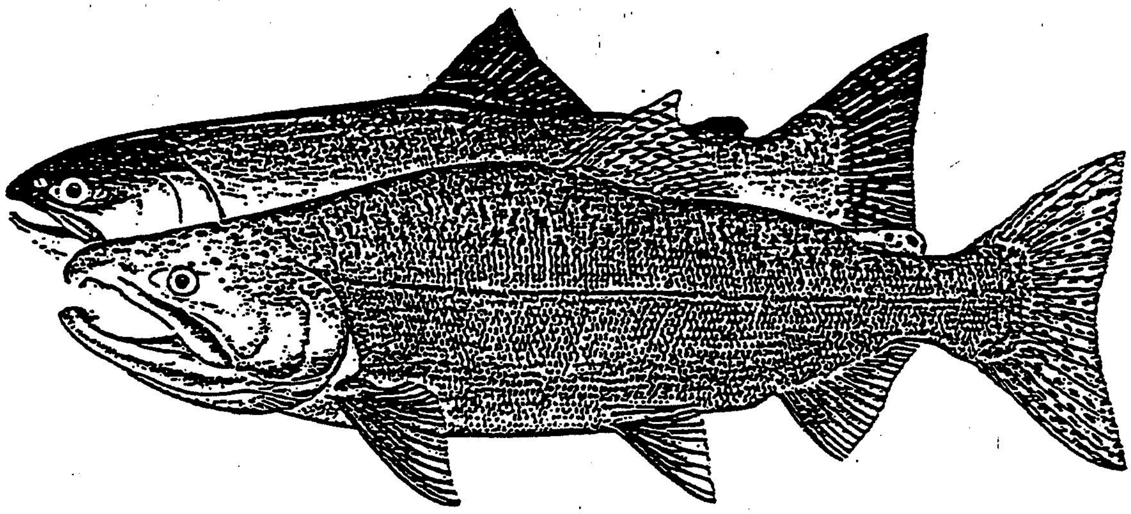
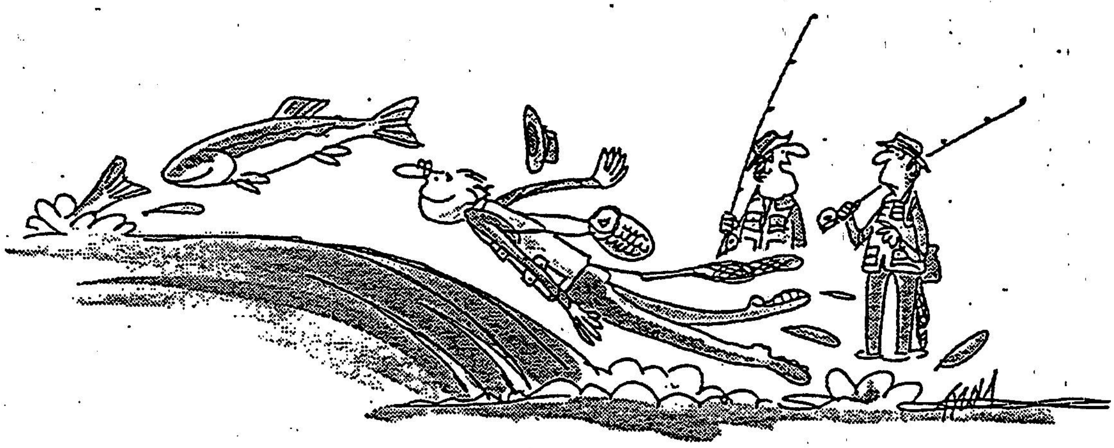
FISHWAY DESIGN GUIDELINES FOR PACIFIC SALMON



Ken M. Bates
March 1992



"That guy thinks like a fish."

FISHWAY DESIGN GUIDELINES FOR PACIFIC SALMON

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The fine print: Most of the information in this paper comes from my fish passage design experience with Washington Department of Fish and Wildlife. The suggestions and recommendations made here are my own however and do not necessarily reflect WDFW policies or standards.

FISHWAY DESIGN GUIDELINES FOR PACIFIC SALMON

INTRODUCTION

This publication describes practical guidelines for the design of fish passage facilities for upstream migrating anadromous fish. Though the standards listed most specifically apply to Pacific salmon and steelhead, the considerations certainly apply to many anadromous and resident species. I hope to expand the scope of this paper to include resident species. The design standards I suggest here are a result of formal studies and practical experience. The practical experience includes failures; learning experiences that define the limits. This paper does not intend to be a treatise on hydraulics, hydrology or biology. Those are the foundation of fish passage technology but I assume the reader is already somewhat familiar with those disciplines.

The scale of systems to which these guidelines apply spans from mainstem passage in rivers such as the Columbia to small culverts under county roads. My definition of fishway is any structure or modification to a natural or artificial structure for the purpose of fish passage. The fishway is a system that may include attraction features, barrier dam, entrances, auxiliary water system, collection and transportation channels, the fish ladder itself, 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. A brief glossary of fishway terms used here is included at the end of this paper.

I hope that this is a useful tool; it is a working paper and won't be finished until it is done. It will be updated periodically. I appreciate comments and criticisms. This paper in no way replaces the professional hydraulic engineering and biological expertise that are necessary for successful design of fish passage facilities.

PREDESIGN DATA REQUIREMENTS

A variety of physical, hydrologic, and biologic considerations will determine whether a given obstruction is passable. Data gathered prior to the design forms the basis for the technical analysis and design. Time taken to collect and understand these data and develop a consensus on relevant design criteria before investing in technical design is a valuable investment.

BIOLOGICAL DATA

Biological data are the fish passage design criteria. 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?

Fish passage design is normally based on the weakest species requiring passage and should accommodate the weakest individual within that species. Management objectives may however direct blockage of certain species or age classes.

<u>Design criteria considerations</u> The appropriate design standard for a specific site may be driven by the project objective. Considerations may include whether the project is mitigation or enhancement. Mitigation is the restoration of passage that is impaired by man-made influences. To be successful, it must usually fully restore passage. Enhancement is the improvement of passage at a natural full or partial barrier. It is more appropriate, as part of an enhancement, to consider cost efficiencies and therefore possibly not achieve the same standard of performance as expected for mitigation.

The development of passage criteria for adult upstream passage and juvenile downstream passage differ. Upstream passage criteria tend to optimize passage conditions. They are based on selecting the best known technology and the 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. Upstream passage conditions are 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 is of course the most basic variable in passage design. The swimming and leaping capabilities of species can determine design criteria; design criteria among species of salmon and steelhead vary little.

Species should also be considered that are not the primary intended target but are present and may or may not require passage. Fishways on the Columbia River were not originally intended for shad passage because they were not a commercially valuable species. Passage research focused on salmon and steelhead. American Shad populations in the Columbia River have expanded from about two hundred thousand in the early 60's to as many as four million passing The Dalles Dam in 1990. Fishways were initially a blockage or at least a hinderance to shad passage; they accumulated within the Bonneville fishway at times to the extent that they blocked the passage of salmon.

Passage design for Pacific salmon and steelhead is a relatively simple task compared to Asian and South Pacific fish passage designs that must accommodate crabs, eels and small weak fish as target species.

Design of fish passage for resident species in North America is also difficult. Migrations for adfluvial spawning, feeding, redistribution due to density and water quality are common among resident fish. They often migrate at younger life stages; their migration timing and motivation is usually 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 greatly 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.

It should be acknowledged that all obstructions, whether mitigated with fishways or not, cause migration delay. A well designed culvert will cause minor delay; the change in hydraulics and light conditions are enough to cause a 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 of fish is critical to fish passage design and is often a function of species. Shore and depth orientation during migration, where they hold, how they respond to hydraulic, light and enclosure conditions may be important factors. Though chum salmon are powerful swimmers, they refuse to leap. A minor plunging drop of less than a foot can be a barrier whereas a steep chute four feet high is easily swum through. Pink salmon behave similar to chum.

The condition of the fish may influence the design criteria. Swimming capabilities of anadromous fish generally decline as fish migrate upstream.

Timing Understanding the seasonal as well as diurnal behavior of the fish is important in setting the period of operation and the range of flows through which the fishway will operate. An understanding of the timing will also help define the impact of delay of a species.

Most adult salmon migrate during daylight hours. Figure 1-1 shows the timing of steelhead passage at Lower Granite Dam in 1992. The timing shown is typical for salmon though it can vary considerably.

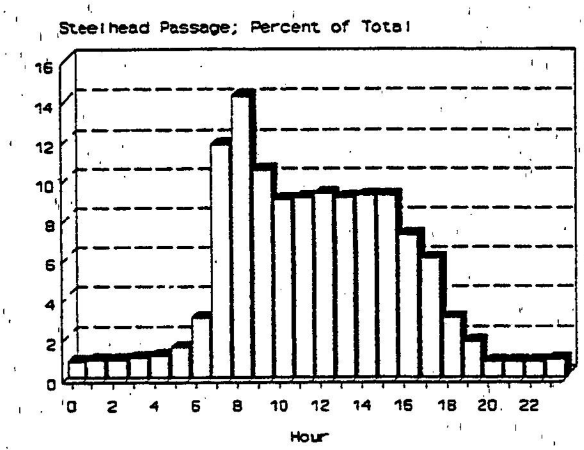


Figure 1-1. Steelhead Passage by Hour, Lower Granite Dam; 1992.

Sockeye passage at Zosel Dam on the Okanogan River 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; 12% of the run moved in a single day. The passage timing of these fish may have been influenced by water temperature. They had been blocked for possibly more than a month downstream by a thermal barrier at the mouth of the Okanogan River.

Age Fish passage programs tend to concentrate on upstream passage improvements for adult fish. The productivity of some stocks however depend greatly on the ability of juvenile fish to redistribute both upstream and downstream into favorable rearing habitats. There is information documenting the value of over-wintering habitat and on the swimming speeds and stamina of juvenile fish.

Though much effort has gone into protecting and enhancing rearing habitats, little data are available regarding the requirements for upstream passage of juvenile fish. Juvenile anadromous fish that remain in fresh water substantial periods of time before migrating downsteam are particularly vulnerable to blockages in small streams.

Fish passage criteria typically ignore the need for upstream juvenile passage. Though not specifically protected, regulations are interpreted to include juvenile fish passage as well as adults. Washington State Department of Fish and Wildlife (WDFW) culvert design criteria assumes that adequate juvenile passage is provided if the hydraulic characteristics for adult passage are achieved during peak flows. It is assumed that the adult passage hydraulic conditions will result in a roughened channel through the culvert and that juvenile fish can tolerate some delay and will be subjected to less severe hydraulic conditions than adult migrants. Alaska Department of Fish and Game (ADF&G) recognizes juvenile migrants by grouping them with other weak fish and providing maximum allowable average culvert velocities for them.

<u>Size</u> The minimum and maximum sizes of fish of each species expecting to pass may determine maximum velocities and drops and minimum depths within a fishway. Swimming capabilities are a function of size of fish; they are a consideration in design of culverts and modifications of falls. Fish passage is designed for the smallest fish of the species requiring passage.

