.

Important hydraulic information requirements include:

- Analyze the flow circulation patterns within the tailwater at various depths and stream flows.

- Determine the water surface elevations. Both the tailwater and forebay rating curves for a wide range of flows are required for fishway design. They should be extrapolated by an acceptable hydraulic technique to include higher and lower flows as necessary.

Turbulence can be a barrier to fish passage and should be understood at a site for fishway design. Very little quantitative information is available relating turbulence to fish passage. Stuart (1962) suggested that aerated water creates a barrier for fish passage though he did not isolate the effects of aeration from turbulence. Indirectly, turbulence is a criteria in the design of formal fishways in terms of appropriate pool volume for energy dissipation (Bell, 1990).

The location of the passage barrier often varies with stream flow. Whether the barrier is turbulence or velocity, the point where fish are actually blocked from moving further upstream often moves a substantial distance between low and high flows. Velocities, turbulence, upwells, reverse currents and aeration can all affect attraction and access to fishways.

Model studies can be a valuable tool to help the designer understand the fishway setting. Models are especially valuable when trying to locate fishway entrances at a proposed dam where the flow patterns in an energy dissipation structure are not well understood or at an existing barrier where hydraulic conditions cannot be observed. A simple two-dimensional model is often adequate to establish fishway entrance locations in conjunction with hydraulic jumps or heavy turbulence below an energy dissipater.

A hydraulic model was used to determine fishway and entrance locations for the Hell's Gate fishway in the Fraser River (British Columbia, Canada). The Hell's Gate barrier is a high flow velocity through a narrow gorge; surface velocities are about 23 feet per second (fps). The location of the high velocity barrier moves up and down the channel several hundred feet with changing river flow. The water surface varies vertically 90 feet during the salmon migration season. A 1:50 scale model of the canyon was built to study the barrier at different flows and to locate the fishway entrances and exits. The data for this type of analysis would be nearly impossible to measure in the field. Six fishways have been built at Hell's Gate; they are located both vertically at different elevations on both river banks and horizontally along the channel to provide fish passage at a wide range of flows.

Funding, regulatory and operational limitations

There are operational limitations that can affect the design and success of the fishway. Such limitations include dam and hydroelectric operating schedules, minimum regulated in-stream flows, maintenance schedule of the dam or related facilities and operation and maintenance (O&M) limitations including personnel, access, and funding. Operation and maintenance funding is often a target of budget cuts. It is, therefore, important to consider the implications of potentially reduced O&M funding on the operation of the fishway. Careful design consideration should be given to the possibility of not achieving the desired operation and maintenance of a fishway facility and its consequences for fish passage success.

Optimal operation and maintenance of a fishway facility is best achieved when personnel have an appreciation for the importance of providing fish passage every hour of the day and a clear understanding of how proper operation and maintenance of the facility can make that happen. The more complicated the operation, the more likely the fishway will not be operated as intended. Often, the most critical fish passage timing coincides with the worst conditions of rain, rapidly changing stream flow, wind, and debris. Crews responsible for operation of fish facilities are also often responsible for other infrastructures that are stressed and require attention at the same time.

Start developing an operations manual during the preliminary design process. Continue its development throughout the design; making sure it is realistic and the operator of the facility is included in its development process.

FISHWAY ENTRANCE

The entrance is among the more difficult design elements of a fishway and the most critical to successful fish passage. The key to successful passage is to bring the fish to the fishway; from the uncontrolled natural river environment to the controlled fishway system. If you can't attract fish into a fishway, they won't get upstream. Once fish are in the entrance pool moving them through the fishway is relatively simple.

Functions and Concepts

Fishway entrances and entrance pools have a variety of purposes; more complicated hydraulic and hydrologic settings require more complicated entrance pool designs. The design of the entrance should consider, as appropriate, the functions and concepts described below.

<u>Access</u>
The most obvious and necessary purpose of fishway entrance pools is to provide fish access to the fishway.

<u>Attraction</u>
The entrance is the key to attraction of fish. The jet of water leaving the fishway entrance is an extension of the fishway into the tailwater that serves to guide fish to the fishway. The further the entrance jet penetrates the tailwater, the further the path is carried. Penetration is a function of the three factors: jet momentum, shape and alignment.

<u>Introduce Auxiliary Water</u>
Auxiliary water is often supplied within the entrance pool or transportation channel to strengthen the entrance attraction jet or to increase velocities within a channel. The flow is introduced through diffuser systems designed, not to delay fish, but to guide them to the fishway.

<u>Hydraulic Control</u>
The entrance controls the hydraulic characteristics of the entrance flow. Design details of the entrance control the shape, orientation, flow characteristics, and stability of the entrance jet.
The geometry of the entrance, and its elevation relative to the tailwater, determines whether exiting flow either plunges or streams.

<u>Transition</u>
The entrance is a transition from river to fish ladder for a range of tailwaters and hydraulic conditions. It is a transition from the natural river environment to the sterile artificial environment of the fishway.

<u>Combine Multiple Entrances</u>
Entrance pools and collection channels may collect fish entering through several entrances into a single ladder. The Columbia River fishways have entrance and collection channels that were intended to collect fish from up to 20 entrances along a powerhouse in addition to as many as three main entrances at each bank.

Fishway Entrance Design

The design of the entrance should consider, as appropriate, the functions and concepts described below.

Location

Some of the most significant design decisions associated with a fishway are the number of fishways necessary and the number and location of fishway entrances are necessary. The location of the fishway entrance should be at the upstream-most point of fish passage. The location must also take into account the locations where fish hold before attempting to pass the barrier, and routes by which they will approach the barrier and fishway. The location may vary depending on the type of barrier and the character and quantity of fishway entrance flow. A large amount of entrance flow water can compete favorably and attract fish from a high velocity barrier whereas a lower level of entrance flow may have to be located to key on a holding area. Both may be necessary in a complex tailwater situation.

Fishways are normally constructed on banklines to provide access for construction, operation and maintenance. Conditions that lead to placing multiple fishway entrances or fishways at each bank include:

- The barrier occurs in a wide channel where a single fishway cannot attract fish from the opposite bank.
- Holding areas are far from each other or from the barrier.
- Migration routes are along each bankline.
- Hydraulic conditions prevent attraction of fish to an entrance location from any part of the channel.

These conditions should be considered at all stream flows within the fish passage design flow window. Multiple entrances may be associated with separate fishways or connected with a transportation channel. A single entrance with an entrance flow of 100 cfs may be adequate in a 150-foot wide river channel that is uniform in cross section and flow distribution.

Fish will normally migrate along the channel banks during high flows to take advantage of the lower velocities. Some salmon are also shoreline oriented; they follow the shoreline for guidance. Crossing the entire channel through the turbulent tailrace of a powerhouse, or other barrier, during high flow may be impossible. The penetration of the entrance flow is also diminished at high flows due to high tailwater velocities and turbulence. Fish tend to not swim back downstream in search of a passage route. If there is a hydraulic barrier between them and the fishway entrance, they are not likely to find it without being delayed.

All of these hydraulic considerations can change through the range of passage design flows. Hydraulic models are especially helpful in fixing the fishway entrance location. Field observations and sketches of flow patterns above and below the barrier should be made, especially for high flows. Observations of fish location and orientation when attempting to pass a barrier are additional valuable information.

Multiple entrances (to provide passage at high and low flow) that each operate within a specific range of flows may be necessary where changes in the tailrace hydraulic conditions are great.

Low flow entrances are located close to the base of dams and are usually only operated when those conditions are present. When a roller bucket energy dissipater is located far downstream from the dam crest, fish can become trapped in the pool between the dam and the back roll. A roller bucket is a specific design of a dam that concentrates the energy dissipation of the spill close to the dam. In that case, the low flow entrance should be located in that pool and be operated at all times. Low flow entrances should also be located beneath the nappe of the spillway when it separates a substantial distance from the dam.

Finding the best location for high flow entrances is more complex. Redundant entrances can be provided if the proper fishway entrance locations are not well identified. As many as four entrances have been provided on fishways in the Yakima River basin. It is cheaper to provide an additional unused port in a fishway wall during initial construction than it is to later extend the fishway to provide an additional entrance.

The hydraulic conditions of a dam tailrace depend on the flow spilled over the dam and the style of energy dissipation built into the dam. The best guide to locating an entrance below a barrier dam is to evaluate conditions at a dam with similar geometry and unit discharge. A high flow entrance must be located downstream of the hydraulic jump when that is the style of energy dissipation employed. It will be further downstream than if a roller bucket dissipater is used.

Be aware of eddies and local flow conditions, especially at high flow. "Upstream" to a migrating fish means nose into the approaching flow. Fish that must approach fishway entrances located in an eddie, may have to swim downstream or cross-current relative to the local direction of flow. A fishway that is built on a bankline can create eddies that make a high flow entrance difficult to find.

Distractions such as spilling water or jets of water can be as effective in leading fish away from entrances as the entrances can be in attracting them.

<u>Entrance Flow</u>

There are no specific fishway entrance flow criteria. For fishways at dams, the entrance flow must be adequate to compete with spillway or powerhouse discharge flow for fish attraction. Site conditions, especially tailwater hydraulics, and channel width, in particular, determine entrance flow requirements.

The greater the momentum of the jet, the further it reaches into the tailwater, and the more successfully it can guide fish to the entrance. (Momentum equals mass times velocity.)
The units are the mass per unit time exiting the fishway and the velocity of the jet. It makes sense that the more flow that can be put through the entrance, the further the jet penetrates the tailwater.

The scale of the river setting gives some insight into entrance flows requirements. The total entrance flow for a number of fishways are shown in **Table x**. The fishway flow in the table is the total flow from all entrances, for all fishways, at each site. For example, Sunnyside Dam has three fishways, and a total of four entrances, with 104 cfs maximum flow at each. Anderson Creek, in contrast, is a single fishway with one entrance. The design flows are the 10% mean daily exceedance flows for the migration season `regardless` of the flow for which specific fishways may have been designed. These fishways operate effectively and are in locations without unusual tailwater conditions. This information is provided only to show the wide range of entrance flows selected and how they relate to river scale; it is not a design criterion and should not by itself govern fishway design.

Fishway Entrance Alignment

Low flow entrances should be aligned perpendicular to the channel alignment or parallel to the barrier to maximize their reach into the channel. High flow entrances may be placed at a 30E angle to the high flow streamline. Ideally, they would be oriented along the edge of the high flow hydraulic barrier.

A benefit of the angled entrance is that the entrance jet penetrates the tailwater to a greater extent than if aligned perpendicular to a turbulent, high velocity tailrace condition. An entrance oriented at too great an angle to the high flow streamline may produce an eddy, causing water to flow upstream along the fishway wall just downstream of the entrance. The protrusion into the stream of the angled entrance provides an abutment and a velocity shadow behind which fish can move upstream. Passage is then blocked by the abutment and high velocities in the stream beyond it. Those fish are right at the alternative passage route however, the fishway entrance.

The Wapato fishway on the Yakima River has good examples of low and high flow entrances. A sketch of the fishway is shown in **Figure x**. and a detail of the entrance pool in **Figure x**.

Entrance Head

The water surface differential between the entrance pool and the tailwater is a criterion established by fish passage requirements and desired entrance flow characteristics.

For Pacific salmon and steelhead, an entrance head of about 1.2 feet is preferred for streaming flow conditions. A range of 1.0 to 1.5 feet is a normal operating range.

Gauley (1967) tested the preference of chinook, sockeye and steelhead for submerged fishway entrances with head differentials of 1.0, 2.0, and 3.0 feet. Theoretical velocities through the orifices were 8.0, 11.3, and 13.9 feet per second (fps), respectively. The study was conducted by comparing the preference of fish between pairs of entrances, not the absolute attraction to each of them. The majority of fish of all three species chose entrances that had 2.0 and 3.0 foot of head when compared to the 1.0 foot entrance head. An increasing number of fish failed to enter any entrance, however, when the head was increased to 2.0 and 3.0 feet. This information is summarized in **Table x**. The fact that these fish chose to remain in the tailwater pool rather than pass through the experimental or control entrances, suggests that they were attracted to the greater flow from the experimental entrance, but would not pass through it. The entrance head of about 1.0 foot is therefore preferred.

Chum and pink salmon have more specific requirements. Though they have no trouble swimming through an entrance with a head differential of 1.5 feet or more, they will usually not jump even a fraction of that height. Chum and pink salmon require a streaming flow hydraulic condition; they must be able to swim over or through any entrance or weir drop. A weir on the Stillaguamish River is an effective barrier to pink salmon when the tailwater does not submerge the weir and the water plunges. At these times, there is less than a foot drop, but pink salmon do not attempt the leap.

Plunging and Streaming Flow Conditions

The concepts of streaming and plunging flow are useful in the design of fishway entrances as well as fishway weirs in pool type fishways. Streaming flow from a fishway entrance is generally the desired condition for fish attraction and passage. A streaming flow is an intact plume of water moving nearly horizontal near the water surface or at the elevation of an orifice entrance. Plunging flow, on the other hand, drops nearly vertically over an entrance sill or weir. Refer to the section on the hydraulics of pool and weir fishways for more discussion of plunging and streaming flow conditions within the fishway.

The effect of the streaming flow extends much further into the tailrace than does the plunging flow. It acts as an extension of the fishway to reach into the tailrace to attract and guide fish to the entrance. If an objective is to maximize attraction at low flow, the entrance should be submerged to optimize the streaming jet flow. Plunging flow drops vertically then upwells downstream a few feet from the entrance and sets up a hydraulic roll in which the surface flow is moving towards the entrance. The downstream effect of the plunging flow is limited to the area of the roll; just feet from the entrance.

A weir or port sill that is broad crested, smooth and with an efficient upstream floor contraction is more likely to stream. Efficient side contractions will also enhance the jet. The best way to ensure that jet is streaming is to backwater it from by the tailwater a downstream hydraulic control. As a rule of thumb, if the weir or sill is submerged (vertical distance from tailwater water surface to weir crest) by a 30% of its depth (vertical distance from water surface upstream of the weir to the weir crest), there will be a streaming flow condition. With less submergence, it tends to plunge. Often the entrance can plunge at low flow, when less attraction is required, but should stream as a jet at higher flows.

Shape and Dimension

The fishway entrance can be an overflow weir the full width of the fishway, a narrow weir with end contractions, a vertical slot, or an orifice. The shape and elevation of the entrance determine the extent of penetration of the entrance jet into the tailwater. The momentum of the jet is dissipated in the tailwater by the shear forces at its boundaries; the less the surface boundary, the less rapidly it will be dissipated. For this reason, an ideal shape is circular and the least desirable, a narrow vertical slot. A practical fishway entrance shape is a rectangular port with a width to height ratio from 0.6 to 1.25.

Entrances vary in size from 12 feet wide by 8 feet deep on the Columbia River (Washington State) dams, 3 to 4 feet wide by 4 to 5 feet deep on the Yakima and Wenatchee Rivers (tributaries of the Columbia) to 18 inches wide by a foot deep on small streams. The smallest recommended entrance port dimension is 30 inches.

Slot entrances are useful where a strong shear velocity, approximately parallel to the entrance jet alignment, is present or is created by the protrusion of the fishway into the stream. The shear velocity must be strong enough to be a substantial passage barrier. The vertical slot is located adjacent to the high velocity and functions similar to the angled high flow fishway entrance described on **Page x**. It creates a velocity shadow so fish can approach the entrance area. The Hell's Gate fishway (Fraser River, British Columbia) and those on Cedar Creek (tributary of Lewis River), and the Klickitat River (tributary of Columbia River) are designed with shear slot entrances.

Fish behavior may also affect entrance geometries. Thompson (1967) tested 371 chinook, coho, and steelhead to find their preference of fishway entrance based on its size and shape. Flows were varied to maintain a constant entrance velocity of 8.0 fps. All species preferred a 3.9 foot square entrance by 9 to 1 over a 1.5 foot wide by 4 foot high entrance. They also tested preferences for 2 foot by 5 foot submerged rectangular orifices aligned vertically and horizontally. All three species preferred the vertical orientation to the horizontal.

At small remote fishways that are not regularly maintained, selection of an entrance width is often a trade-off between being narrow enough to produce an attractive streaming jet with the flow available and wide enough to stay clear of debris. To maintain the desired entrance head, an overflow weir is commonly used in lieu of a small orifice. A common minimum width for weir notches for debris concerns is 18 inches.

Light

Concurrent with the entrance dimension tests discussed above, Gauley (1967) tested the preference for lit or dark entrances with 1.0 foot of head. Even when given the choice of the large entrance which was dark (3.9 ft. by 3.9 ft.) or the smallest (1.5 ft. by 2.0 ft.) entrance that was lit, 80%, 90% and 69% of the chinook, coho and steelhead, respectively, chose the lit one. A similar test, using sockeye salmon, found that lit entrances were preferred by the majority (86%) tested.

These tests used an array of 1000 watt mercury vapor lights suspended over the water surface which gave an average light intensity of 850 foot-candles at the water surface and 38 foot-candles at mid-orifice depth (equivalent to a bright cloudy day).

Other fishway studies on Columbia River dams have evaluated entrance lighting conditions with variable results. Improved passage has occurred at sites when a 150 watt submerged thallium iodide light was lit at fishway entrances as compared to either an unlit condition or use of a 500 watt quartz iodide light. The unit tested was a 150 Watt Edo Western Model 1207 and was described as "a mercury vapor lamp with thallium iodide added to the high pressure mercury discharge." This produces a blue-green spectral component that penetrated very well through water. The quartz iodide light improved fish passage but to a much smaller degree. The unlit conditions had normal ambient light within the fishway. In addition to intensity, the use of light as an attraction should also consider the sensitivity of fish to various light frequencies. It makes sense that they would be most sensitive to green or shorter wavelengths that are not absorbed in water as are higher frequencies.

Field surveys in the Fraser River Canyon show that upstream migration slows during hours of darkness leading to large accumulations of salmon in resting pools downstream of difficult passage areas such as fishways and rapids (Saxvik, 1990). To stimulate night passage, floodlights were installed at some of the Fraser River fishways beginning in 1989. The lighting allowed fish to continue through the fishways at night relieving downstream accumulation and congestion of fish. The lighting increased the fishway capacity by extending the daily period of passage. The capacity was also increased by eliminating the congestion of fish that had reduced passage capacity.

Flexibility should be built into the control system of lights so they can provide a range of intensity through a gradual transition section, from light ambient conditions, to dark fishway conditions, or to mimic ambient conditions, as turbidity varies.

Elevation

The entrance head differential must be maintained as the stream flow increases. The rising tailwater can backwater, causing submergence of the entrance unless adjustments are made. This can be done by mechanically raising the entrance weir or by increasing the entrance flow.

Entrances that behave as submerged weirs can become orifices at higher flows as they are submerged by the higher tailwater. No adjustment is needed for a port entrance; the velocity is constant as long as the entrance flow, and the port area, remain constant. The entrance elevation can also be automated by using a floating bulkhead entrance. An orifice within the floating bulkhead remains at the same elevation, relative to the tailwater, because the bulkhead follows the tailwater elevation.

Vertical slot entrances, on the other hand, are backwatered by increasing tailwaters. The effective area of the slot increases and thus the entrance head and velocity are diminished unless auxiliary water is added. An exception to this is wing gate entrances described below.

It is prudent to provide a safety factor in the entrance sill elevation by including the capability of setting the entrance lower than expected. Potential channel degrading or scour should be taken into account especially if a new dam is being constructed that will either trap sediment or scour the bed by energy dissipation. Streambed controls are especially vulnerable because they cause the downstream channel to scour. A bed control built at bed level downstream of a sediment trap in Swan Creek, a Puyallup River tributary, was left suspended three feet above the bed after a single flood. The streambed degraded from under the controls due to efficient sediment capture in the trap and clearwater scour.

Entrance Gate

Entrance gates are used to control and optimize the fishway entrance hydraulics. Adjustments can be made to entrance elevation, width, and head differential. These conditions may be optimized with a vertical slot as part of a vertical slot fishway but slot entrances are often inferior to gated entrances. A tall narrow jet is easily overpowered by turbulent tailwater conditions.

An upward closing gate with a lifting yoke can be used as an adjustable entrance sill. Large entrance gates should be motorized, or at least equipped with nut driver attachments, if they are to be operated as expected. Gate stems and stem blocks commonly fail; therefore, extra sturdy components should be used. Entrance gates submerged in roller bucket energy dissipaters should be extra heavy duty to withstand vibrations and turbulence. (Do not use a gate stem through the middle of the entrance when using a rising stem gate.)

Wing-gates are like a door that turns on a vertical hinge and they are normally built in tandem as double doors. The sill elevation of the entrance does not change. They control the head differential by the opening of the door through a range of tailwater elevations.

Entrance Pool and Transportation Channel Design

The design details of the entrance pool and transition to the fishway are critical to fish passage. Essentially, most passage problems within fishways occur in entrance pools or collection channels. Fish pass several pools before they establish a continuous upstream movement pattern. Most dropbacks occur over the first weirs or the entrance of the fishway.

Hydraulics

The shape of the entrance pool, the location of auxiliary water diffusers, and the entrance to the ladder should be laid out to create a stable flow pattern and transportation velocity leading fish from entrances to the fish ladder. Excess space where eddies, flow separations, or dead water could potentially occur should be eliminated from entrance pools and channels. Corners should be rounded or filled and stagnant areas eliminated.

Wall deflections or channel expansions should be limited to about 1:8 to prevent flow separations.

A instability in the flow can be created by an entrance pool that has multiple entrances to accommodate tailwaters that are separated from each other hydraulically. Surging can occur as flow is alternately and cyclically increased and decreased through one entrance and then the other. Entrances with independent tailwaters should be hydraulically isolated from each other by inserting several fishway weirs between them.

Velocity

In transportation channels, a uniform velocity from 1.0 to 4.0 fps should be maintained; 2.0 fps is a normal operating criteria. Salmon move at a relative speed, with reference to the ground, of about 2 to 4 ft/s whether swimming at **prolonged** or **burst speed**. Laboratory studies have not found an optimum velocity within that range consistent for all species. Transportation velocities are also applied to the lower end of the fishway when a high backwater floods it. When that occurs, an increased cross-section area results, reducing velocity (unless auxiliary water is provided).

Light

Studies conducted at the **Fisheries Engineering Research Laboratory** found no statistically significant improvement in passage time for summer chinook, sockeye or steelhead through pipes when a gradual light transition zone was provided. However, it is generally believed that fish delay at changes in light conditions. Considering the pronounced preference of salmon and steelhead for lighted entrances, efforts should be made to light transportation conduits and provide light transition areas at their entrances.

AUXILIARY WATER SYSTEM

The auxiliary water system is the source, control, and supply of supplementary water to the lower end of the fishway. Additional purposes include:

- Provide additional flow at the **fishway entrance** for enhanced fish attraction.
- Maintain desired flow and velocity in **transportation channel**.
- Supply water for parallel fishway legs.
- Supply water for fishway flow control.

Diffuser Design

Auxiliary water is introduced to the fishway through wall or floor diffusers. Diffusers may be constructed from bar grating, perforated plate, or wood racks.

There are four objectives of a good diffuser design:

- To introduce adequate auxiliary water with a uniform distribution.
- To minimize maintenance demand; operator friendly.
- To discourage attraction of fish.
- To protect fish from injury.