<u>Run size</u> The ultimate size of the peak of the run may control the size of fishway or collection pools. Hell's Gate fishways on the Fraser River were are the earliest example that I am aware of in which the size of the fishway was regulated by the size of the run expected. This is rarely the case; hydraulic considerations within the fishway pools normally control the design.

For examples of sizing fishways for the size of run, see Section 5.

SITE DATA

Site data are the physical description of the barrier and river channel and uplands associated with the barrier and design and operation of the fish passage resolution. Getting a good site description is most essential for small projects where extra field trips can become a substantial burden to the project.

The best way to describe topography is by a stadia survey or a series of cross sections if dealing with a length of channel. The bathymetry of plunge pools should be included in the survey. Channel and bar configurations should be analyzed 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.

<u>Geology, soils</u> Soil conditions relate primarily to construction and structural design considerations. They may dictate the basic fishway concept selected.

<u>Access</u> Access includes considerations of 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.

<u>Flood Protection</u> Record flood information including forebay and tailwater high water marks, bed load information and debris quantity and character.

<u>Check lists</u> Check lists remind the designer of the many details of information needed at a site. 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 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; 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 likely 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. The analysis of barriers is not addressed here.

A variety of design flow criteria have been suggested or used. Gebhards and Fisher (1972) suggested an allowable migration delay of 6 consecutive days for salmon and trout. Dryden and Stein (1975) recommend that a 7 day impassable period should not be exceeded more than once in the design period of 50 years, and that a 3 day impassable period should not be exceeded during the average annual flood. The States of California and Washington suggest that passage should be provided 90% of the migration period of the target species (Kay and Lewis, 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 presented design flow criteria for fish passage at instream stormwater detention basins; "fish passage criteria 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). For culverts, Alaska Department of Fish and Game (ADFG) 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 frequency analysis. Snow melt runoff peaks are typically not as high but last longer and therefore lead to an event duration analysis.

Hydrologic criteria may also depend on whether the objective of fish passage is mitigation or enhancement; the design criteria listed here are intended as mitigation criteria. Enhancement opportunities should not be lost only because they impractical by the application of mitigation criteria.

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 (Powers and Saunders, 1996) performed multiple regression analyses on streamflow data from 188 Washington streams with drainage basins less than 50 square miles and minimum gauging records of 5 years. Models for prediction of Q_{hp} (10% exceedance flow) were developed for three hydrologic provinces in Western Washington for winter and spring months. Two regions have prediction models for highland streams (gauge elevation above 1000 feet) and second models for lowland sites; a total of 10 models were developed. No valid correlation was found for Eastern Washington.

The models are presented here only as an example; they can not be used in other regions without first being verified for that region nor should the be used for watersheds that exceed 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 (1-1):

$$Q_{hp} = aA^bP^cI^d \qquad (1\text{-}1)$$

The parameters are defined as:

A	Basin area in square miles;
P	Mean annual precipitation at the gauging station in inches;
I	Rainfall intensity; 2-year, 24-hour precipitation;
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 are reported by Powers and Saunders; they 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. Powers and Saunders recommend, "the imprecise nature of accurately predicting high passage design flows would more often than not influence the user to add the standard error." Summaries of the regression constants and the statistics of the basins for each region are provided in the Appendix.

Structural design of the fishway will depend on an analysis of flows higher than the high passage design flow and are not discussed here.

Third rule for naive engineers: Constants defined in technical manuals are treated as variables.

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 that I am aware of. The low fishway design flow should be considered in the negotiation of instream flows. Fish passage considerations that should be given to instream flows include adequate flow for fish attraction and adequate flow for operation of screen bypasses.

A necessary tool for any river engineering work is a set of flow exceedance curves by month for, at least in this case, the extent of the migration season.

HYDRAULICS

Hydraulics is the science of the static and dynamic behavior of fluids and can be observed, analyzed or modeled. Hydraulic principles are applied to the river channel and passage barrier to appropriately locate the fishway entrances and exit and to determine the required scale of the facility and entrance flows. Hydraulics at the fishway entrance and within the fishway are the basis of successful fish passage.

Flow circulation patterns within the tailwater should be understood at various depths and stream flows. Water surface elevations, both tailwater and forebay rating curves, are required for fishway design. They should be based on observations through a range of low to high flows. They should be extrapolated by an acceptable hydraulic technique to include higher and lower flows as necessary.

Turbulence can be a barrier and should be understood at a site for fishway design. Little work has been done on turbulence related to fish passage. Stuart (1962) suggested that aerated water creates a barrier for fish passage. He did not isolate the effects of aeration from turbulence. His observations of fish barriers, however, may have been turbulence or a combination of both aeration and turbulence. Indirectly, turbulence is a criteria in the design of formal fishways in terms of appropriate pool volume for energy dissipation (Bell, 1990). Be careful in interpreting turbulence observed in a model. Turbulence is a function of viscosity; scale models are usually governed by laws of gravity so viscous forces may not be directly scaled.

The location of the passage barrier often is a function of stream flow. The barrier 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 dissipator.

A good example of use of a model to determine fishway and entrance locations is the Hell's Gate fishway in the Fraser River. 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 O&M limitations including personnel, access and funding. O&M funding always seems in jeopardy; consider the implications of potential reduced O&M funding on the operation of the fishway. Careful consideration should be given to the possibility of not achieving the desired consistent operation and maintenance of a fishway. Consider the likelihood of such a situation and its consequences for fish passage success based on a specific facility design.

Proper fishway operation and maintenance is best achieved when there is a clear understanding of the intended operation and an appreciation for the importance of fish passage every hour of the day. 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. Pacific salmon often start migrations in response to freshets. Fall freshets usually come with wind that carries debris, especially fall leaves, into the stream.

The preliminary design process is a good time to start developing an operating manual. Continue its development throughout the design; make sure it is realistic and the operator of the facility agrees to it and is committed to it as it is developed.

FISHWAY ENTRANCE

The fishway entrance is often the most difficult design element and the most critical to successful fish passage.

The key to successful passage is to bring the fish to the fishway; to bring them from the uncontrolled natural river environment to the controlled fishway system. As Jack Orsborn so aptly puts it:

NFI = NFO

No fish in; No fish out. 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, CONCEPTS

Fishway entrances and entrance pools have a variety of purposes; more complicated hydraulic and hydrologic settings require more complicated entrance pool designs. The application of these functions and specific guidelines will be discussed in the entrance and entrance pool design sections that follow.

Access The most obvious and necessary purpose of fishway entrance pools is for fish access to the fishway. Other more subtle purposes though influence its design.

Attraction The entrance is the key to attraction of fish. Think of the jet of water leaving the fishway entrance as an extension of the fishway into the tailwater. That extension is a path that guides 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.

Introduce Auxiliary Water 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 to not delay fish but to guide them to the fishway itself.

Hydraulic Control The entrance controls the hydraulic characteristics of the entrance flow. 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 determine whether the flow that exits it either plunges or streams.

Transition 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 above.

<u>Location</u> The location of the fishway entrance should logically be at the upstream-most point of fish passage. 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.

Fishways are normally constructed on banklines where construction, operation and maintenance access are simple. Conditions that lead to placing fishway entrances at each bank include:

- wide channel; a single fishway cannot attract fish from the opposite bank of a wide channel;
- holding areas far from each other or from the barrier;
- migration routes along each bankline;
- hydraulic conditions that prevent or distract fish passage from any part of the channel to the entrance.

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 in the bankline boundary layer. 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 will likely 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 below and above the barrier should be made especially for high flows. Observations of fish location and orientation when attempting to pass a barrier are valuable.

Multiple entrances that operate each within a specific range of flows may be necessary where changes in the tailrace hydraulic conditions are great. Low and high flow entrances are often provided.

Low flow entrances are located close to the base of the dam. They are usually operated only at low flow. When a roller bucket energy dissipator is located far downstream from the dam crest, fish can become trapped in the pool between the dam and the back roll. 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 for the sake of 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. 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 dissipator is used. Roller buckets contain the dissipation within a narrow segment just below the roller bucket.

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. The entrance flow must be adequate to compete with spillway or powerhouse discharge flow for fish attraction. Site conditions and especially tailwater hydraulics and channel width help 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 is defined as mass times velocity.

$$Momentum = Mass \times Velocity \qquad (2\text{-}2)$$

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. Table 2-1 shows the total entrance flow for a range of fishway scales. 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 on the other hand 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.

Table 2-1. Entrance Flows at Various Fishways.

Fishway; Location	Entrance Flow; cfs (Q_E)	Design Flow; cfs (Q_{hp})	Q_E/Q_{hp} %
Sunnyside Dam Yakima River	416	7,400	5.6
Sunset Falls Skykomish River	234	6,000	3.9
Naches Cowiche Naches River	92	2,500	3.7
Centralia Dam Nisqually River	80	1,750	4.6
Easton Dam Yakima River	120	1,300	9.2
Anderson Creek; Nooksack trib.	9.7	112	8.7

These fishways operate effectively; they are in locations without unusual tailwater conditions.

This information should not govern a design; it is provided only to show the wide range of entrance flows selected and how they relate to river scale.

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 30° 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 the high velocities in the stream beyond it. Those fish are right at the alternative passage route however, the fishway entrance.

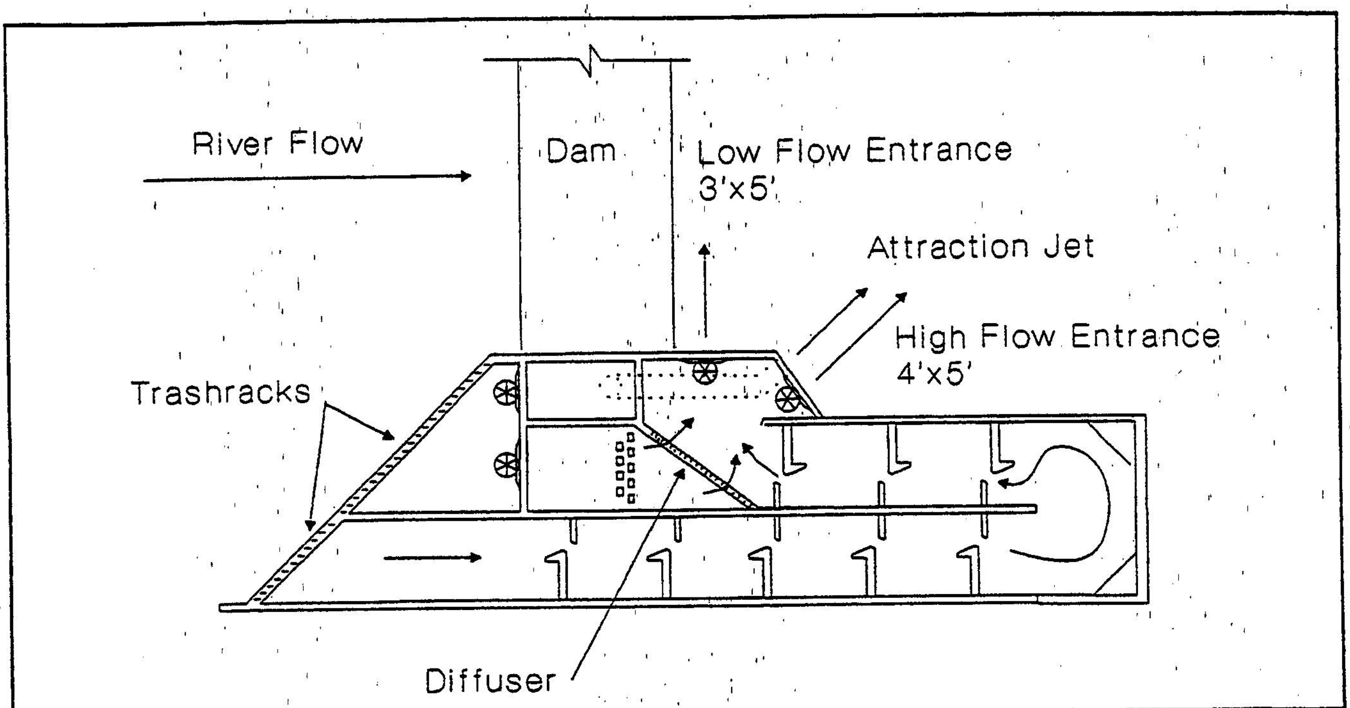


Figure 2-1. Wapato E. Branch Fishway; Yakima River

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 2-1 and a detail of the entrance pool in Section 3.