The spaces between bars of a diffuser must be sized to exclude fish and prevent injury. They should also be narrow enough that fish cannot injure their eyes as they nose into the spaces between the diffuser bars. Fish are commonly seen pushing into the gaps as if trying to force their way through. Openings should be small enough to protect the smallest fish present. Senn (1984) suggests opening dimensions of 1.5 inches for chinook, 1.0 inch for coho and steelhead and 0.75 inch for sockeye for fish collection traps. Picket traps on the Cedar River and auxiliary water diffusers on the Wenatchee River, have clearances of 1.0 inch for sockeye without gilling problems.

Overall, diffuser size should be enough to maintain a velocity such that fish are not attracted to it. Diffusers, like screens, are designed with a gross velocity criterion, the flow divided by the effective diffuser area. A diffuser velocity of 1.0 fps is generally applied for salmon. However, studies have shown passage delays when auxiliary water is added through diffusers at velocities as low as 0.25 fps. Delays generally increase with higher diffuser velocities (Gauley,1964)

To attract fish away from the diffuser and into the fish ladder, a steady attractive stream of flow should be directed from the fishway along the face of the diffuser and at an angle slightly away from it. This depends on a good entrance pool design. The Wapato fishway entrance pool is an example of a good layout of entrance pool, auxiliary water diffuser, and fishway (**Figure x**).

An energy dissipation chamber and/or baffle system is usually needed upstream of the diffuser panel to assure a tranquil and uniform flow distribution through the grating. A common flow distributor is two rows of vertical steel channels, a foot apart, and offset from each other, and each with about

50% open area. The idea is to create a few tenths of a foot of head loss. Another good distribution system, used in floor diffusers, is the stepped baffle shown in **Figure x**. This system could also work for a wall diffuser when turned vertically.

Wall Diffusers

Wall diffusers have a great advantage over floor diffusers in their ease of maintenance since they can be easily cleaned from overhead with a rake.

The upstream side of the diffuser grating should be clear of horizontal support bars so debris can be cleared. If there is grating over the auxiliary water chamber, lightweight hinged grating is recommended. The entire upstream side of the rack should be accessible for raking. The grating should therefore be mounted flush with the upstream wall of the diffuser port. The entire diffuser grating should be submerged at the lowest water surface in the pool. Alternatively, insure that the diffuser flow is reduced when it is exposed. Water will spill through the exposed portion of the diffuser and fish, often attracted to spilling water or its aeration, will leap at it. Standard commercial bar walkway grating is used for diffuser grating.

Floor Diffusers

An advantage of floor diffusers is that fish are less attracted by upwelling water than flow from a wall diffuser. The disadvantage is that they are difficult to clean. Several floor diffuser systems have been designed to be pivoted or hinged, allowing the flushing of debris. This design though has not been utilized extensively.

Auxiliary Water Supply

Auxiliary water can be supplied to the fishway by gravity from the forebay, pumped from the tailrace, or a combination of both. Gravity auxiliary water control gates can often be designed so they are essentially self controlling. A proportional weir or orifice gate can be used to match the control gate flow characteristics to the auxiliary water flow requirements.

Chimneys

Chimneys are a passive device used to control flow progressively to a series of fishway pools as the tailwater rises and increasingly backwaters the fishway pools. A purpose of the auxiliary water, in this situation, is to provide additional flow over the submerged weirs to maintain a minimum velocity in the backwatered pools to keep fish moving through the channel.

A chimney system is shown schematically in Figure x. Water is supplied from the auxiliary water supply chamber through a flow control orifice or a porosity panel. At low tailwater, the chimney supplies no flow to the diffuser because the water surface in the chamber is below the elevation of the orifice. The orifice maintains a constant head differential between the chamber and the fishway. The fishway pool and chamber pool water surfaces, therefore, rise with rising tailwater. When the water level in the water supply chamber rises to the level of the chimney flow control orifice, water flows through the orifice and diffuser and into the fishway. The orifice controls the quantity of flow. A series of progressively higher chimneys will supply water to higher fishway elevations as the tailwater continues to rise. With increasing tailwater, an increasing flow is required to the auxiliary water supply chamber. This concept can be used to supply wall diffusers also.

Water Source

Do not supplement the fishway with water from sources other than the primary water supply. Doing so may alter the scent of the water and confuse the homing instinct of fish. No surface water runoff, or water with human scent, should be allowed to enter the fishway.

The difference between deep and shallow forebay water supplies should be considered. Fish passage facilities at Green Peter Dam on the Santiam River in Oregon are no longer in operation for a number of reasons. When the facilities were operated, returning adults were not were primarily attracted to a 10 cfs juvenile bypass outfall rather than the fishway flow of 50 cfs or the powerhouse flow of up to 5,000 cfs. The source of water for the juvenile bypass was surface water from the reservoir. The fishway and powerhouse water sources were both deep in the stratified reservoir. As juveniles, these fish had moved through the reservoir in shallow water; as adults they may have recognized it as a separate source from the deep water and tried to follow it back upstream.

It is especially important to provide some hatchery drain water to hatchery fishways. At the Cowlitz salmon hatchery, less than 1 cfs of hatchery drain water is added to 23 cfs of fishway water and 150 cfs of fishway entrance water to effectively guide fish. Another 175 cfs of hatchery drain water goes directly to the river upstream of the fishway barrier dam.

There is some belief that turbid water tends to attract fish and motivates them to move. The turbid water may be the equivalent to a freshet that induces fish to migrate. No specific data is available to demonstrate the effect of turbid water.

The safety of juvenile fish moving through debris racks, energy dissipaters, and diffuser systems of auxiliary water supply systems should be considered. It may be necessary to screen the auxiliary water supply, where practical, to eliminate cleaning maintenance requirements and prevent loss of juvenile fish passing through it.

OTHER GUIDANCE AND ATTRACTION MEANS

Attraction and Guidance

Auxiliary attraction jets

Attraction jets adjacent to fishway entrances can improve passage in some situations. The intent is to provide a strong jet that penetrates the tailwater to reinforce and buoy the entrance jet. The jet must have a high enough velocity to act as an effective barrier to passage. Several of the Yakima River (Washington) fishways have attraction jets including the Wapato Dam fishway (**Figure x**) but they have not been evaluated for their effectiveness. There are also several examples of attraction jets used with the Alaska steeppass fishways (See **Chapter x**).

Sloped or notched weir

Special weir configurations are often used to help attract fish. Barrier dams are often built with a slope or notch to supply extra attraction water in the vicinity of a fishway entrance just downstream of it. Sloped and notched weirs have not been evaluated for their effectiveness though they appear to be of marginal benefit. At low flow they are not needed because the fishway is usually attractive enough. At high flow, the distribution of flow often overwhelms the fishway entrance with turbulence. Notches would be helpful in a very long crest and where the range of fish passage flows is not great. If used, these weir shapes should be carefully designed using examples of dams with similar geometries and flows to evaluate the need and size of the notch as well as the location of the fishway entrance.

Distractions

Distractions that might attract fish away from the fishway entrance are as important as attraction to the fishway. Conditions in the tailrace that concentrate flows should be eliminated or diffused so fish are not attracted to them.

The hydraulic conditions at dam abutments often attract fish. A contraction occurs as the flow passes the wall abutment, concentrating a small portion of flow several feet away from the wall alignment. A low flow shadow is left immediately next to the wall alignment. Fish approach the dam in the low flow shadow and are attracted to the concentrated flow. For this reason, abutment walls should be designed as efficient contractions to eliminate this distraction.

When an **ogee weir** crest bends at an angle point creating a dogleg alignment, a distraction is created. If the crest angle points upstream, flow from the two doglegs combine and form a strong jet in line with the bisecting angle of the dogleg. The crests can be tapered up to a high point at the vertex to decrease the flow from both legs. Baffle blocks can also be installed on the dam apron to break up the resulting jet.

FISH LADDERS

For the purpose of this document, the fish ladder is defined as the structure through which fish swim to a higher elevation to gain passage. It obviously is the central component of the entire fishway structure.

Fishways can be divided into six classifications based on their hydraulic design and function and include:

- Pool and Weir.
- Vertical slot.
- Roughened channels.
- Hybrid fishways.
- Mechanical fishways.

The appropriate choice of a particular fishway style for a site depends on a number of variables including:

- Species and age classes to be passed.
- Scale of system; channel, hydrology.
- Degree of flow control available.
- Dependability of operation and maintenance.
- Debris, bedload and ice considerations.
- Mitigation and enhancement goals.
- Capital and O&M costs.

Critical design elements, dimensions and limitations of these six styles relevant to the passage of Pacific salmon and steelhead are discussed in the next sections.

Pool Style Fishways

Pool style fishways have a series of distinct pools in which the energy of the flow entering each one is entirely dissipated prior to flowing to the next. Pool and weir fishways and vertical slot fishways are included here.

Fish Behavior

Fish behavior and swimming abilities affect design concepts and details of fish ladder design. Fish move through fishways in different patterns. Early-chinook tend to use orifices and late-chinook and sockeye prefer weirs. The movement of early and late-steelhead is the reverse of this. Shad use weirs exclusively and are wall-oriented. They follow the walls and can be trapped in corners where there is no exit. Shad require **streaming flow** conditions for best passage. (Squawfish, suckers, and carp use orifices.)

The fishways on the Columbia River dams were not initially designed for shad passage. The flow control sections had orifices with no surface overflow. Unlike Pacific salmon, shad would not pass through the orifices. During shad runs, which coincided with salmon runs, the accumulation and eventual death of shad resulted in the blockage of salmon passage.

Chum and pink salmon will not leap. They are strong fish but require a slot, orifice, or submerged weir for passage. These species tend to spawn lower in river systems in comparison to the other salmon species and may not have evolved the ability to pass over water falls or other obstructions.

Pool Volume

The volume required in a fishway pool must provide adequate hydraulic and fish capacity. However, a design based solely on hydraulic capacity usually provides for fish capacity. **Fishway hydraulic capacity** is the pool volume that provides adequate energy dissipation. Adequate hydraulic capacity prevents a carryover of energy to the next downstream pool, controlling turbulence and aeration, creating a resting area. The **Energy Dissipation Factor** (EDF) defines capacity of the fishway. EDF is essentially the maximum amount of turbulence allowed in a fishway for fish to still be able to successfully move through. More specifically it is the ratio of the kinetic and velocity energy entering a pool and the effective volume of the pool to dissipate that energy.

High turbulence is in itself a barrier to passage; lower levels eliminate fish resting or holding areas. The value of the EDF is different for size and species of fish and for type of facility. **Equation x** defines EDF.

V_{pool} = Effective energy dissipating volume of the pool (ft^3)
(= Unit weight of water (lb/ft^3)
Q = Flow entering the pool (ft^3/s)
h = Head of the flow entering the pool (ft)

The maximum recommended EDF for adult salmon and steelhead is 4 foot-pounds per second per cubic foot of pool volume. Europeans use 200 watts/m3 (about 4.0 $ft\text{-}lb/sec/ft^3$) as a recommended EDF for salmon and 3 $ft\text{-}lb/sec/ft^3$ (150 $watts/m^3$) for shad (Larinier, 1990).

The total EDF for a fishway pool must account for all flows entering it; add together the energy supplied by orifices and weirs. Portions of the pool, because of the pool length or shape, may not contribute to energy dissipation since the energy dissipation and turbulence are concentrated where water enters the pool. It is recommended that no pool length greater than ten feet and no pool depth greater than five feet be included in energy dissipation volume calculation.

The pool volume may also depend on required **fish capacity** in situations of very large and concentrated runs. It is the pool volume required for fish passage based on a maximum instantaneous loading rate and the allowable density of fish. The pool volume required as a function of fish capacity can be determined by **Equation x**.

V_{pool} = Volume required per pound of fish (ft^3)
C = Number of fish per hour (fish/hour)
r = Rate of fish movement (minutes/pool)

The pool volume recommended for fish is about 0.4 ft3/lb fish. Columbia River fishway capacity experiments indicated a significant delay of fish when fish were at a density of 0.15 ft3/lb when compared to a density of 0.36 ft3/lb (Elling, 1959). The fish were a mixture of fall chinook, sockeye and coho. The concentration of fish caused streaming flow conditions to develop at a density of 0.86 ft3/pound resulting in passage delay. (**Streaming flow** in this test was partially due to the weir configuration, however.)

Fish tend to accumulate in the lower pools of a fishway or where hydraulic conditions change. It takes several pools before they acclimate and resume consistent progressive movement. Once they enter the fishway, salmon spend approximately 3 minutes per pool for the Columbia River fishways.

If the size of run is used to determine the resting volume of fishway pools, the maximum expected density of fish should be the statistic used. Lacking other site data, the maximum density of fish is estimated as a specific portion of the entire run. For salmon, 10% of the run can typically pass a site in a single day. This estimate is verified by recent records from collection and counting stations on the Wenatchee, Cedar and Yakima Rivers in Washington State. At the Bonneville Dam (Columbia River (Washington), typically 2 to 8% of the chinook and steelhead, and 5 to 8% of the sockeye and coho, pass in a single day at the peak of each of those runs. About 12% of the Okanogan River (Washington) sockeye passed Zosel Dam in a day after they had been delayed for about a month by high water temperatures.

Nearly all passage occurs during the day with 60% from daylight to noon and the remaining 40% from noon to darkness. Based on these estimates, the maximum hourly passage rate would be approximately 1.0% of the total run. It is estimated that the maximum pink and sockeye salmon passage rates at Hell's Gate (Fraser River, British Columbia) in 1989 and 1990 were more than 20,000 fish per hour (Saxvik, 1990, 1991). That rate would account for about 1.5% and 0.6%, respectively, of the total runs. In addition, simultaneous runs of different species have to be considered when calculating expected loading rates.

Fish capacity is rarely a significant factor in the sizing of fishways. There are few fishways through which the rate of passage is due to their fish capacity.

The design of the Bonneville Dam (Columbia River) fishways were the first to be based on expected density as a fishway design parameter. It was expected that 100,000 fish might pass through each fishway in a single day. In 1986, approximately 47,000 salmon passed through both fishways in a single day. It is not uncommon for over 50,000 shad to pass in a day at Bonneville.

The Hell's Gate fishways (Fraser River, British Columbia) were the first designed based on providing for fish capacity. That design capacity was realized in 1954 when 2.0 million sockeye passed in six days (Andrew, 1990). The average rate was estimated to be 20,000 fish per hour in a single fishway.

In 1989, a new low level fishway was constructed at Hell's Gate with the capacity designed to be the same as the high level fishways at the same site, 6,000 fish per hour. This low flow capacity was based on the assumptions of 4.0 cubic feet per fish and a travel time of about one pool per minute. In 1990, 3.4 million Adams River sockeye moved through the ladder in less than 30 days (Saxvik, 1991). The peak hourly rate is estimated to have been 20,000 fish per hour. Accounting for the actual volume in the fishway at the time (5.0 feet of depth; design depth was 4.0 feet) the estimated passage rate was 2.4 times the intended designed capacity.

The typical minimum fishway pool depth for weir & pool and vertical slot fishways varies from 3 to 8 feet. The minimum depth required is based on experience and depends on the scale of river, just as with entrance flows. There is also a minimum depth for vertical slot fishways to operate will hydraulically as described below.

Orifices

The minimum size recommended for orifices within fishway weirs is 15 inches width by 18 inches height for salmon. Orifices as small as 12 inches wide by 15 inches high are used however. The primary concern with smaller orifices is the increased risk of plugging by debris.

The Ice Harbor fishway (Columbia River), is a good example of the use of orifices (**Figure x**). The orifice located below the overflow section of the weir enhances it plunging action by reinforcing the roller circulation. Orifices can also be used alone, without overflow weirs, as a flow control device (refer to flow control section).

Orifices should be shaped with efficient entrance contractions as shown in the **Figure x** to provide the most stable flow.

Head Differential

The recommended head differential between pools is normally 1.0 foot for most salmon and trout, 0.75 foot for chum and shad, and 0.25 foot for grayling. The lesser head differential for chum insures a **nappe** that the fish can then swim through. The head can be much greater if it is through a submerged slot or contained in a chute without free falling flow.

Depth over Weirs

One foot of water depth is a normal design. Increasing the depth to 1.2 feet in studies of the Ice Harbor style design significantly decreased the median passage time. The water depth over the weirs in large Columbia River pool and weir fishways has been increased to 1.1 foot to help dampen flow instabilities. In some cases, the depth has been increased to 1.6 feet to induce streaming flow for shad passage, increasing the fishway flow from 82 to 115 cfs.

A minimum of three inches of depth over tributary fishway weirs without flow control is reasonable for leaping fish. Where pinks or chum are to be passed, a notch with a minimum width of 1.5 feet and submerged by at least 6 inches by the next downstream weir works well. The notch should widen toward the top to help pass debris.

Freeboard

Freeboard from the water surface to the top of the wall should be a minimum of three feet for chinook, steelhead, and coho. It is not uncommon for fish to leap out of fishways with lower walls. They will often leap at the upstream weir, miss, and bounce off a wall. Efforts should be made to minimize unnecessary leaping by eliminating concentrated spills near the walls and upwelling in corners. The freeboard in smaller fishways can be achieved by extending the wall with a fence on top of the fishway wall flush with the inside wall.

Fishway Bends

Long fishways are often laid out to switch back on themselves through a series of 180E bends. Weaver (1963) reported significantly longer passage times through corner and bend pools.

Regardless of the fishway style, details of the bends should be considered carefully to eliminate upwelling in corners and to maintain a consistent flow pattern. An additional pool length at the bend is often required to realign the flow to the downstream weir or slot. The jet flow from an orifice or vertical slot entering a turning pool should be aligned to follow the outside wall of the turn. The outside walls of the turn should be shaped with a radius or large fillet to carry the jet around the bend without impacting the end wall and upwelling.

If the fishway slots or notches are aligned so the jet must follow the inside wall, the wall should be extended for a minimum of 8 feet downstream of the weir or a baffle should be added to deflect the flow into the center of the pool. For vertical slots, the required baffle is essentially the same as the short wall forming a vertical slot.

Pool and Weir Style Fishways - Design Considerations

Pool and weir fishways have distinct pools in which the energy of the flow entering is entirely dissipated. The hydraulic controls between the pools are overflow weirs with or without orifices. This is the most common style in the Pacific Northwest and is used in all scales of fish passage.

A primary limitation of the pool and weir fishway is their narrow range of operating flow. The minimum depth of flow commonly determines the lower limit of flow over a weir. That minimum depth for fish passage is commonly 0.25 feet. The upper limit of flow is at the level when the **Energy Dissipation Factor** is exceeded or when the flow enters an unstable regime (described below). If the flow regime is consistently streaming, the upper limit will be determined by turbulence (inadequate energy dissipation) or the velocity of the streaming jet.

Hydraulics

The normal flow circulation in a pool and weir fishway is the **plunging regime** (**Figure x**). This circulation is set up by the **nappe** from the upstream weir plunging toward the fishway floor, moving downstream along the floor, then rising along the face of the next weir and either dropping over the weir or rolling back upstream along the surface of the pool. **Streaming flow** typically occurs at higher flow levels than for the plunging regime. A continuous surface jet passes over the crests of the weirs and skims along the surface of the pools. The weir is **backwatered** by the downstream weir. Shear forces create a circulation in the pool opposite to that in the plunging regime. (Rajaratnam (1988) provides a good description of these flow regimes and their respective empirical hydraulic formulae.)

Hydraulic instability occurs in the transition between the upper range of plunging flow and the lower range of streaming flow. This transition regime should be avoided. Passage studies have repeatedly shown that when fishway flows operate at the transition point, passage delays occur. The instability can also set up large hydraulic oscillations that migrate through the fishway. The streaming regime should be used with caution because the energy is not dissipated in each pool and the streaming jet is difficult to control.

The shape of the weir crest and the presence and design of orifices within the weir, affect the hydraulics of the downstream pool. The orifice in **Figure x** supports the plunging circulation set up by the spill above it. An orifice in the streaming mode would conflict with the circulation.

The weir crest and orifice are effective in extending the plunging regime of flow. **Table x** shows in an 8 foot pool, the plunging regime extended by **33%** (3.9 cfs/ft to 5.2 cfs/ft) by rounding the crest and adding an orifice. The unstable regime was essentially eliminated. This data is from Andrews (pers. comm.) and supported by the results of others (Rajaratnam, 1988).

Alternating notches, though commonly used in small pool and weir fishways, may not provide any benefit over traditional designs. Their intended purpose is to better utilize the entire pool volume for energy dissipation. An alternative is to allow the water to skip to the next pool, preserving some of the pool volume as rest area. Bedload and debris are passed when notches are in line.

A consideration overlooked in the selection of fishway styles is providing for the passage of juvenile salmon. Coho juveniles (100 to 120 mm) can easily ascend a pool and weir fishway if the hydraulic conditions are appropriate. Thousands of coho juveniles are commonly observed in the spring moving upstream in the Lake Symmington fishway at Big Beef Creek, a tributary to Hood Canal in Washington State. Thought there may be more juvenile fish migrating upstream in this situation because of upstream lake rearing habitat, the need for upstream juvenile passage is considered as a general requirement unless documented otherwise.

Ice Harbor Fishway

The Ice Harbor fishway (Columbia River) is a 1-on-10 (one foot vertical to 10 feet horizontal overall slope) pool and weir fishway with orifices, flow stabilizers, and a non-overflow section in the middle of each weir. It was originally developed for this site in the 1960s at the Fisheries Engineering Research Laboratory at Bonneville Dam.

The half Ice Harbor fishway is, as the name implies, half of the Ice Harbor fishway, cut along the centerline (**Figure x**). It is the recommended weir configuration for moderate to large applications where good flow control is available.

The full Ice Harbor fishway is 16 feet wide with two 5 foot overflow weirs, requiring a flow of about 70 cfs. As many as 1,371 fish have passed through a full Ice Harbor fishway in an hour without a sign of delay (Weaver, 1966).

Chinook and steelhead made significantly faster ascents when the depth over the weirs was increased from 0.95 to 1.20 feet, with the orifice open. The opposite was true when the orifice was closed.

Vertical Slot Fishway - Design Considerations

Similar to pool and weir fishways, vertical slot fishways have distinct steps with hydraulic control provided by a narrow vertical slot open at the top and full depth of the fishway (**Figure x**). Its greatest advantage is that it is entirely self-regulating.

It operates without mechanical adjustment through a range of tailwater or forebay water surface elevations. The only flow requirement is that a minimum water depth equal to the depth of the vertical slots, be maintained. The difference in elevation between the tailwater (entrance pool) and forebay (exit pool) is nearly equally divided among all of the fishway steps. Any change in forebay and/or tailwater water surfaces is automatically compensated by distributing the change throughout the fishway. The upstream and downstream water surfaces may vary independently.

Energy is dissipated in each pool by the jet mixing with water in the portion of the pool between the larger baffles. As additional flow passes through the fishway, the pool depths increase creating additional pool volume and maintaining the appropriate energy dissipation.

The vertical slot fishway was first developed for application at Hell's Gate (Fraser River, British Columbia). Model studies by Milo Bell and C.W. Harris were used to develop the concept of the twin vertical slot fishway for Hell's Gate. For smaller systems with less fish capacity, the vertical slot fishway was later modified by splitting it down the centerline creating the standard single vertical slot fishway (**Figure x**).

Flow

Flow through a vertical slot is a function of the slot width, water depth in the slot, and head differential across the slot (**Equation x**).