<u>Entrance Head</u> 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 et al (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 are 8.0, 11.3, and 13.9 fps at these heads. They evaluated only preferences between pairs of entrances, not attraction to them. A majority of fish of each of the three species chose the 2.0 and 3.0 foot entrance heads 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 2-2.

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.

Chum and pink salmon have more specific requirements. Though they

Table 2-2. Fish failing to enter experimental entrance or control entrance with 1.0 ft head.

	Head on experimental entrance	Fish failing to enter either entrance
Chinook salmon	1.0 ft.	0.0 %
	2.0 ft.	9.1 %
	3.0 ft.	29.7 %
Steelhead trout	1.0 ft.	1.1 %
	2.0 ft.	8.8 %
	3.0 ft.	14.7 %

have no trouble swimming through an entrance with a head differential of 1.5 feet or more, they will not jump even a portion of that height. They require a streaming flow or submerged weir condition; something they can orient to and swim through. They may appear to leap in some situations but my observation is that they swim up a steep plume or nappe. 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. There is less than a foot of drop, but pink salmon do not attempt the leap.

<u>Shape and Dimension</u> The fishway entrance can be an overflow weir 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 of its boundary, the less rapidly it will be dissipated. For this reason, an ideal shape would be circular and the least desirable would be a narrow vertical slot. A more practical shape is a square or rectangular port with a width to height ratio from 0.6 to 1.25.

A jet will stream from the entrance only if it does not plunge. A plunging flow will drop nearly vertical and set up a hydraulic roll and surface counterflow downstream of the entrance. A streaming flow, on the other hand, will remain intact near the water surface or at the elevation of an orifice 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.

Entrances vary in size from 12 feet wide by 8 feet deep on the Columbia River dams, 3 to 4 feet wide by 4 to 5 feet deep on the Yakima and Wenatchee Rivers 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 2-5. It creates a velocity shadow so fish can approach the entrance area and the high shear velocity beyond the entrance prevent passage past the entrance. The Hell's Gate fishways and fishways on Cedar Creek, a tributary of Lewis River, and the Klickitat River are designed with shear slot entrances.

Fish behavior may also affect entrance geometries. Thompson et al (1967) tested 371 chinook, coho and steelhead to find their preference for size and shape of fishway entrance. 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.

<u>Light</u> Daytime lighting requirements at fishway entrances is clear. Concurrent with the entrance dimension tests discussed above, Gauley et al (1967) tested the preference for lighted or dark entrances with 1.0 feet of head. Even when given the choice of the large (3.9 ft. by 3.9 ft.) entrance which was dark or the smallest (1.5 ft. by 2.0 ft.) entrance which was lighted, 80%, 90% and 69% of the chinook, coho and steelhead chose the lighted one.

In a similar test they found that lighted entrances were again chosen by 86% of the sockeye 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. This is equivalent to a bright cloudy day.

Hiram's Law:
If you consult enough experts, you can confirm any opinion.

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 150W Edo Western model 1207 and was described as "a mercury vapor lamp with thallium iodie 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. Sensitivity of fish to various light frequencies should be accounted for. It makes sense that they would be most sensitive to green or shorter wave lengths 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 and large accumulations of salmon in resting pools downstream of difficult passage areas such as fishways and rapids has been common (Saxvik, 1990). Floodlights were installed at some of the Fraser River fishways beginning in 1989. The lighting allowed fish to continue through the fishways at night and eliminated the downstream accumulation and congestion of fish overnight. The fishway capacity was increased by the lighting by extending the daily period of passage. The capacity was increased by secondarily 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 tansition section from light ambient conditions to dark fishway conditions or to mimic ambient conditions as turbidity varies.

Experimental lights within the Hell's Gate and other Canadian fishways have resulted in continued passage during the night and thereby reduced crowding and delay during the following day.

The use of lights in conduits has also been tested and is reviewed on Page 2-10 in the section on transportation channels.

<u>Elevation</u> The entrance head differential must be maintained as the stream flow increases. The rising tailwater backwaters and drowns out the entrance unless the entrance adjusts to compensate. This can be done by mechanically raising the entrance weir or by increasing the entrance flow. Both of these options are discussed later; entrance gates on Page 2-9 and auxiliary water systems in Section 4.

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 as 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.

If an objective is to maximize attraction at low flow, the entrance should be submerged to optimize the streaming jet flow. The flow predominantly streams when it is backwatered by the tailwater to at least 30% of its depth. 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 tailwaters.

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. Stream bed controls are especially vulnerable; 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 stream bed degraded from under the controls due to efficient sediment capture in the trap and clearwater scour.

<u>Entrance Gate</u> Entrance gates are used to control and optimize the fishway entrance hydraulics described above; 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; extra sturdy components should be used. Entrance gates submerged in roller bucket energy dissipators should be extra heavy duty to withstand the vibrations and turbulence there. A rising stem gate is necessary to not have a gate stem through the middle of the entrance.

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

ENTRANCE POOL AND TRANSPORTATION CHANNEL DESIGN

The detail designs of the entrance pool and transition to fishway are critical to fish passage. Essentially all passage problems that I am aware of 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.

<u>Hydraulics</u> Shape the pool and locate auxiliary water diffusers and ladder entrance to provide a stable flow pattern and transportation velocity to lead fish from entrances to fish ladder. Excess space where eddies, flow separations or dead water may occur should be eliminated from entrance pools and channels. Corners should be rounded or filled; dead ends and areas should be

eliminated. The Wapato fishway entrance shown in ? is a good example.

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

If an entrance pool has multiple entrances to different tailwaters that are separated hydraulically from each other, a flow instability can be created. Surging can occur as one entrance draws the entrance pool down, that tailwater pool fills and backwaters the entrance pool the entrance flow decreases and then the tailwater pool drains. This sequence repeats alternating between entrances. The entrances can be isolated from each other hydraulically be inserting several fishway weirs between them; a junction pool and parallel fishway legs may be required.

<u>Velocity</u> In transportation channels, a uniform velocity from 1.0 to 4.0 fps should be maintained; 2.0 fps is a normal operating criteria. Laboratory studies have not found an optimum velocity within that range consistent for all species. It is prudent to design the system capacity for the higher velocities though they may not be used. Transportation velocities are also applied to the lower end of the fishway when it is flooded by a high backwater. When it is flooded, the increased cross section area results in a reduced velocity unless auxiliary water is provided. Auxiliary water is discussed in Section 4.

Salmon move at a relative speed, with reference to the ground, of about 2 to 4 fps whether swimming at a prolonged or burst speed.

<u>Light</u> 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. It is generally believed that fish delay at changes in light conditions however. 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. See the section on entrances, Page 2-7 for specific light suggestions.

AUXILIARY WATER SYSTEM

The auxiliary water system is the source, control and supply of supplementary water to the lower end of the fishway. There are four general purposes of auxiliary water:

- 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 are bar grating, perforated plate or wood racks.

There are four objectives of a good diffuser design:

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

The spaces between bars of a diffuser must be sized to prevent fish passage and 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 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 criteria, the flow divided by the overall diffuser area. A diffuser velocity of 1.0 fps is generally applied for salmon. 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 et al, 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 shown in Figure 3-1 is an example of a good layout of entrance pool, auxiliary water diffuser and fishway.

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 head loss. Another good distribution system used in floor diffusers is the stepped baffle shown in Figure 3-2. This system should also work for a wall diffuser when turned vertically.

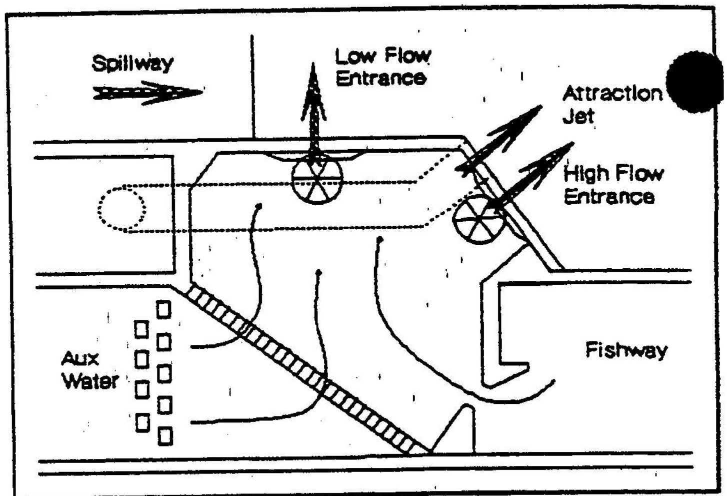


Figure 3-1. Wapato fishway entrance pool.

<u>Wall Diffusers</u> Wall diffusers have a great advantage over floor diffusers in their ease of maintenance; they can be cleaned from overhead with a rake.

Make sure the upstream side of the diffuser grating is clear of horizontal support bars so debris can be raked. An unobstructed access must be provided from overhead. If there is a grating over the auxiliary water chamber, light-weight hinged grating should be provided appropriately for access for cleaning. The entire upstream side of the rack must be accessible for raking; the grating should be mounted flush with upstream wall of the diffuser port therefore.

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. Fish are often attracted to spilling water or its aeration and leap at it.

Standard commercial bar walkway grating is used for diffuser grating.

<u>Floor Diffusers</u> An advantage of floor diffusers is that fish are less attracted by upwelling water than flow from a wall diffuser or at least they don't jump at it. They are difficult to clean however. Several floor diffuser systems have been designed to be pivoted or hinged to allow flushing of debris. I am not aware of any of these currently in operation.

AUXILIARY WATER SUPPLY

Auxiliary water is supplied by gravity from forebay, pumped from the tailrace or combination of both. Gravity auxiliary water control gates can often be designed so they are essentially self controlling. This is done by matching the control gate flow characteristics to the auxiliary water flow requirements; a proportional weir or orifice gate is required.

<u>Chimneys</u> 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 and maintain a desired velocity in the backwatered pools for attractive transportation conditions. See the discussion in Section 3 regarding transportation channels.