$Q_{v\text{-slot}}$ = Fishway flow (ft^3/s)
C = Orifice coefficient (typically 0.75)
w = Slot width (ft)
D = Depth of water upstream of the slot (ft)
g = Gravitation constant (32.2 ft/s^2)
h = Head across the slot (ft)

Early model studies by Andrew and Pretious found coefficients of 0.82 to 0.62 for 12-inch slots with and without sills, respectively (**Andrew, n.d.).** Flow measurements, by the Bureau of Reclamation, in the Sunnyside fishway on the Yakima River, a tributary of the Columbia River, determined coefficients of 0.91 to 1.04 for 15-inch slots without sills (Onni Perala, pers. comm.). The relationship between slot depth and discharge at several head levels (C=0.75, 12 and 15 inch slot widths) are presented in **Figure x.**

The drop is not always equal through all of the slots. The flow through each slot, of course, has to be identical. The depth of water in each slot may vary, however, if the forebay and tailwater depths do not change equally as the river flow changes. This will create either a **M1 backwater curve** in the lower pools (the tailwater rising faster than the forebay and the rating curves converge at higher flows). An **M2 drawdown curve** occurs in the upper pools when the forebay rises faster than the tailwater; the rating curves diverge.

Different design processes are required for the backwater or drawdown situations. However, in both cases, the floor elevations are based on minimum depth requirements at low flow. The number of slots is determined by the maximum forebay to tailwater head differential whether it is at low or high flow. The water surface profile for the low or high flow profile is analyzed for the backwater (converging ratings) and drawdown (diverging ratings) cases, respectively, to verify that the minimum head differential through the slots maintains the minimum transportation velocity. A slot velocity of 3.0 fps, which is equivalent to about 0.25 feet of head, is recommended as a minimum. A normal minimum recommended depth, at the upstream side of a slot, is 5 feet; some are commonly operated as low as three feet.

Dimensions

The dimensions of the vertical slot and pool are critical to the stability of flow. The dimensions shown in **Figure x** should be adhered to unless specific experience or studies indicate that other configurations work. **Katopodis (1991)** has tested a number of vertical slot fishway designs and suggests several minor variations in the geometry of the slot that also work well.

Because of site constraints, the dimensions of the vertical slot ladder built at Tumwater Dam (Wenatchee River) in 1986 were modified. A 15-inch slot was used with pools that were 8 feet long by 12 feet wide. The additional pool width was intended to compensate for the reduced length **(pool or ladder?)**. The result was very unstable flow with surge amplitudes greater than three feet. To stabilize the flow, the slot width was reduced to 12 inches and 12 inch sills were installed in the slots.

Sills across the bottom of the slots tend to stabilize flow. Without them, especially at low depths, the flow tends to bypass the pool and move directly towards the next slot. The jet enters less of the **cushioning pool** and its energy may not be dissipated. The change of direction is caused by the fact that without a sill, the flow is forced to spread; it passes through the slot with a certain depth and is forced to occupy a foot less depth in the downstream pool assuming one-foot of differential. The sill allows the jet to occupy the same depths above and below the slot and, therefore, stay more intact. Sills should be placed across the slot at the floor if the vertical slot is operated with upstream depths less than about 5 feet or where the head differential may exceed the standard 1.0 foot. They offer some benefit to the pool hydraulics at any depth but also incrementally diminish the fishway flow.

Standard widths of vertical slots are 12 and 15 inches. Clay (1961) suggested slots as narrow as 6 inches for smaller fish. Other dimensions of the vertical slot, in this case, wou-ld be reduced proportionately.

Hell's Gate (Fraser River) main double vertical slot fishways have 30-inch slots and pools that are 18 feet long by 20 feet wide. The slots are up to 30 feet high. The maximum head differential through those slots is 0.6 ft. (Recall, these fishways were designed for fish capacity rather than hydraulic capacity.)

Passage

The full depth vertical slots allow fish passage at any depth. The path of fish passage is assumed to not be tortuous; fish are able to move directly from slot to slot in nearly a straight path. This concept has not been verified. Hydraulic studies by Katopodis (1991) verified that the velocity through the slot is constant throughout the vertical profile.

The vertical slot is not usually suited for species that require overflow weirs for passage or that must orient to walls. Pink salmon passage through Seton Creek (drainage?) vertical slot ladder has been timed at an average of 48 seconds per pool (Andrew, 1990).

Roughened Channels - Design Considerations

Roughened channels are chutes or flumes with roughness, designed to reduce velocity, allowing fish passage. Examples of designed roughened channels include the Denil style fishways and culverts with or without baffles. Fish are expected to swim the length of a roughened channel in a single swimming effort whether it is in **burst**, **prolonged,** or **sustained** swimming modes.

Expectation of successful fish passage through roughened channels must consider turbulence as a potential passage barrier. Turbulence can be a barrier to fish passage depending on its scale and intensity relative to a fish's size and swimming ability.

Fish tend to be more attracted to the roughened channel design in comparison to a plunging overflow weir (for a given flow) due to the (**what about the velocity?**) velocity of the jet exiting the fishway.

The exit (flow inlet) to any roughened channel should be carefully designed to minimize the water inlet head loss due to flow contraction and a sudden drawdown. The depth of water in the fishway and, therefore, its capacity, is reduced by the extent of the drawdown.

Denil

The Denil is an artificial roughened channel. It is used extensively throughout the world though it usually is not the first choice of fishway style in the Northwest due to its limited operating range and vulnerability to debris blockages. Primary use of the Denil fishway in this region is for temporary fish passage, either until permanent facilities are constructed, or during reconstruction of an existing fishway.

A normal slope of 17% is recommended though they have been successfully used at slopes up to 25%. The most commonly used size is a 4-foot width. (Standard dimensions are shown in **Figure x**.) A wide range of flows are possible depending on fishway size, slope and water depth. Rearranging the non-dimensional equations developed by **Katopodis** (**citation?**), the flow for a Denil design similar to that in **Figure x** is given in **equation x**.

Q = Fishway flow (ft3/s)
D = Depth of flow above the vee baffle (ft)
b =Open width of the fishway between the baffles (ft)
S = Fishway slope (ft/ft)

Flow control is important though not as critical in comparison to a weir and pool fish ladder. The **forebay** elevation must not fluctuate more than several feet to maintain good passage conditions. Centerline velocities increase towards the water surface in Denils where D/b is greater than 3.0 (**Katopodis **?**). The height of the Denil fishway has no limits; additional height adds attraction flow and operating range without additional passage capacity because of the higher velocities in the upper part of the fishway. However, Denils are typically constructed with depths of 4 to 8 feet. Standard length sections are 30 feet; they can be built out of plywood, steel, or concrete with steel baffles.

Alaska Steeppass

The Alaska Steeppass (ASP) is a specific style of Denil fishway originally developed for remote installations. Steeppasses are used in the Northwest primarily as trapping and evaluation facilities and for temporary fish passage during construction of other facilities. There are also small ASP installations at small falls and dams.

The ASP is more efficient than the standard Denil in controlling velocities; it has a more complex set of baffles that are angled upstream into the flow. It requires less flow than the Denil, from about three to six cfs for the standard ASP depending on slope. The normal slope recommended is about 25% though they have been used successfully up to a slope of 33%.

The concerns regarding debris and limited operating range are more critical in an ASP than a Denil because it has smaller open dimensions. A standard ASP has an open area between the baffles of 22 inches high by 14 inches wide and requires 3 to 8 cfs at the recommended slope for adequate passage depth. **Katopodis (pers comm)** suggests that the clear dimension between the baffles be no less than 40% of the length of fish passing. **Katopodis (1991)** provides dimension less hydraulic flow equations that are rearranged into the following equation:

Q_{ASP} = Fishway flow (ft^3/s)
b =Open width of the fishway (ft)
Yo = Depth of the flow above the floor vanes (ft)
g = Gravitation constant (32.2 ft/s^2)
S = ASP Fishway slope (ft/ft)

The average velocity in the ASP can be calculated from **equation x** and is the usual basis for ASP design. The point velocity varies through the vertical profile. **Rajaratnam (?)** found that the vertical profile of velocity in a full flowing standard ASP ($Y_o/b=1.6$) varied by a factor of 2 and exhibited nearly linear variation with depth, the lowest velocities occurring at the water surface. ASP's that have a greater relative depth (Y_o/b) than 2.1 have the highest velocities near the middle of the profile. Velocities and Y_o/b increase correspondingly.

The primary advantage of the ASP is that it is prefabricated, modular, and relatively light weight. ASP units are usually fabricated out of aluminum in 10-foot lengths and bolted together with end flanges. (A 10-foot unit weighs 1500 pounds.) The cost of a unit can be based on its weight and the current cost of aluminum fabrication. (Plastic fabricators are interested in fabricating an ASP fishway and claim they can be competitive with aluminum in cost and durability.)

Flow control is very important; the **forebay** water surface cannot vary more than a foot without creating passage difficulties. The **tailwater** should be maintained within about the same range to prevent a plunging flow or a **backwatered** condition that reduces the entrance velocity and, therefore, attraction. Slatick (1975) found that the median passage time for salmon increased four-fold, and 25% fewer salmon entered the fishway when the downstream end was submerged by 2.5 feet. ASP units can be hinged at either end to accommodate water surface fluctuations. The fishway flow will change, of course, with changing slope.

ASP sections are usually set in lengths of 20 to 30 feet. Resting pools are provided between sections. The design of resting pools between sections of ASP is important in order that energy is dissipated, upwelling does not distract fish and velocity does not carry over into the downstream section. Blacket (1987) concluded a delay of fish in a resting pool can delay following fish. He studied fish passage through ASPs that were 180 feet long, a 22% slope, with and without resting pools. Though passage was 31 to 69% greater through the ASP with resting pools, there were no obvious passage problems for sockeye, pink, chum, and chinook salmon in either case.

The maximum passage rate observed through a single ASP was about 1850 sockeye per hour over 2.5 hours and 400,000 in less than four weeks. It was concluded that the ASP fish passage capacity was not exceeded based on the rate of fish dropping back out of the fishway entrance pool. Slatick (1975) estimated the passage capacity of chinook in an ASP was between 650 and 1140 fish per hour. Shad will pass through a steeppass, though reluctantly. Slatick found that nearly 100% of spring and summer migrant salmon entered the ASP within an hour while only 61% of the shad had entered the fishway after three hours.

To provide **auxiliary water**, a box conduit or open trough can be attached to the side of the ASP. The high velocity from the conduit or trough reinforces the flow from the fishway. The open trough is used when the tailwater backwaters the fishway significantly; the flow is open to the tailwater regardless of the tailwater elevation. Examples of ASPs using auxiliary water in Washington State include French Creek, a Snohomish River tributary, and Elk Creek, a Chehalis River tributary. Trapping counts at Elk Creek found a significant increase in passage on the days auxiliary water was provided. The auxiliary water at Elk Creek actually reverses the **tailrace** circulation in the vicinity of the entrance as a passage improvement.

Roughened Chute

Orsborn (1984) tested a narrow chute with 1.5 inch by 1.5 inch blocks across the floor at 6 inch spacing for roughness. Chum and coho had passage rates exceeding 95% at slopes of 27% and 15%, respectively. The test flume was eight-feet long.

Engineered Steepened Stream Channel

Constructed channel fishways are intended to replicate steep natural channels. If adequate land is available, a natural channel can often be constructed around a low barrier that remains as a flow control spillway. Such channels have been constructed with **control sills** and with rough rock linings. Specified boulder sizes are placed in a pattern to optimize roughness, as well as fish, flood, and debris passage. The boulders are either imbedded into a cobble and gravel streambed to slopes up to about 5.0% or anchored into a concrete channel subgrade for slopes up to 8.0% (Bates, **1992**). There are no standard empirical methods for predicting fish passage through these fishways. Generally, they are designed to be stable for a high structural design flows and average velocities are used to predict fish passage. Hydraulics of the channels can be estimated using flume data presented by Sayre (1963) and Peterson (1960).