A chimney system is shown in Figure 3-2. A porosity panel or orifice creates a constant head loss between the diffuser pool and entrance pool. At low tailwater, the chimney supplies no flow to the diffuser. A constant head is maintained between the diffuser pool and entrance pool and between the entrance pool and the tailwater. The entrance pool and diffuser pool water surfaces therefore rise with rising tailwater. When the diffuser pool water surface rises to the level of the chimney flow control orifice, water flows through the orifice and diffuser. The supply orifice controls the quantity and should be designed with an adjustable open area. A series of progressively higher chimneys will supply water to progressively higher fishway as the tailwater continues to rise.

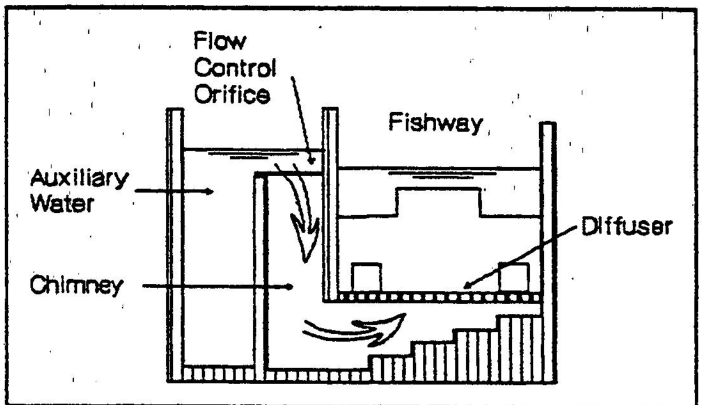


Figure 3-2. Chimney flow distributor and floor diffuser.

The chimney concept can be used to supply wall diffusers also.

<u>Source</u> Do not be supplement the fishway with water from sources other than the primary water supply. They that 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. The reservoir at Green Peter dam on the Santiam River is stratified. The fish facilities are no longer in operation for a number of reasons. When the facilities were operated, returning adults could not be attracted into a fishway. They were primarily attracted to a 10 cfs juvenile outfall that had a reservoir surface water source rather than the fishway of 50 cfs or powerhouse of up to 5000 cfs. The fishway and powerhouse water sources were both deep in the reservoir. As juveniles, these fish had moved through the reservoir in shallow water; as adults they likely 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.

Their 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.

Screen the auxiliary water supply where practical to eliminate cleaning maintenance requirements and prevent loss of juvenile fish passing through system.

OTHER GUIDANCE AND ATTRACTION MEANS

Auxiliary attraction jets. Attraction jets adjacent to fishway entrances improve passage at least in some situations. The intention is to provide a stronger jet that penetrates the tailwater to reinforce and buoy the entrance jet. It must have a high enough velocity to act as an effective barrier to passage. Several of the Yakima River fishways have attraction jets as shown for Wapato Dam fishway in Section 3. These have not been evaluated. Attraction jets are attached to the outer wall of Alaska steeppass fishways at several locations; see Section 5.

Sloped or notched weir Special weir configurations are often used to help attract fish. Be careful that a notched weir does not add so much water that it drowns out the entrance with turbulence. Sloped and notched weirs have not been evaluated as far as I know. I think they are of marginal if any benefit. At low flow they are not needed because the fishway is attractive enough. At high flow, the distribution of flow is only marginally affected; likely not enough to change overall tailrace flow patterns enough to attract fish. Notches would be helpful in a very long crest and where the range of fish passage flows is not great.

Angled weir

Crown spill

Distractions Distractions that might attract fish away from the fishway entrance are as important as attraction to the fishway. Any concentrated flows in the tailwater should be eliminated or diffused to eliminate their attraction.

The hydraulic conditions at dam abutments often attract fish. A contraction occurs as the flow passes abutment the wall; it concentrates 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. Abutment walls could be designed as efficient contractions to eliminate this distraction.

When a 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

This section considers the fish ladder itself; the actual structure through which fish climb to a high elevation. It is part of an entire fishway system.

I divide fishways into six classifications based on their hydraulic design and function. Critical design elements, dimensions and limitations of the styles that are relevant to passage of Pacific salmon and steelead are discussed in this section.

<u>Pool and weir fishways</u> have distinct pools in which the energy of the flow entering is entirely dissipated. The hydraulic control between the pools are overflow weirs with or without orifices.

<u>Vertical slot fishways</u> also have distinct steps but the hydraulic control is a narrow vertical slot open at the top.

<u>Roughened channels</u> are chutes or flumes with roughness designed to control the velocity to a point adequate for fish passage. A natural stream channel is a roughened channel as are Denil style fishways and culverts with or without baffles.

<u>Hybrid fishways</u> are a combination of weir and pool, vertical slot or roughened channel fishways. Pool & CHUTE

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

<u>Elver and climbing passes</u> 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 lampreye.

Appropriate selection of a fishway style for a specific site depends on a number of variables:

- 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.

DESIGN CONSIDERATIONS; POOL STYLE FISHWAYS

<u>Fish Behavior</u> 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. See Page 5-6 for a description of streaming and plunging flow conditions.

The fishways on the Columbia River dams were not initially designed with the consideration of shad passage. The flow control sections had orifices with no overflow sections. Shad would not pass through the orifices. The accumulation of shad then blocked salmon passage. As a result, hundreds of shad died in a day in the fishways.

Squaw fish, suckers and carp use the orifices.

Chum and pink salmon will not leap. They are strong fish but require a slot, orifice or submerged weir for passage. This may be due to the fact that they spawn lower in the river systems than other species and have not in their evolution developed to pass over water falls or other obstruction.

<u>Pool Volume</u> The volume required in a fishway pool must provide both adequate hydraulic capacity and fish capacity. The hydraulic capacity nearly always governs. It is the volume for adequate energy dissipation within the pool. This prevents a carryover of energy to the next downstream pool and reduces turbulence and aeration to the point that resting area is provided. The energy dissipation criteria for salmon and steelhead is based on a maximum energy dissipation of 4 foot pounds of energy per second per cubic foot of volume.

This criteria is applied by Equation (5-1) where V_{pool} is the

h upstream includes velocity? cf.

$$V_{pool} = \frac{\gamma \times Q \times h}{4ft\text{-}lb/ft^3/sec} \qquad (5\text{-}1)$$

$\gamma = 62.5$ lbs/ft³

required effective energy dissipating volume of the pool. γ is the unit weight of the fluid (water) in pounds per cubic feet, Q is the flow entering the pool in cfs and h is the head of the flow entering the pool in feet. Portions of the pool, because of its length or shape, may not contribute to energy dissipation. It is recommended that no pool length greater than ten feet be included in energy dissipation volume calculation. Europeans use the same (200 watts/m^3) for salmon and 3 ft-lb/sec/ft^3 (150 watts/m^3) for shad (Larinier, 1990).

The pool volume may also depend on required fish capacity in situations of very large and concentrated runs. It is a volume requirement based on a maximum instantaneous loading rate and the

$$V_{pool} = \frac{C}{60} \times \frac{V}{r} \qquad (5\text{-}2)$$

allowable density of fish. The pool volume for fish capacity can be derived from Equation (5-2) where v is the volume required per fish in cubic feet, c is fish passage in number of fish per hour and r is the rate of fish movement in minutes per pool.

The pool volume recommended for fish is about 0.4 cubic foot per pound of fish. Columbia River fishway capacity experiments indicated a significant delay of fish when loaded at a density of 0.15 ft^3/pound when compared to a density of 0.36 ft^3/pound (Elling and Raymond, 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 ft^3/pound and some delay occurred as a result. The streaming flow in this test was partially due to the weir configuration however. See Page 5-6 for a discussion on streaming flow.

It is interesting though I presume just coincidental that this volume recommendation is essentially the same as the standard long term holding density for chinook, 0.5 ft^3/pound used by WDF (Bob Hager, pers. comm.).

Fish tend to accumulate in the lower pools of a fishway or where hydraulic conditions change. It takes several pools before they accommodate and resume consistent up-ladder movement. Once they enter the fishway itself, salmon spend 2.5 to 4 minutes travel time per pool in the Columbia River fishways.

To size a fishway for the size of run; the resting volume within the pools is based on the maximum expected density of fish. 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. At Bonneville Dam, typically 2 to 8% of the chinook and steelhead and 5 to 8% of the sockeye and coho pass in a day at the peak of each of those runs. About 12% of the Okanogan River sockeye passed Zosel Dam in a day after they had been delayed for about a month by high water temperatures.

Nearly all passage is during the day with 60% from daylight to noon and the remaining 40% from noon to darkness. A typical distribution of passage is shown in Section 1. Based on these estimates, the maximum hourly passage rate would be 1.0% of the total run. It is estimated that the peak pink and sockeye salmon passage rates at Hell's Gate in 1989 and 1990 were each 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. Simultaneous runs of different species have to be considered when calculating expected loading rates.

The design of the Bonneville Dam fishways was the first time the expected density was calculated as part of a fishway design. It was expected that 100,000 fish might pass through each fishway in a single day. The closest approach to that estimate that I am aware of is 47,000 salmon through both fishways in a day in 1986. It is not uncommon for over 50,000 shad to pass in a day.

The Hell's Gate fishways were the first to actually be designed for fish capacity. The capacity is believed to have been reached in 1954 when 2.0 million sockeye passed through Hell's Gate in six days (Andrew, 1990). The average rate was estimated to be 20,000 per hour fish in a single fishway.

In 1989 a new low level fishway was constructed at Hell's Gate on the Fraser River. The design capacity of the fishway was intended 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 foot 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 minimum fishway pool depth for weir & pool and vertical slot fishways varies from 3 to 8 feet. The depth required depends on the scale of river, just as entrance flows.

<u>Orifices</u> The minimum size recommended for orifices within fishway weirs is 15 inches wide by 18 inches high for salmon. The primary reason for not allowing smaller orifices is the increased risk of plugging by debris. Orifices as small as 12 inches wide by 15 inches high are used.

The best use of orifices is as used in the Ice Harbor design fishway shown in Figure 5-2. The orifice located below the overflow section of the weir enhances the plunging action of the weir by reinforcing the roller circulation. Orifices can be used alone without overflow weirs as a flow control device; see the section on flow control.

> **The Min-Max rule of Government: The minimum criteria cited will be the maximum value applied.**

Orifices should be shaped with efficient entrance contractions to provide the most stable flow.

<u>Head Differential</u> 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 fish can swim through. The head can be much greater if it is through a submerged slot or contained in a chute without free falling flow.

<u>Depth over Weirs</u> 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 it has been increased to a depth of 1.6 feet to induce streaming flow to improve shad passage. This change increased the fishway flow from 82 to 115 cfs. See Page 5-6 for a description of plunging and streaming flows.

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. 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 side wall. Efforts should be made to minimize unnecessary leaping by eliminating concentrated spills near the walls and upwelling in corners.

An easy way to extend the freeboard in smaller fishways is construct 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 180° bends. Weaver and Thompson (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 to carry the jet around the bend without impacting a wall and upwelling.

If the jet must follow the inside wall, the wall should be extended for a minimum of 8 feet downstream of weir or add a baffle 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 FISHWAYS

Pool and weir fishways are the most common style in the Pacific Northwest and are applied to all scales of fish passage. Streambed controls at culverts fall into the category of pool and weir fishways though their design criteria differ and will be discussed separately in the section on tributary fish passage.

A primary limitation of pool and weir fishways is their narrow range of operating flow when no other flow control is provided. The lower limit of flow is the depth of flow over a weir, typically 0.25 feet. The upper limit is the flow at which the energy dissipation criteria discussed on Page 5-2 is exceeded or at the point the flow enters an unstable regime as 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.

<u>Pool and Weir Hydraulics</u> Figure 5-1 shows plunging and streaming regimes in a fishway. The normal flow circulation in a pool and weir fishway is termed plunging regime. 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 occurs at higher flows than 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 et al. (1988) provide a good description of these flow regimes and empirical hydraulic formulae for both regimes.

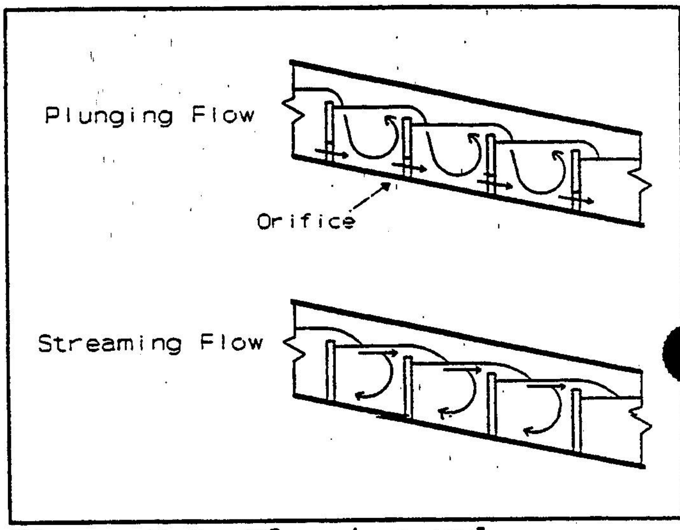


Figure 5-1. Plunging and Streaming Flow Regimes in Pool and Weir Fishway.

A hydraulic instability occurs in the transition regime between the upper range of plunging flow and the lower range of streaming flow. The transition regime and should be avoided. Passage studies have repeatedly shown that when the flow transitions, there is a delay in passage. The instability can also set up large oscillations that gallop through the fishway. The streaming regime should only be used with care. Energy is not dissipated in each pool of the fishway; the streaming jet is difficult to manage.

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 5-1 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 5-1 shows in an eight foot pool the plunging regime extended by 36% (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 (n.d.) and corresponds well with data reported by Rajaratnam et al (1988).

Though alternating notches are commonly used in small pool and weir fishways, I do not believe they are a benefit. Their intended purpose is to better utilize the entire pool volume for energy dissipation. I prefer to allow the water to skip to the next pool and preserve some of the pool volume for resting area. Bedload debris is also better scoured when notches are in line.

Table 5-1. Limits of Flow Stability; Pool and Weir Fishways. (Flow is cfs per length of weir in feet.)

	Upper Limit of Plunging Flow		Lower Limit of Streaming Flow	
	Flow	Head	Flow	Head
8-foot pool				
Square Crest	3.9 cfs/ft	1.1 ft	6.1 cfs/ft	1.1 ft
Square Crest, ports	4.2 cfs/ft	1.0 ft	±4.2 cfs/ft	
Round Crest, ports	5.2 cfs/ft	1.0 ft	±5.2 cfs/ft	
10-foot pool				
Square Crest	4.0 cfs/ft	1.1 ft		
Round Crest	4.4 cfs/ft	1.0 ft		

A consideration not often required in the selection of fishway styles is the passage of juvenile salmon. Coho juveniles in the size range of 100 to 120 mm can easily ascend a pool and weir fishway if the hydraulic conditions are appropriate. Thousands of coho juveniles are observed every spring moving upstream en the Lake Symmington fishway at Big Beef Creek.

Ice Harbor Fishway The Ice Harbor fishway is a 1-on-10 pool and weir fishway with orifices, flow stabilizers and a non-overflow section in the middle of each weir. It was initially developed in the 1960's at the Fisheries Engineering Research Laboratory for use at Ice Harbor Dam.

The half Ice Harbor fishway (Figure 5-2) is just as the name implies, half of the full Ice Harbor fishway, cut along the centerline. 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. A flow of about 70 cfs is required. As many as 1,371 fish have passed through a full Ice Harbor fishway in an hour without sign of delay (Weaver et al, 1966).

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

The 1.20 feet of depth was reported by Weaver et al as head differential but I believe they actually tested water depth.

VERTICAL SLOT FISHWAY

A vertical slot fishways also has distinct steps; the hydraulic control is a narrow, full height vertical slot open at the top. Its greatest advantage is that it is entirely self regulating. A vertical slot fishway is shown in Figure 5-2.

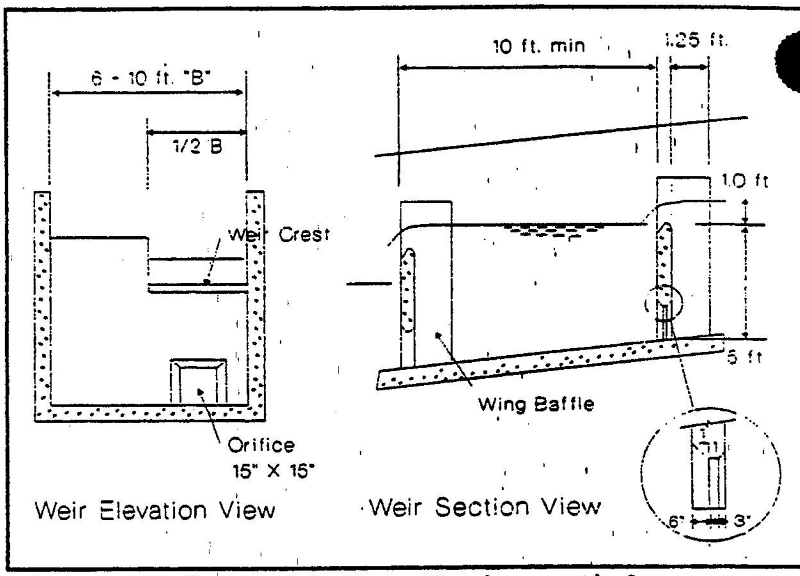


Figure 5-2. Half Ice Harbor Fishway.

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

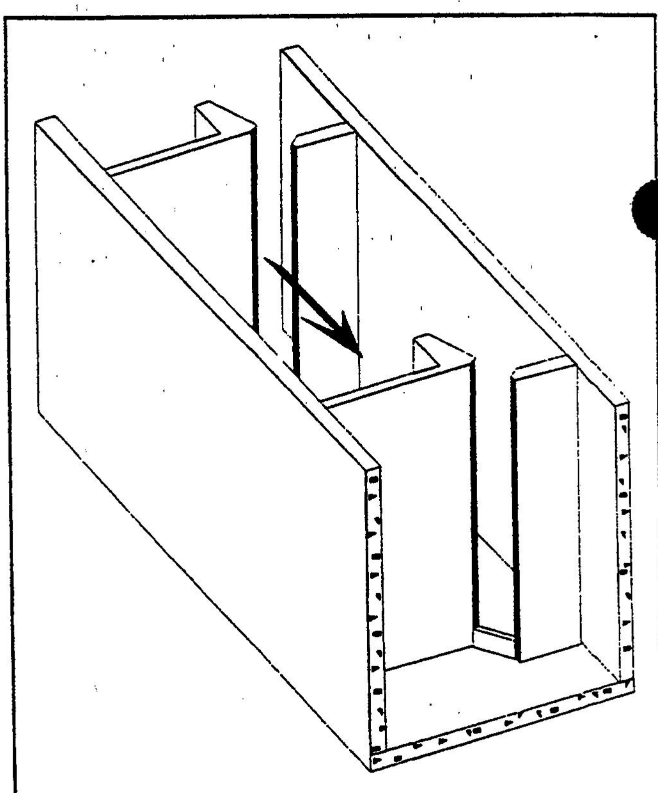


Figure 5-3. Single Vertical Slot Fishway.

Energy is dissipated in each pool by the jet cushioning and 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 on the Fraser River. 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 application in smaller systems and less fish capacity, it was later modified by splitting it down the centerline creating the standard single vertical slot fishway as shown in Figure 5-2.

Flow Flow through a vertical slot is a function of the slot width, water depth in the slot, and head differential across the slot as defined by Equation (5-3).

$$Q_{v\text{-}slot} = CwD\sqrt{2gh} \quad (5\text{-}3)$$

This is an orifice equation with $Q_{v\text{-}slot}$ being the fishway flow, C is an orifice coefficient, w is the slot width (ft), D is the depth of water upstream of the slot (ft), g is the gravitational constant (ft/sec^2) and h is the head across the slot (ft). The orifice coefficient is normally taken as 0.75. 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 reveal coefficients of 0.91 to 1.04 for a 15-inch slots without sills (Onni Perala, pers. comm.). Figure 5-4 and Figure 5-5 show the vertical slot flow graphically for a coefficient of 0.75.

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 an M1 backwater curve in the lower pools when the tailwater rises 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.

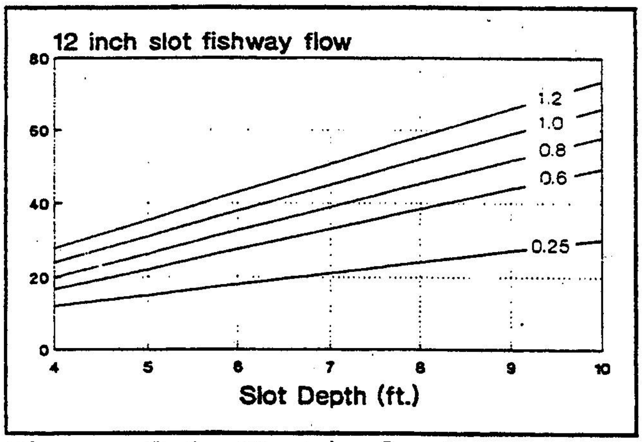


Figure 5-4. Vertical slot rating for various head differentials.

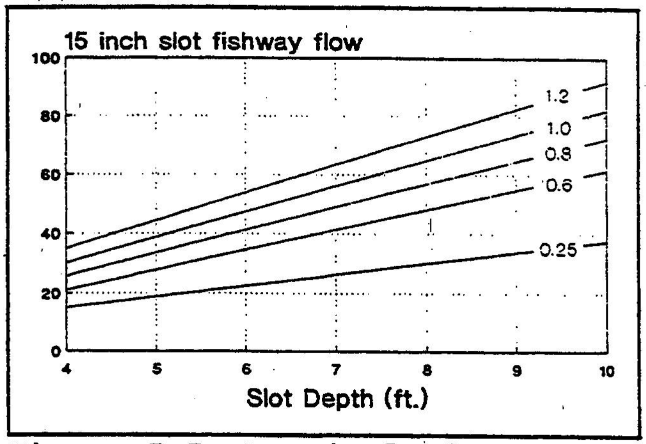


Figure 5-5. Vertical slot rating for various head differentials.

Different design processes are required for the backwater or drawdown situations. The floor elevations are based on minimum depth requirements at low flow for either case. The number of slots is determined by the maximum forebay to tailwater head differential whether it is at low or high flow. The low flow water surface profile or the high flow profile are 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 five feet; some are commonly operated to as low as three feet of depth.