Mill Creek fishway, located on a tributary to the Bogachiel River (Washington), has 18 inch riprap imbedded in a concrete slurry. It is 95 feet long on a slope of 8.0%. It has a 10-yr design flow of 1200 cfs and a **high passage** design flow of 160 cfs. It was constructed in 1970 and has required one major repair to replace rock since then.

Colony Creek fishway **(river drainage?)** is constructed over a deep, soft, clay substrate. A barrier dam serves as a flow control spillway and an orifice, at the fishway exit, controls peak flows to the fishway. The channel slope is 3.4%. The fishway channel has a 4 foot toe width and a riprap liner 18 inches thick. Boulders, 24 inches in diameter, were placed on alternating sides of the channel on the riprap bed 4 feet on center. The boulders act as roughness elements to control the velocity. Six inches of 3 inch pit run gravel was placed over the riprap bed between the boulders. The pit run gravel seals the riprap below it and provides some channel diversity through the fishway. The fishway is below a pond so no other bed material will enter the channel.

A practical limit of slope for rock lined constructed stream channels is about 3.5% without specific design of roughness elements and their anchoring system. Steeper channels could be built but only with very careful design and construction; bed sills are often recommended at the steeper slopes.

Hybrid Fishways

Hybrid fishways are a combination of weir and pool, vertical slot, or roughened channel fishways.

Pool and Chute Fishway

The pool and chute fishway is an alternative to pool and weir fishways. They operate through a wider range of stream flows without other flow control. The pool and chute is a pool and weir fishway at low flow, and a cross between a pool and weir and a roughened chute, at high flow. The weirs are vee-shaped with a horizontal weir set into a notch at the apex of the vee.

At low flow, the fishway performs as a pool and weir fishway with the flow plunging and dissipating in each pool. At high flow, a streaming flow condition exists down the center of the fishway where the bulk of the flow passes. Plunging flow and good fish passage conditions can be maintained on the edges of the pools. This style of fishway is very good at passing debris since the entire streamflow normally passes through the fishway and is, therefore, substantially submerged at highest flows. The open design encourages debris to wash over the weirs and out of the fishway. The economy of the concept is achieved by exceeding the usual fishway pool volume criteria based on energy dissipation in each pool.

Pool and chute fishways should not be used where the total drop exceeds about six feet until the concept is more thoroughly tested. It is not clear that uniform flow conditions at highest flows have been achieved in the modeling and prototypes so far tested. Greater velocities, flow instabilities, and downstream channel impacts may be created with greater heads. In addition, with such high velocities, even minor disturbance of the desired flow patterns by dimensional error in design or construction can potentially cause flow instabilities throughout the entire fishway. Additional research is required to develop comprehensive design standards.

The general configuration of the pool and chute is shown in **Figure x** which depicts the Town Dam fishway (Yakima River). The following guidelines are based on observations of a number of pool and chute fishways. The high design flow for adult salmon just fills the vee to the top of the sloping shoulder weirs. For juvenile salmon passage, it should be about three feet horizontally from the top of the shoulder. The outer areas then remain as holding areas and passage corridors. The width of the fishway is modified to provide these design passage conditions. The length of the pools is half their width.

Standard notch dimensions tested are a width equal to 15% of the pool width and a depth equal to 8% of the width. It is expected that the notch width could be as wide as necessary to provide additional flow capacity; this has not been tested. The sloping shoulders have been designed with 1:4 slopes.

Start the design by selecting a weir differential and a fishway slope. Weir differential is the elevation between weirs varying between 0.5 and 1.0 foot. The upstream weir and next weir are lowered relative to the gradient of the other weirs by 0.2 feet and 0.1 feet, respectively, to account for less velocity head entering the fishway.

Bates (1991) reported the results of a model study including Chezy roughness coefficients of the pool and chute fishway at slopes of 4.9 (**?**), 11.1, and 16.7 (**?**)%. **Powers (pers com)** has calculated roughness at three additional slopes based on prototype high flow measurements (**Table x**). This study also showed that streaming flow could not be created at slopes greater than about 12%. Slopes approaching that are appropriate for fishways with passage design flows up to perhaps 90 cfs. The lower gradient tested is appropriate for an estimated 250 cfs and greater.

Pool and chute fishways have been constructed in several locations in Washington and California. The largest was constructed in 1988 by the Bureau of Reclamation on the Yakima River and is shown in **Figure x**. It has a high design passage flow of 343 cfs when the total river flow is 3880 cfs. Based on model data by **Bates (1991)**, the velocity of the jet exiting the fishway is 11.5 fps and, 20 feet downstream, 7.1 fps. This indicates the need to use this concept with caution. If not sited appropriately, the high energy jet will scour the downstream channel and/or banks. The steep slope tested by Bates created a velocity of 2.2 fps, 20 feet downstream, because the flow was plunging instead of streaming.

Pool and chute fishways have been installed inside of short culverts. However, culverts must be very wide to accommodate the design criteria described above.

The pool and chute fishway shown in **Figure x** is a variation constructed on Kenney Creek, a Nooksack River tributary. It is a switchback pool and chute. The entire stream passes through the center of the fishway like the standard pool and chute. Low flows follow a more circuitous route in a pool and weir configuration. It has a high passage design flow of 27 cfs and a 100-year flood flow estimated at 460 cfs that is entirely contained within the outer fishway walls. The switchback layout has the advantage that though its fish passage hydraulic profile is 8.0%, the structure has a physical profile of 16%. The Kenney Creek fishway was designed to fit into a short reach of channel between a road culvert and the main channel of the Nooksack River (Washington).

Mechanical fishways

Mechanical fishways include lifts, **brails** and **locks**. They are mechanically operated fishways that can raise fish over an obstacle or into a trap or hauling tank.

Elver and climbing passes

Elver and climbing passes are fishways through which fish climb either by using their fins or suction parts. The only relevant fishway in this category for the northeast Pacific would be for lampreys.

FISHWAY FLOW CONTROL

The purpose of flow control is to extend the range of flows the fishway operates effectively. Flow control accommodates fluctuations in the forebay water surface while maintaining acceptable ladder flow conditions. The degree of flow control required depends on the style of fishway.

There are essentially five styles of flow control; they can be used individually or together:

- Self adjusting fishway.
- Spillway control.
- Orifice or vertical slot flow control section.
- Adjustable weirs.
- Multiple level exit.

Self Adjusting Fishway

Vertical slot and orifice fishways are both self-adjusting. As long as the **forebay** and **tailwater** elevations do not exceed the height of the slots, the fishway functions as intended. The Denil and pool and chute fishways are also intended to be self adjusting, though their ranges of operation are more limited.

Spillway Control

Flow control can be initiated at the forebay by a spillway; its effectiveness, a function of length. Automated spillway gates can control pool elevation to within a few tenths of a foot.

Orifice or Vertical Slot Control Section

Flow control can be provided with a special section of fishway upstream from the primary fish ladder. The flow control section contains orifices and/or vertical slots through which fish pass. The hydraulic slope through the flow control section increases as the forebay rises. Greater flow and head loss therefore, occur through the section compensating for change in forebay elevation. To accommodate the change in flow through the control section, either auxiliary water can be supplied, or excess water discharged, below the control section.

Auxiliary Water Flow Control

Auxiliary water flow control sections are usually designed to carry the full fish ladder flow at high **forebay**. The auxiliary water is supplied to the lower fish ladder except during the highest **forebay** condition.

Figure x is a schematic of an orifice flow control section including the hydraulic profiles of the high and low forebay conditions. Easton Dam fishway (Yakima River) for example has a constant ladder flow of about 27 cfs. This is supplied from two sources; the **orifice control section** (9 cfs at low forebay to 27 cfs at high forebay) and the **auxiliary water system** (from 18 cfs at low forebay to 0 at high forebay). This type of auxiliary water system operates contrary to the forebay; less flow is needed with increasing head. Therefore, unless it can be operated very carefully, and with close attention, the auxiliary water control gate should be automated and electronically tied to the forebay water surface.

Minimum orifice sizes are similar to those in fishways. Debris will plug the orifices which are difficult to maintain due to their depth. Care should be taken in design of the orifice so jets do not align, and energy is not carried, from one orifice to the next. They can be designed with a geometry as if they were very short slots in a vertical slot ladder.

Vertical slot flow control is preferred to orifice flow control but requires substantially more flow. It consists of simply a vertical slot ladder section ahead of the primary ladder. The flow control section can also be a combination of orifices and slots.

Bleed-Off Flow Control

The bleed-off flow control section is hydraulically similar to the auxiliary water flow control section. Auxiliary water instead of being supplied at low forebay, the excess water is discharged from the downstream end of the flow control section at high forebay conditions. It is used when the normal operating condition is the low forebay and accommodates peak flows.

An Alaska steeppass fish ladder, located on Elk Creek, a Chehalis River tributary, utilizes an orifice flow control section. Part of the excess flow (from the flow control section) is wasted back to the stream, the remainder is used as auxiliary attraction water at the fishway entrance.

Adjustable Weirs

Instead of bringing the forebay to the fishway, adjustable weirs and multiple level exits take the fishway to the forebay. Telescoping or tilting weirs, in the upper portion of the fishway, can accommodate a small variation in forebay elevation.

Adjustable weirs should be automated and tied electronically to the forebay water surface. They are usually actuated individually. As many as six tilting gates are mechanically tied together and operated as a single unit on the Takase Weir in Japan (Watanabe, 1990) accommodating forebay fluctuations of up to 11.5 feet.

Telescoping gates are preferred over tilting weirs. They have a wider operating range than tilting weirs with the same control section length. They also have better flow conditions within the pools; tilting gates disrupt normal flow patterns within the pools.

The Nibutani style gate is another style of adjustable weir flow control (Watanabe, 1990). The control section is hinged at the downstream end and the upstream end is raised and lowered mechanically to follow the forebay water surface. The flow control section of the Nubutani Dam in Japan is designed with 20 weirs through a length of 120 feet. It has a forebay operating range of 22 feet.

Multiple Level Exit

If a forebay is operated in more than one distinct operating range, multiple level exits may be necessary. The Roza Dam (Yakima River) has a forebay water surface, at the upper range, maintained within several tenths of a foot by **spillway roller gates**. Because of icing conditions, and for maintenance purposes, the roller gates are opened and the forebay is drained, to a nominal elevation, 15 feet below the high forebay range for about a month each year. A lower exit simply branches off of the fishway at the appropriate elevation and exits through a gated conduit in the dam. When not in use, the lower branch is closed. In the case of Roza Dam, three telescoping weirs provide flow control at the lower level exit. The switch between high and low exits is manual; the fishway must be inspected each time and any stranded fish removed.

Multiple exits can be used to accommodate a variable forebay if the fluctuations are gradual and not frequent. The Nagura Dam (Hida-gawa River, Japan) has exits from each of the top nine fishway pools. Each pool has a sluice gate exit about a foot lower than the pool above it. Only one gate is operated at a time depending on forebay level.

FISHWAY EXIT

Fish exiting the fishway into a forebay often hesitate as they acclimate. To help fish make this transition, a couple of characteristics should be taken into consideration and included in design. To get upstream, fish must swim into current and tend to follow the shoreline. Therefore, the fishway exit should be located where fish can orient to a shoreline and into a consistent current that will guide them upstream.

The exit should be at a depth comparable to depths within the fishway. Forebay currents should be understood through the complete range of design flows. River flow passing the falls, powerhouse, or spillway may set up eddies within the forebay leading to fish having difficulty orientating upstream.