<u>Dimensions</u> The dimensions of the vertical slot and pool are critical to the stability of flow. The dimensions shown in Figure 5-6 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.

I learned this the hard way. Because of site constraints, the dimensions of the vertical slot ladder built at Tumwater Dam on the 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. 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 the 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 five feet or where the head differential may exceed the standard 1.0 feet. 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. Slots as narrow as 6 inches are suggested by Clay (1961) for smaller fish. Other dimensions of the vertical slot, in this case, would be reduced proportionately.

Hell's Gate 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. Remember that these fishways were designed for fish capacity rather than hydraulic capacity.

<u>Passage</u> 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 vertical slot ladder has been timed at an average of 48 seconds per pool (Andrew, 1990).

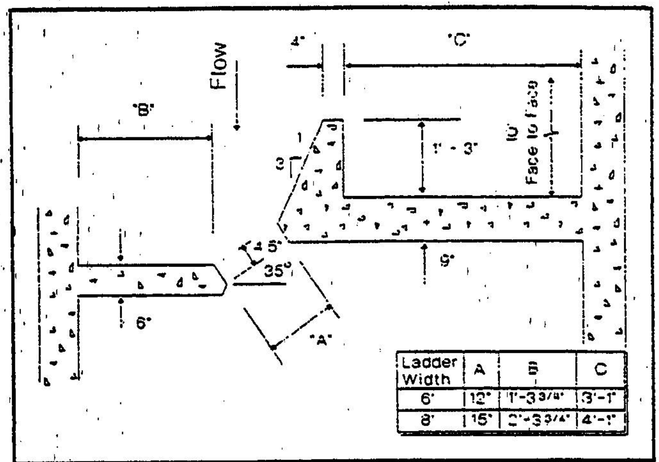


Figure 5-6. Vertical Slot Dimensions.

ROUGHENED CHANNELS

Roughened channels are chutes or flumes with roughness designed to control the velocity to a point adequate for fish passage. Examles of roughened channels are natural stream channels, Denil 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 mode.

Expectation of successful fish passage through roughened channels must consider turbulence as a potential passage barrier. As described in the Culverts section of this paper, turbulence can be an effective barrier depending on its scale and intensity relative to the size and swimming ability of the fish.

Roughened channels naturally have a velocity that is more attractive than a plunging overflow weir for a given flow due to the velocity of the jet exiting the fishway and possibly its aeration.

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.

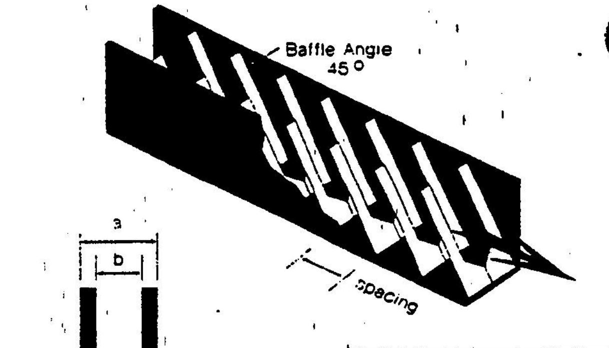
Denil The Denil is an artificial roughened channel. It is used extensively throughout the world though is usually not the first choice of fishway style in the Northwest due to its limited operating range and vulnerability to debris blockages. Several sticks crosswise in a Denil and it can effectively be a blockage.

Primary use of Denils 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

$$Q = 5.73D^2\sqrt{bS} \qquad (5\text{-}4)$$

25%. Standard dimensions are shown in Figure 5-7; the most commonly used size is the 4 foot width. A wide range of flows are possible depending on fishway size, slope and water depth. Rearranging the non-dimensional equations developed by Katopodis and Rajaratnam, the flow for a Denil design similar to that in Figure 5-7 (Design 4) is given in Equation (5-4). Q is the flow (cfs), D is the depth of flow above the vee baffle (ft), b is the open width of the fishway between the baffles (ft) and S is the fishway slope (ft/ft).



a	b	c	d	Spacing
4'	2'-4"	2'-0"	1'	2'-8"
3'	1'-9"	1'-6"	9"	2'-0"
2'	1'-2"	1'-0"	6"	1'-4"

Figure 5-7. Denil Fishway.

Flow control is important though not as critical as for a weir and pool ladder. The forebay must be maintained within several feet to maintain good passage conditions in the Denil. According to the velocity profiles developed by Rajaratnam and Katopodis, centerline velocities increase towards the water surface in Denils where D/b is greater than 3.0. 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. Denils are typically constructed with depths of 4 to 8 feet.

Standard length sections are 30 feet; they can be built out of plywood or steel or concrete with steel baffles.

<u>Alaska Steeppass</u> The Alaska Steeppass (ASP) is a specific style of Denil fishway originally developed for remote installations. Steeppasses are used in the Northwest primarily in 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%; they have been tested and 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 2 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 and Rajaratnam (1991) provide dimensionless hydraulic flow equations that are rearranged into the following dimensionless equation:

$$Q_{ASP} = 0.97b^{5/2}\left(\frac{y_o}{b}\right)^{1.55}\sqrt{gS} \qquad (5\text{-}6)$$

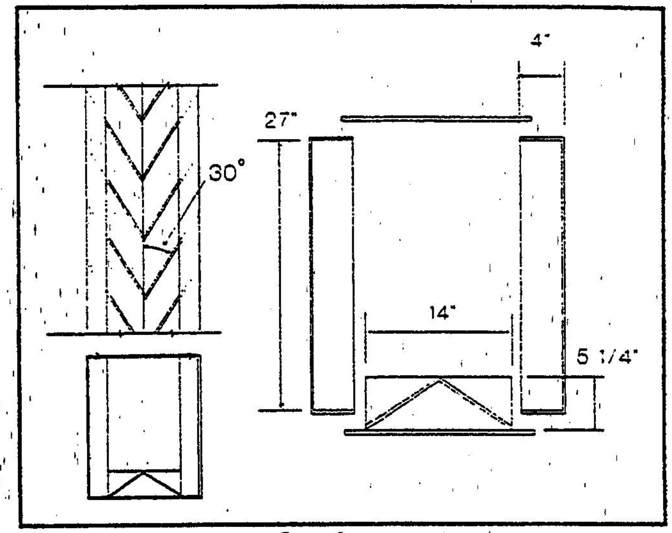


Figure 5-8. Alaska Steeppass Fishway.

Q_{ASP} is the fishway flow, b is the open width inside the fishway, y_o is the depth of flow above the floor vanes, g is the gravitational acceleration and S is the ASP slope.

The English unit equation for the standard ASP derived from the Rajaratnam and Katopodis work is:

$$Q_{ASP} = 1.12S^{.5}y_o^{1.55}g^{.5} \qquad (5\text{-}7)$$

Q_{ASP} is in cfs, y_o is in feet, g is in feet/second^2.

The average velocity in the ASP can be calculated from Equation (5-7). It is this average velocity that ASP designs are normally based on. The point velocity varies through the vertical profile. Rajaratnam and Katopodis found the the velocities to vary through the vertical profile in a full flowing standard ASP ($y_o/b=1.6$). The velocities varied by a factor of 2 and nearly linearly with depth with the lowest velocity at the water surface. ASP's that have a greater relative depth (y_o/b) than 2.1 have the highest velocity near the middle of the profile that increases with increasing y_o/b.

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 passage through ASP's 180 feet long at 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 by Blacket through a single ASP was about 1850 sockeye per hour over 2½ hours and 400,000 in less than four weeks. He concluded 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 but reluctantly. Slatick found that nearly 100% of spring and summer migrant salmon entered the ASP within an hour whereas 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. The French Creek, a Snohomish River tributary, and Elk Creek, a Chehalis River trib are examples of this. Trapping counts at Elk Creek show a significant increase in passage on the days the auxiliary water is on. The auxiliary water at Elk Creek actually reverses the tailrace circulation in the vicinity of the entrance as a passage improvement.

<u>Roughened Chute</u> Orsborn and Powers (1984) tested a narrow chute with 1½ inch by 1½ 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.

<u>Engineered Steepened Stream Channel</u> 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 boulders 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 flow 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).

A number of roughened channels and stream simulation channels have been constructed recently to replace road culverts that were fish passage barriers. Roughened channels and stream simulation are two design procedures that are identified in the WDFW *Fish Passage at Road Culverts* manual. See that document for a definition of the processes and design details. They are described there as being inside of culverts but much of the design process can be used in open channels.

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.

A roughened channel in Colony Creek in Washington State 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.

Hybrid Fishways – Pool and Chute

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

The pool and chute fishways are an alternative to pool and weir fishways. They operate through a wider range of stream flows without additional flow control means. 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 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.

The pool and chute design has the following benefits over the traditional pool and weir fishway.

- For small tributary application (less then 5 square miles drainage area in Western Washington), all of the flow can be contained in the fishway so false attraction to fish from a spillway or other flow control device is eliminated.
- Flood flows that are contained within the fishway normally scours bed material and lift debris from the fishway, reducing maintenance.
- Diverse passage routes are available to fish moving upstream (leaping and swimming).
- Fishway pool sizes can be half as large relative to a traditional pool and weir.

The hydraulic conditions that define passage success depend on the presence of a streaming flow regime at high flows. Empirical roughness coefficients were developed from model studies and prototypes to assist in making this calculation. The recommended fishway application is limited because of limited hydraulic verification. Powers described ten case studies by which roughness coefficients were estimated.

Pool and chute fishway nomenclature is shown in the following two figures. The basic layout consists of a center weir section and two higher baffles sections on the end of each weir. The baffles slope upwards towards the fishway sidewalls. There are four flow regimes which vary depending on the depth over the weir; 1) weir plunging flow; 2) weir streaming flow; 3) baffle plunging flow; and 4) baffle streaming flow. If the flow is plunging, the weir or baffle portion can be calculated as a sharp crested weir (broad crest if the head/weir thickness is less than two). At high flow, when the water level reaches near the ends of the baffle sections the flow streams over the crest of the weirs and a portion of the baffle. At this point the weirs and a portion of the baffles act together hydraulically. Rajaratnam et al. (1988) observed this in a model study of pool and weir fishways and noted that for low slopes and short pools, the streaming flow will be smooth with a constant depth over the weirs. But for higher slopes and longer pools the streaming flow will likely have a wavy appearance and in some cases contain undular jumps over a portion of the total length.

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.

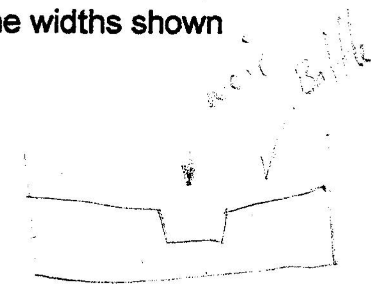
The following parameters describe elements of design of the pool and chute fishway. They are listed and described here in about the order they would be considered in a normal design.

Fishway alignment
The plan view alignment of the fishway must be in line with the flow approaching from upstream. When used at the outlet of a culvert, the alignment must be parallel to the culvert flow; and be far enough downstream so the flow expands from the culvert to the full width of the fishway.

Fishway slope
Start the design by selecting a weir differential and a fishway slope. Weir differential is the elevation of each weir above the next one downstream and usually varies between 0.5 and 1.0 foot. Weir differential is selected by the species and size of fish as if the fishway were a standard pool and weir fishway. 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. The slope will vary as the pool length changes since the weir differential criteria will remain constant. A maximum slope of 12% is recommended based on case studies reported by Powers and that it is difficult to achieve streaming flow at higher slopes as reported by Bates.

Fishway width
The fishway must be wide enough so the flow spreads out over the baffle sections and there is room to dissipate some of the energy of the center stream. If the width is too narrow, flow will overtop the baffle sections and the area between the baffles will be too turbulent. The final fishway width will be determined by trail and error. The widths shown in Table xx are a good first estimate to start the design.

Fish passage design flow	Fishway width
10 cfs	8 ft
40 cfs	12 ft
80 cfs	18 ft
120 cfs	24 ft
300 cfs	32 ft



Pool length
The recommended pool length is 50% of the pool width. In case studies reported by Powers, pools shorter than about 45% of the width did not provide adequate holding area for fish. Pools greater than about 55% of the width did not develop streaming flow and the hydraulic conditions were more turbulent.

Weir length and height
The weir height controls the pool depth at low flow. A minimum of 2.5 feet is recommended as cover for fish. Depths should be greater in larger rivers where fish may be accustomed to greater depths. Depths greater than four feet may fill with sediment.

The weir length is generally at least 20% of the fishway width. Shorter weirs do not provide enough overall fishway capacity and the value of the pool and chute fishway is lost. The weir length could be increased significantly in a well-designed fishway since the streaming and plunging flow regimes are independent of each other.

Streaming flow transition

The transition to streaming flow can be predicted based on work by Rajaratnam et al (1988).

$$Q = 0.25\sqrt{g}bS_oL^{3/2}$$

Q	= flow in cfs
g	= acceleration of gravite (32.2 ft/sec^2)
b	= the length of the weir (ft)
S_o	= the slope of the fishway (ft/ft)
L	= the distance between weirs (ft).

The depth of flow at the streaming transition can be calculated by combining the equation for streaming flow transition with the following weir equation.

$$Q = Cbh^{3/2}$$

Q	= flow in cfs
C	= weir coefficient
h	= head over the weir (ft)

The resulting equation to predict the depth of flow at which the transition to streaming occurs is:

$$h_s = \left[\frac{0.25}{C}\sqrt{g}S_oL^{3/2}\right]^{2/3}$$

Baffle height and top slope

The recommended height of the baffle at the edge of the weir is 75% of the depth of the streaming flow depth. The slope of the baffle up to the fishway walls is such that a fish passage corridor is maintained along the walls. A slope of 4:1 (horizontal to vertical) is recommended based on case studies by Powers.

The parameters described above are developed as a first estimate of fishway geometry. The following parameters are then tested to see if the geometry satisfies recommended criteria. To meet these criteria, adjustments to the fishway width, weir length and/or baffle slope may be required. Adjustments should be made only within the recommended values.

Fish Passage Corridor

The fish passage corridor is defined as the non-overflow area along the walls of the fishway that provide resting areas and good upstream passage conditions. It is measured as the horizontal distance from the inside wall to the edge of the water at the baffle. Because the baffle is sloped, the flow near the end is restricted and the downstream pool can be calm compared to the center section of the fishway that is streaming and turbulent. A passage corridor width of two feet is recommended.

Fishway flow
Select a depth of water such that the recommended fish passage corridor is created. Calculate the total flow by summing flows over portions of the weir that are streaming and plunging. For the streaming flow portion use the Chezy equation. For the plunging flow portion use a standard weir equation accounting for submergence as appropriate. Verify that the fishway design flow is greater than or equal to the intended fish passage design flow.

For streaming flow, the cross sectional area is taken as that flow area where the depth over the baffle or weir is greater than the streaming transition depth defined by a weir equation using the streaming flow discharge calculated from the transition equation.

Pool volume factor
The pool volume factor is applied to quantify turbulence in the passage corridor. The pool volume, Equation XX is applied to just the baffle portions of the fishway. Just the baffle portions are used as the pool width and just the flow over the baffle sections is used as the fishway flow. Similar to a pool and weir fishway, a maximum value of four foot-pounds per cubic foot per second is recommended.

Examples
The general configuration of the pool and chute is shown in figure x which depicts the Town Dam fishway (Yakima River).

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 (2?) additional slopes based on prototype high flow measurements (table x).

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 [TW19]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.

FISHWAY FLOW CONTROL

The purpose of flow control is to extend the range of river flows through wich the fishway operates within criteria. Flow control accomodates fluctuations in the forebay water surface while maintaining acceptable ladder flow conditions.

The degree of flow control required for a fishway depends on the style of fish ladder. The recommended range of operation of different ladder styles is discussed in previous sections.

There are essentially five styles of flow control; they might 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 self adjusting. As long as the forebay and tailwater elevations do not exceed the height of the slots or structure, the fishway functions as intended. The Denil and pool and chute fishways are intended to also be self adjusting though their ranges of operation are much more limited.

Spillway Control A spillway that controls the fishway forebay provides flow control. Its effectiveness is a function of its length. Automated spillway gates can control pool elevation to within a few tenths of a foot.

Orifice or Vertical Slot Control Section A flow control section is a portion of the fishway upstream from the primary fish ladder specifically intended for that purpose. It 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. To accomodate the change in flow through the control seciton, either auxiliary water can be supplied or excess water bled off below the control section.

Auxiliary Water Flow Control Auxiliary water flow control sections are ususally designed to carry the full fish ladder flow at high forebay. The auxiliary water is suplied to the lower fish ladder at anything but the highest forebay condition.

Figure 6-1 is a schematic of an orifice flow control section including the hydraulic profiles of the high and low forebay conditions. Easton Dam fishway on the 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 none at high forebay).

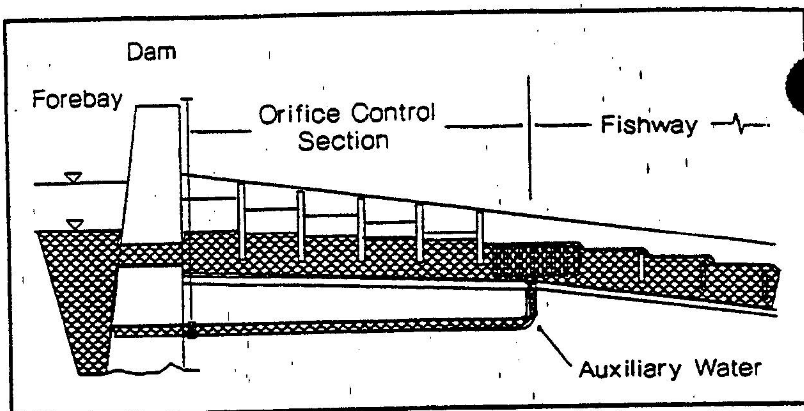


Figure 6-1. Schematic of Auxiliary Water Orifice Flow Control Section.

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 orficies which are difficult to maintain du 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.

<u>Bleed-Off Flow Control</u> The bleed-off flow control section is hydraulically similar to the auxiliary water flow control section. Instead of auxiliary water being supplied at low forebay, however, excess water is bled off at the downstream end of the flow control section during high forebay conditions. It is used when the normal operating condition is the low forebay; the flow control accomodates peak flows.

Elk Creek fishway, on a Chehalis River tributary, has an Alaska steeppass fish ladder with an orifice flow control section above it. Part of the excess flow from the flow control section is wasted back to the stream and the remainder is used as auxiliary attraction water at the fishway entrance.

<u>Adjustable Weirs</u> 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 accomodate 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 et al, 1990). Forebay fluctuations of up to 11.5 feet are accommodated at that fishway.

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

Another style of adjustable weir flow control is the Nibutani style gate describe by Watanabe (1990). The control section is hinged at the downstream end. 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 and a length of 120 feet. It has a forebay operating range of 22 feet. There are other examples of this concept designed in Yugoslavia. As far as I am aware, none have been constructed.

<u>Multiple Level Exit</u> If a forebay is operated in more than one distinct operating range, multiple level exits may apply; Roza Dam on the Yakima River is an example. The forebay water surface at the upper range is maintained within several tenths of a foot by spillway roller gates. Because of icing conditions and for maintenance purposes the roller gates are open 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 gated 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 are removed.

Multiple exits can be used to accomodate a variable forebay if the fluctuations are gradual and not frequent. The Nagura Dam on the Hida-gawa River in 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

EXIT DESIGN

Fish exiting the fishway into a forebay often tend to delay; they may be disoriented and take some time to adjust again to the new environment.

To get upstream fish must swim into current; they also tend to follow the shoreline. The exit must 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 that confound the problem. The classic example of this situation is the south fishway at Bonneville Dam. Figure 7-1 shows a sketch of the major and minor migration routes of fish leaving Bonneville Dam. Radio tagging studies determined that a significant number of fish moved "upstream" into the river current and along the bankline that led them to the spillway where they fell back downstream. An eddy at the northern side of the tip of Bradford Island created the counter flow that guided the fish to the spillway. The fish then returned through the fishway and were counted again. One radio tracked chinook fell back three times and was later tracked 250 miles upstream.

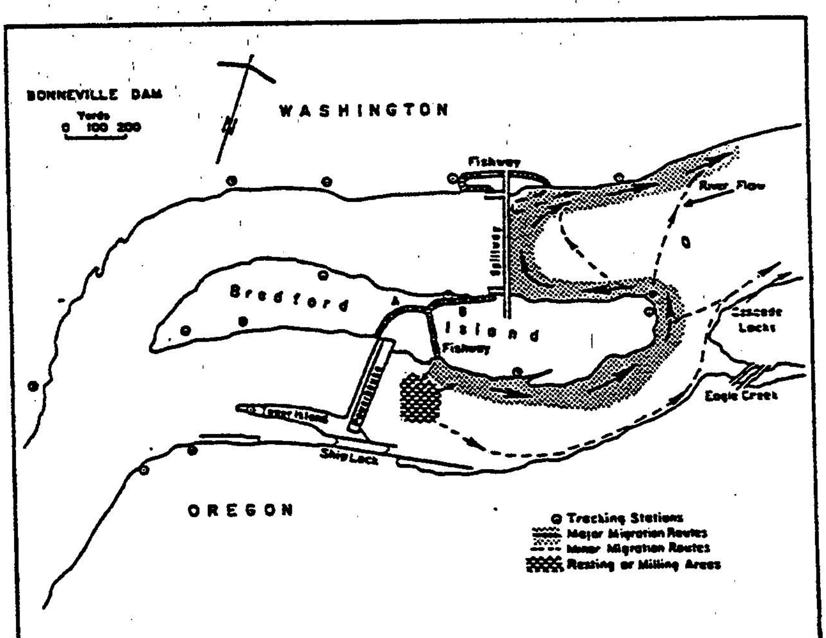


Figure 7-1. Plan view of Bonneville Dam showing upstream major and minor migration routes.

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; fish left the tip of Bradflor Island and swam directly upstream at flows greater than 400,000 cfs. An additional powerhouse is now located in a new channel north of the spillway shown in Figure 7-1.