Avoid exit location next to the spillway or powerhouse intakes. Try to locate the exit on a bankline that will guide fish upstream rather than in the center of the channel. Extend the exit channel upstream if necessary to locate the exit in an area of consistent positive downstream flow.

The exit location also determines the water source of the fishway. Avoid locating the exit in a stagnant area where water quality may be poor or where there is any risk of contamination entering the river. For attraction to the fishway, water quality in the ladder must be the same as the water from powerhouses or spillways; consider odor, temperature, and surface water runoff.

At the south fishway of Bonneville Dam (Columbia River) radio tagging studies determined that a significant number of fish moved “upstream” into the river current and along the bankline, leading them to the spillway where they were swept downstream (**fallback**). An **eddy** at the northeast point of Bradford Island created the counter flow that guided fish to the spillway. Fish then returned through the fishway and were counted again. (One radio tracked chinook fell back three times though was later tracked 250 miles upstream.) The rate of **fallback** depended on river flow and varied from 13.4%, at flows between 140,000 and 200,000 cfs, to as high as 67%, at river flows over 200,000 cfs. The eddy apparently is washed out at very high flows (flow greater than 400,000 cfs). Fish then swam directly upstream. (An additional powerhouse is now located in a new channel north of the spillway shown in **Figure x**.) Fallback has been studied at other dams on the Columbia River and appears to be less than 10%. (Most fish that fallback survive.)

Trash Rack and Other Design Details

The exit should have a trash boom and/or coarse trash rack. Consider wind and current directions to help determine the rate of debris accumulation.

Debris racks that are cleaned manually with rakes should have a maximum normal velocity no greater than about 2.0 fps. Velocities increase when debris accumulates, making it difficult to clean the rack manually with a rake. There are standard mechanical trash cleaning rakes that are self-operating, on a timer system, or manually operated, similar to a back-hoe with a rake attachment.

Water velocities sweeping across the face of the fishway should be taken into consideration in the design of a trash rack. Higher velocities can result in substantial head loss across the trash rack as the kinetic energy of the sweeping flow is lost. Excessive head loss can result in decreased fishway flow, depending on the fishway flow control mechanism, leading to increased sediment deposition.

High velocities can also cause fallback as fish may become disoriented when exiting the fishway.

For salmon, vertical bars should have 5 to 10 inches of clearance and horizontal bars spaced no closer than 18 inches apart. Horizontal bars should be inset, or on the back side of the vertical bars, so debris can slide up the rack's outside face. A curtain wall above the trash rack, and flush with its face, is helpful for diverting floating debris when there is adequate depth that the additional open rack is not needed. A curtain wall, if it is designed at the right elevation, allows larger debris, during high flows, to accumulate, making its removal easier in comparison to it capture within the bars of the trash rack.

A sluice is often used to maintain depth of water at the fishway entrance. Consider also access for equipment to clean debris and sediment from the exit and forebay. Where substantial deposition of large debris is likely, a system for winching heavy debris off the rack is helpful.

Slope the face of the trash rack at 1:4 or 1:5 (vertical to horizontal) for leverage and easy manual cleaning. Provide a sturdy railing for cleaning and consider the need for lights for night maintenance. Provide structural freeboard on the fishway exit to prevent flood damage. Provide stoplogs or a closure gate for de-watering the fishway for maintenance.

A trash boom can be helpful. The ideal trash boom is a **shear boom** designed to carry debris past the fishway exit to the spillway or falls. Small fishways usually need nothing more than a single shear log chained at both ends or attached with a sliding ring to a vertical post. For larger debris, and greater buildups, consider a double or triple log boom for accumulating debris.

MISCELLANEOUS DESIGN CONSIDERATIONS

Install staff gages to help optimize fishway operation. Make sure the staff gauges will be visible for the operators. Consider even the orientation of deck grating bars so staff gauges below the grating can be seen easily. Ideal staff gage locations include:

- Above and below entrances to measure entrance head and flow.
- At auxiliary water diffusers and trash racks to determine the extent of debris plugging.
- At fishway weirs, to measure flow.
- In the forebay, as a river flow gauge

An operation manual should include the following items:

- Staff gauge elevations identifying high and low flow regimes for entrance gate operation. (The low and high flow operating regimes should overlap so there is a narrow range through which either gate can be operated.)
- Settings of entrance gates. (They are normally either entirely open or entirely shut.)
- Head differentials that must be maintained at entrances, trash, and diffuser racks.
- Settings of auxiliary water systems based on auxiliary water system staff gauges and river flow.

Additional design considerations include:

- Counting, collection, sorting and loading facilities.
- Security, lights intrusion and flow alarms.
- Safety, attractive public nuisance.
- All surface water must drain away from the fishway. Odors and contaminants can be a deterrent to fish passage.

TRIBUTARY FISH PASSAGE DESIGN

Many miles of salmon and steelhead spawning and rearing habitat have been blocked by small natural falls and man-made barriers such as dams and road crossings. Several watersheds in Washington State were surveyed in 1984 to identify all human-related barriers to salmon migration. Two of the drainages, one urbanized and the other rural (combined area of 30 square miles and a total channel length of 50 miles) had 6% and 24%, respectively of their **area** cutoff from salmon use (**Tom Burns, WDF, pers. com.**). Since the upper reaches of these watersheds provide the best spawning habitat, as much as 50% of the spawning habitat was potentially lost. This situation is not uncommon throughout Washington State and indicates the importance of identifying and correcting migration barriers to restore threatened salmon stocks.

TRIBUTARY FISHWAY CONSTRUCTION CONCEPTS

Perhaps the most important design consideration with tributary fishways are that sites are often remote, seldom inspected, and have little or no flow control. With this in mind, and in an effort to minimize construction and maintenance costs, alternative fish passage concepts and construction methods have been developed for both adult and juvenile salmon. These concepts are described here and are primarily intended for use in small tributaries.

Project Construction

Construction costs are potentially reduced by:

- Prefabricating units for remote installation.
- Designs that utilize the channel itself as the fishway.
- Designs that do not require equipment access.
- Concepts that exceed normal fishway design standards without reducing efficiency.

Log Sills

Log sills are **control sills** built into the stream bed, spanning the entire channel width and, as described here, are intended for fish passage (**Figure x**). Log sills have also been used successfully for stabilizing certain channel erosion problems, holding spawning gravel, and for creating holding and rearing pools. The designs for those purposes are somewhat different than for fish passage, intending to create a concentrated flow and deeper plunge pools.

Log sills are a low-cost and durable means of fish passage for streams with natural gradients of less than 3% and channel toe widths of less than 30 feet. Log sills are typically installed in a series with a spacing from 125% to 175% of the channel width and a minimum spacing of 15 feet.

A closer spacing causes the scour pool of each log to extend to the next sill downstream and does not allow bed material to accumulate and **protect** the upstream face of the downstream sill. Log sills are not structurally durable in themselves; they support the streambed which protects and seals the log weirs. When used for fish passage, sills within a series, should be constructed with equal cross-channel lengths for uniform hydraulic conditions at high flows.

A pair of logs, each with a minimum diameter of one-foot, are placed into the streambed. (It is recommended that the sum of the diameters at any point along the structure is at least three feet.) The downstream pool will scour to a depth greater than two feet below the downstream control elevation. The bottom log is offset upstream on a line about 45E from vertical to allow the scour to undercut the upper log. The top log is strapped to precast concrete blocks buried below each end of the sill. To control deflection of the upper log, use a lower log with a diameter approximately 0.04 of the log length.

Careful anchorage, or ballasting, of the logs is a critical to their durability. The design described here depends entirely on the concrete ballast block. In situations where bedrock is encountered, single log sills have been anchored using 9/16" galvanized steel cable and C-10 HIT Hilti dowelling cement (Espinosa, 1991).

Double logs are used to prevent the scour pool from undermining the structure. The ends are buried into trenches and excavated into the streambank a minimum of five feet. The logs are normally Douglas Fir due to availability, straightness, and longevity. Longevity is determined by the amount of bed material abrasion. The sills are installed level and are permanently submerged thereby resisting decay. Retired mill boom logs have been a good source of logs; they are long and straight, and preserved by years of saltwater use.

A seal is attached to the upstream face of the top log, buried 2 feet and extended upstream at least 6 feet. Geotextile fabric is used with a tensile strength of at least 600 pounds and a burst strength of at least 1200 pounds. Geotextile fabric has good longevity, availability and flexibility for ease of construction. It is easier to install than impermeable material which billows in the current during installation. The fabric must be extended into the trenches to completely seal the structure.

Riprap mixed with soil is packed over the ends of the logs within the trenches and on the banks extending to six feet downstream of the sills. The riprap is bank protection, not ballast. A pool is excavated two feet deep by six feet long in the channel downstream of each log sill in anticipation of a scour pool that will develop naturally. If a pool is not initially constructed, there is a risk that the first high flow will stream over the sills, energy will not be adequately dissipated, and the downstream channel will be damaged. The bank rock fill material must extend to the floor of the pool. In installations where bed material does not pass into, and through the fishway, the floor of the pool should also be lined with riprap.

The maximum fish passage design flow is approximately 9.5 cfs per foot sill length. (The maximum safe high design flow has not been determined though a flow of 15 cfs per foot of length has been observed for a series of log sill structures without failure.

The weir coefficient for a log weir submerged to 50% of its depth is about 2.7 based on field measurements.

N = Number of sills required
H = Elevation gain to be achieved (feet)
L = Spacing of the sills (15 ft minimum recommended) (feet)
S_o = Initial channel slope (foot/foot)
S_d = Desired channel slope (foot/foot)

Because of the recommended minimum spacing and maximum elevation drop, the maximum final slope of a series of log sills is 5%. However, it is difficult to steepen a channel with an initial natural slope greater than about 3% with this style of log sill.

Sills should be located in straight sections and at the entrance and exits of channel bends. They should not be installed in bends because there is a risk that if a lower sill of a series fails, those above it will be undermined and also fail. If bed sills are placed in a series, deeper sills should be placed at approximately every fifth sill. The deeper sills should be designed as independent dams, assuming the downstream controls do not maintain a backwater. Their purpose is to prevent the chain reaction and the failure of the entire series.

Following installation, a notch is cut in the crest of the sill. The shape and size of the notch depends on the species requiring passage and the low flow expected at the time of passage. The notch generally slopes down to form a plume that fish can swim through rather than be required to leap. The notch should not be so large that, at low flow, the top of the log is de-watered.

In 1953, 41 in-stream structures in Sequoia National Forest in Northern California were evaluated following 18 years of operation. The evaluation found that the most common reason for structural failure of log dams and deflectors was inadequate anchorage of the ends (**Ehlers, 1954**). The most common factor of the successful structures was the presence of dense willow stands; they helped anchor the ends of the logs. After 18 years, the 9 remaining log dams (15 were originally constructed) showed no signs of rot or deterioration even though they were partially exposed.

Log sills can be placed with a single excavator or by hand in small de-watered installations. Current (**1994**) total costs of constructing a log sill within a flowing stream is about $3000. Maintenance of full spanning sills is much less intensive than formal fishways because the channel is not constricted and debris freely passes. Accumulation of a moderate amount of debris does not present a risk to the structure and can provide good rearing cover in the plunge pools. Of about 150 log sills of this type installed by Washington Department of Fish and Wildlife since 1983, two have failed by being undermined. They were single log structures.

<u>Plank Sills</u>

Rough-cut milled timbers when placed across the bed of a channel, form sills similar to log sills. They can be constructed by hand and are intended for placement in small or spring source streams with regular flow. They are installed with a maximum drop between pools of 8 inches. When installed in steady spring source streams, a series of plank sills can be installed at a slope up to 7%. Plank sills have an application limited to channel toe widths of about 10 feet. The maximum standard timber length available is 16 feet; each end is imbedded three feet into the bank.

Untreated fir timbers are used in perennial streams where the wood will be always be submerged. Cedar is used in ephemeral streams. The planks are trenched into the bed of the channel and anchored with U-bolts to steel pipes driven into the streambed. The sills are tilted about 20E downstream so the nappe spills free of the sill for better juvenile fish access. The ends are buried in the channel banks and the excavated trenches, backfilled with light riprap rock mixed with soil.

Plank sills are especially useful for providing upstream juvenile salmon passage and are well suited for streams with sandy beds. In the last 5 years **(**update?)**, WDF has constructed 44 of these structures without a failure.

Plank sills have been constructed in wide channels using zig-zag and spider weir designs. Both designs are primarily intended for juvenile fish passage.

<u>Precast Concrete Fishways</u>

In areas that are remote from concrete plants or in situations that are difficult to de-water and pour concrete, precast concrete fishways can be installed. Three styles have been used: 1) a series of reinforced pre-cast concrete troughs fitted together to form pool and weir fishways; 2) separate precast wall and floor units that are bolted together to form a pool and weir fishway and; 3) drop structures that are fabricated in one piece complete with wing walls, cutoff wall, and plunge pool .

Integrating the fishway with precast foundation blocks eliminates the need for cast-in-place concrete and assures accurate grade control. The capability of available lifting equipment limits the size of the troughs; units as large as 20 feet long 4 feet wide and 3.6 feet deep have been used. The joints between units are tapered to fit closely and self-align. (The use of keyways have not been successful.) A commercial tar impregnated compression seal is used between the concrete units. Wood stoplogs are installed in guides in the concrete as fishway weirs.

The second style uses separate precast wall and floor units that are bolted together to form a pool and weir fishway. This is not as efficient a means of construction and is used only when required by lack of access by appropriate heavy equipment. The precast units are typically 4 feet by 5.8 feet and 5 inches thick. They can be skidded into sites with hand equipment. A commercial product similar to this in Japan uses this concept to build large formal fishways.

The third style of precast concrete fishway consists of drop structures that are fabricated in one piece complete with wing walls, cutoff wall, and plunge pool. They have been used to control the grade and provide fish passage in small relocated streams.

These designs are obviously limited by the weight of the units. Since the fishway pool volumes are limited, their use is restricted to small or spring-fed streams with consistent flow.

Laminated Beam Weirs

Narrow bedrock channels present difficult construction and maintenance problems. They are often remote, difficult to access (personnel, equipment and supplies), and difficult to de-water for construction. In these situations, laminated beam weirs are useful because they can be delivered and installed entirely by labor crews.

Appropriate anchor points are chosen in the rock walls of a narrow ravine. The channel floor and walls are frequently shaped by minor blasting as necessary to provide a reasonably smooth face of sound rock. Guides are attached to the channel walls with rock bolts; the guides are long enough that the lowest anchor bolts are just above the waterline during low flow. The submerged portion of the guide is cantilevered below this and supported by a single shear pin anchored vertically in the channel floor near the center of the weir. Milled, untreated, 4 by 6 inch fir timbers are each trimmed to appropriate lengths to fit into the guides and tight to each rock wall. They are stacked one on another and connected with spikes.

"Ecology" Blocks

Precast rectangular blocks and, especially Jersey median barriers, are not suitable for fish passage sills. Limitations of their use include difficultly setting them with precision, scour, settling, and rolling.

Gabions

Gabions are not a good fish passage device because they are unstable, deteriorate, and are easily damaged. A benefit often stated of gabions is the possibility of using locally available stream gravel and cobble for fill. Fill of this type is like trying to stack marbles; the gabion deforms and quickly loses its intended shape. It may also roll as it deforms. Galvanized gabion wires do not withstand the erosion of bed material wear. Gabions used in Chico Creek (Puget Sound, Washington), with only slight bedload abrasion, failed in three years. Another drawback to the use of gabions is that debris can easily snag either breaking them or distorting the wire fabric leading to their failure.

In addition, fish passage conditions over gabions is often poor. They are difficult to seal (and keep sealed). They act as a shallow weir and require a rigid notch imbedded into the crest for fish passage. Perhaps the only good use of gabions for fish passage is as a foundation for log or timber weirs. However, in this use they should not be exposed to the bed of the stream.

UPSTREAM JUVENILE PASSAGE

Fisheries scientists have documented the benefit of the upstream movement of coho salmon fry and fingerlings from river mainstems into sheltered off-channel ponds (Skeesick, 1970; Cederholm, 1981). For many species, an upstream juvenile migration strategy is essential or enhances survival. Juvenile coho salmon (*Oncorhynchus kisutch*), chinook salmon (*O. tschawytscha*), and steelhead trout (*O. mykiss*) may migrate upstream and into tributaries in response to water quantity or quality conditions, predation, or population pressures (WDFW, 1990). Juvenile fish that are able to escape harsh winter river conditions and reside in spring fed tributaries during that period, survive at a significantly greater rate than those that don't (Cederholm,1981).

Coho fry (40 to 60 mm in length) migrate in Western Washington during May and June and fingerlings (80 to 100 mm) migrate from October through December (**King, 1990; Peterson, 1982**). Migration peaks in both seasons coinciding with increased flow (**not necessarily for the spring period only snow dominated runoff**).

Chinook move into mainstem tributaries in Eastern Washington in the spring and summer months during high flows in the mainstems.

Juvenile Passage Structures

Fishways

Steepened rock channels, formal fishways, and streambed controls have been constructed specifically for upstream juvenile salmon passage. Juvenile passage is usually provided through adult pool and weir fishways if adequate **still water** is provided in the pools and depth over weirs is limited. Most of the fishway styles described in the Tributary Fish Passage Design section of this report are effective for juvenile passage. The biggest difficulty in providing juvenile passage through fishways is the common lack of **flow control** in small tributary fishways. Flow from off-channel habitat is often supplied by spring or groundwater sources and is, therefore, very stable compared to river mainstem flows.

Construction costs for nine juvenile passage projects built by Washington Department of Fisheries recently varied from $1000 to $6000 (1993 dollars ****update?** per foot of rise. Construction costs increase substantially as the design flow increases or the total head differential exceeds about three feet (Powers, 1993).

Culverts

Culverts have been designed for juvenile passage by specifying culvert wall roughness or placement of large streambed material in the floor of the culvert with the expectation of adequately low velocities for passage. Culverts are often fitted with baffles to increase roughness and reduce the average velocity or, with weirs, to build interior pool and weir fishways. However, there has been little consideration of turbulence created by the added roughness of baffles or roughness and their effect on fish passage. See the WDFW guideline *Fish Passage at Road Culverts* for details.

Zig-Zag and Spider Weirs

Spider weirs are a special design of plank weirs normally intended for juvenile fish passage. The Tributary Fish Passage Design section of these guidelines describes plank weirs. Zig-zag and spider weirs are shown in **Figure x**. Both can span broad channels and are often used to create wetland and juvenile rearing habitats. The plank crest elevations for spider weirs can be designed to create a switchback channel route to elongate it and provide small steps for passage.

Fryway

Weir and pool fishways are constructed with special considerations to optimize hydraulic conditions, taking advantage of juvenile salmon ability to leap (Powers, 1993).

To provide juvenile coho passage into sloughs and beaver ponds a portable, inexpensive fryway has been developed, tested, and constructed in Alaska and Washington. Providing dependable upstream passage for fry into beaver ponds must consider unique conditions. The pond water surface can vary considerably with changes in flow and beaver activity. The limited swimming ability of fry limit hydraulic conditions for passage. Continuing beaver activity can plug or block open fishways. For an effective fry passage program, fry must be distributed into many isolated ponds making a large number of remote installations necessary.

A fryway was tested with a prototype installation in April - May, 1987 in Washington State. Two parallel fryways with different test conditions were installed to temporarily replace a pool and weir fishway. Traps were placed at the upstream end of each fryway. Fish successfully passing each fryway were counted daily and moved into the pond above the fryways. The more successful of the two was used in the next test as a control to evaluate other configuration changes such as baffle spacing and fryway slope. The parallel evaluation was intended to compare both attraction to the fryways and passage through them.

The fryway tested is shown schematically in **Figure x**. It consists of a 12-inch diameter PVC pipe with a series of vee-notch weirs inside. One end of the pipe is submerged in the pond and attached with a flexible coupling to an entrance pipe that passes through the dam and is submerged in the tailwater of the dam. The upstream end is attached to flotation tanks and includes an elbow so the exit is submerged in the pond. The flotation is designed to raise and lower the fryway exit and maintain a constant flow of 0.5 cfs through the fryway. The exit tested has successfully eliminated plugging by beavers; it consists of a PVC pipe similar to the fryway with many two inch holes distributed throughout its length and circumference. This fryway is similar to a design developed independently in British Columbia, Canada (**Smallwood, n.d.)**.

The fryways tested in Washington successfully passed juvenile coho as small as 68 mm at slopes up to 35%. The fryway slope of 25% passed 2.7 times as many fry as the 35% slope though only 10% less than the 15% installation.

Adult coho successfully moved upstream through the fryway during the initial testing. However, there is a risk of these fish being injured or trapped inside the fryway, and a recent installation included an adult barrier rack installed below the fryway.

Additional hydraulic and biological testing of the fryway are needed before specific design criteria or limitations can be defined.

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GLOSSARY

This is a brief glossary of terms used in this paper and how they specifically relate to fishways. Fishway nomenclature is defined with reference to adult fish passage; the fishway entrance is, therefore, where the fish enter and the water exits.

Auxiliary Water - Flow added to the fishway flow to:

- Enhance attraction to the fishway.
- Maintain desired velocity in a transportation channel.
- Supply flow for parallel fishway legs.
- Provide water for fishway flow control.

Baffle - A device mounted on the floor or wall of a channel for one of the following purposes:

- Increase boundary roughness, reducing the average velocity within a channel or specifically within the boundary layer of the baffle.
- Reduce channel cross section to increase the velocity within the channel.
- Create low velocity zones for fish holding.
- Deflect flow or control its direction.
- Create turbulence to suspend sediment.
- Create headloss to uniformally distribute flow.

Barrier - A hydraulic (height, depth, velocity), physical, chemical, or temperature barrier to fish passage. It may be partial, temporal, or complete. A partial barrier blocks some species or age groups. A temporal barrier is a block at only certain flow conditions. A complete barrier is a block at all times and hydraulic conditions.

Burst Swimming Mode - Burst swimming mode that can only be sustained for a short period of time, about 7 seconds. It is also know as darting speed.

Diffuser - An open grating, or perforated plate, that distributes auxiliary flow to a fishway. It can be located on a wall or floor.

Entrance - Fish entrance to the fishway.

Exit - Fish exit from the fishway.

Fishway - A system that may include special attraciton devices, entrances, collection, and transportation channels, the fish ladder itself, exit and operating and maintenance standards.

Fish Ladder - The structure that actually allows fish to swim, or carries fish, to a higher elevation. (It is a component of the entire fishway system.)

Forebay - The area of the stream, upstream of a dam or fishway, at the fishway exit and/or the auxiliary water supply intake and/or the dam spillway.

Instream Fishway - A fishway built within the stream channel, and without flow control, other than its own internal hydraulic control.

Momentum - A quantity of motion measured by the product of velocity and mass of a moving object. It is proportional to the product of velocity and flow of water.

Nappe -

Tailwater - The area of the stream, downstream of a dam or fishway.

Travel Swimming Speed - The swimming speed of a fish relative to the ground. It is the actual speed of passage.

Prolonged Swimming Mode - Fish swimming mode that can be endured for some time, 7 seconds to minutes, but results in fatigue.

Relative Swimming Speed - The swimming speed of a fish relative to the water.

Sustained Swimming Mode - The swimming mode of a fish that can be maintained indefinitely without fatigue.

Tailwater - The area of the stream downstream of a dam, or fishway, at the fishway entrance and/or below the dam spillway.