Fallback has been studied at other dams on the Columbia River. Fallback rates appear to be generally less than 10%. Most fish that fall back survive.

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 or on an island. 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 exit in 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.

TRASH RACK AND 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. Much higher velocities, and they are increased when debris accumulates, make it difficult to manage a rake by hand. 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.

The river velocities that sweep across the face of the fishway are important. Higher velocities will result in substantial head loss across the trash rack as the kinetic energy of the sweeping flow is lost. Excess head loss may result in a decreased fishway flow depending on the fishway flow control mechanism and it may result in sediment deposition. They can also likely cause some fallback of fish that may be disoriented when exiting the fishway.

For salmon, vertical bars should have 5 to 10" clearances. Horizontal bars should be spaced no closer than 18" apart. Horizontal bars should be inset or on the back side of the vertical bars so debris can slide up the outside face of the trash rack. A curtain wall above the trash rack and flush with its face can be helpful when there is adequate depth that the additional open rack is not needed. If it is designed at the right elevation, larger debris during high flows will pile up against the wall where it is easier to remove than when it is twined into the bars of the trash rack.

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

Slope the face of the trash rack at 1 horizontal to 4 or 5 vertical 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 dewatering 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

Provide staff gages for operation

- 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 a fishway weir to measure fishway flow;
- in the forebay as a river flow gauge.

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.

An operation manual should include the following items:

- River flow (staff gauge elevation) which identify high flow 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 gates can be operated.
- Settings of entrance gates; they are normally either entirely open or entirely shut.
- Head differentials that must be maintained at entrances and trash and diffuser racks.
- Settings of auxiliary water systems based on auxiliary water system staff gauges and river flow.

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.

STRUCTURAL DESIGN

Debris, bed load, ice and flood protection

In-stream protection; scour, flotation

Abrasion (weirs, vertical slot floor); steel caps

Materials

TRIBUTARY FISH PASSAGE DESIGN

Fish passage concepts for small streams are presented in this section. More detail is provided here because it is the detail that makes the success of this scale of project.

Many miles of salmon and steelhead spawning and rearing habitat are 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 made barriers to salmon migration. The two basins have a total area of 30 square miles and a total channel length of 50 miles. Portions of the basins blocked from salmon use varied from 6% in a rural watershed to 24% in an urbanized watershed (Tom Burns, WDF, pers. com.). Since the upper reaches of these watersheds provide the best spawning habitat, likely as much as 50% of the spawning habitat was not accessible.

Tributary fishway sites are often remote, seldom inspected and have little or no flow control.

Improved access into these areas is normally provided by the construction of cast-in-place concrete fishways. 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. The ideas described here are primarily intended for use in small tributaries. Some are new ideas; others are refinements of methods used previously. Construction cost savings are made by:

- prefabricating units for remote installation,
- designs that utilize the channel itself as the fishway,
- designs that do not require equipment access and
- concepts that exceed normal fishway design standards without reducing efficiency.

TRIBUTARY FISHWAY CONSTRUCTION CONCEPTS

The following fishway concepts have been designed and constructed recently by Washington Department of Fisheries. Not all of these ideas are new.

<u>Log Sills</u> Log sills are control sills built into the stream bed as shown in Figure 10-1 and spanning the entire channel width. They are a low cost and durable means of fish passage for streams with natural gradients of less than about 3% and channel toe widths of less than about 30 feet. The log sills described here are intended for fish passage. Similar designs are used with the objective of enhancing rearing or spawning habitat. The design of habitat structures is often different in order to create a concentrated flow and deeper plunge pools.
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.

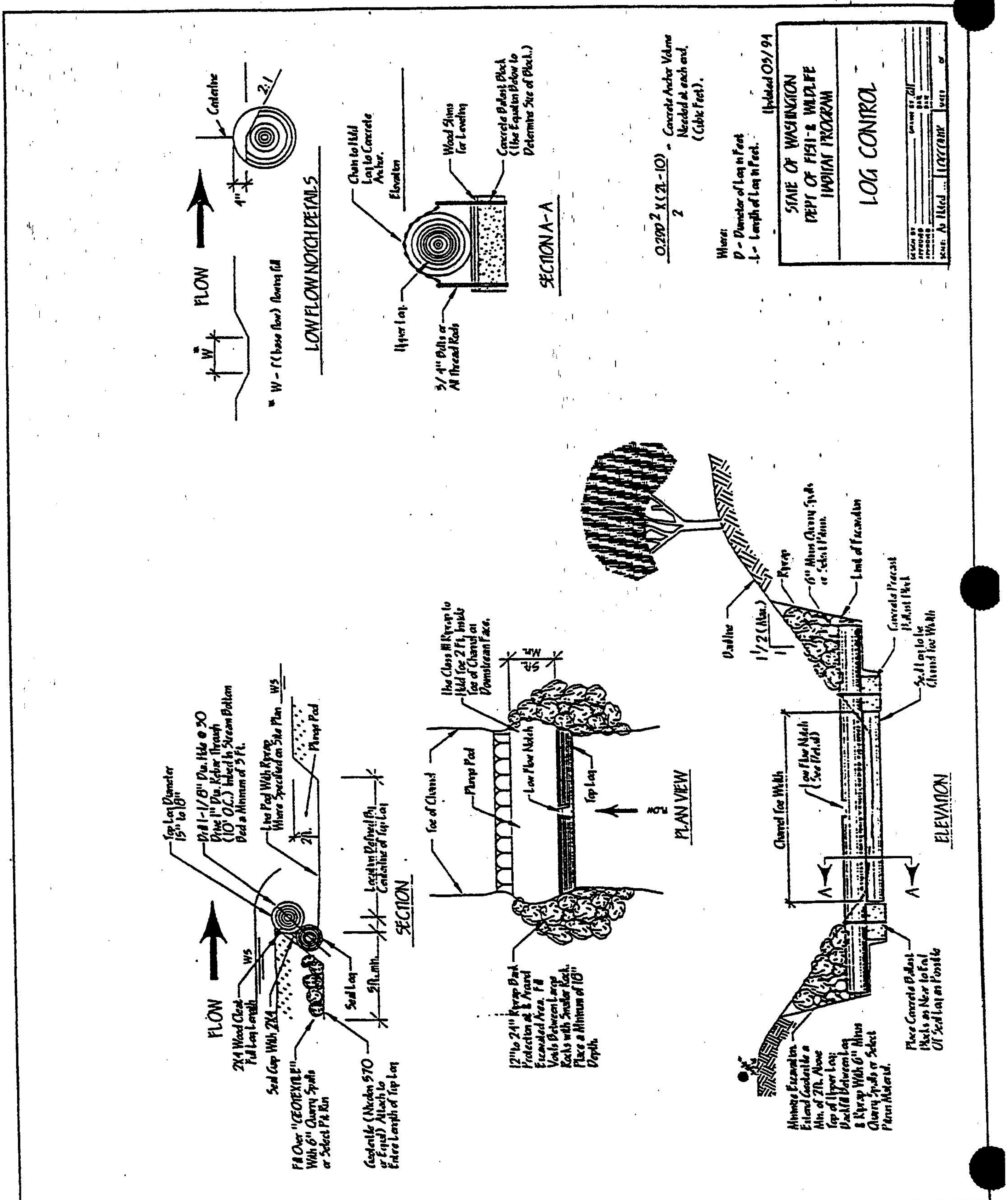


Figure 10-1. Streambed log sill design detail.

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 lengths for uniform hydraulic conditions at high flows.

A pair of logs, each with a minimum diameter of one foot are placed into the bed; 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 45° 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 and adequate to anchor the logs. A good rule of thumb to control deflection of the top log is to use a log with a diameter 1/25th of the log length.

Beach's Law
No two identical parts are alike.

Careful anchorage or ballasting of the logs is a critical to their durability. The design described here depend entirely on the concrete ballast block.

In 1953, 41 instream structures in Sequoia National Forest in Northern California were evaluated after 18 years of operation. The most common reason for structure 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 that also helped anchor the ends of the logs.

Double logs are used to prevent the scour pool from undermining the structure. The ends are buried into trenches excavated into the streambanks a minimum of five feet. The logs are normally douglas fir due to availability, straightness and longevity. Their longevity is determined by the amount of bed material abrasion; the sills are installed level, they are permanently submerged and resist decay. Retired mill boom logs have been a good source of logs; they are long and straight and preserved years of salt water use. After 18 years, the 9 remaining log dams of the original 15 in the Sequoia National Forest study showed no signs of rot or deterioration even though they were at least partially exposed during most of that time.

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 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 rock.

By my observations, the maximum fish passage design flow is limited to about 9.5 cfs per foot of length of the log sill. The maximum safe high design flow has not been quantified. The highest known flow incurred in my experience by a series of log sill structures is 15 cfs per foot of length. The weir coefficient for a log weir submerged to 50% of its depth is about 2.7 based on field measurements. Heiner (1991) found a weir coefficient of about 3.8 for full scale unsubmerged smooth (PVC pipe) weirs in a laboratory.

Because of the recommended minimum spacing and maximum elevation drop, the maximum final slope of a series of log sills is 5%. It is difficult to steepen a channel with an initial natural slope greater than about 3% with this style of log sill. The number of sills required to steepen a channel is given by Equation (10-1) by simple geometry where N is the number of sills required, H is the elevation gain to be achieved, L is the spacing of the sills (15 feet minimum recommended), S_o is the initial and S_d the desired

$$N = \frac{H}{L \times (S_d - S_o)} \qquad (10\text{-}1)$$

channel slope (in ft/ft).

Sills should be located in straight sections and at the entrance and exits of channel bends; they should not be installed in bends. There is a risk that if a lower sill of a series fails, those above it will be undermined and also fail; dominoes. If a number of bed sills are placed in a series, deeper sills should be placed at intervals, say, 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.

Log sills as described here can be placed with a single piece of equipment or by hand in small dewatered installations. The current (1994) total cost of construction of 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.

A notch is cut in the crest of the sill after it is installed. 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 through a free nappe. Be careful to not make the notch so large that at low flow the top of the log is dewatered.

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.

Single log sills have also been cabled into bedrock channels using 9/16" galvanized steel cable and C-10 HIT Hilti dowelling cement (Espinosa and Lee, 1991).

Log sills are also good 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 and are not discussed here.

Plank Sills Rough cut milled timbers are placed across the bed of a channel to form sills similar to the log sills described above. They are intended to be constructed by hand 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. They are tilted about 20° downstream so the nappe spills free of the sill for better juvenile fish access. The ends are buried in the channel banks; the excavated trenches are filled with light riprap rock mixed with soil.

Plank sills are especially useful for providing upstream juvenile salmon passage. They are well suited for streams with sandy beds. In the last 5 years WDF has constructed 44 of these structures without a failure. A benefit of plank sills is they can be constructed entirely by hand. The cost of construction of a plank sill varies greatly since the primary cost is labor; the amount of labor depends on site conditions such as bank height and soils.

Plank sills have been constructed in wide channels using zig-zag and spider weir designs. They are primarily intended for juvenile fish passage and are described in the Upstream Juvenile Passage section.

Precast Concrete Fishways In areas that are remote from concrete plants and in situations that are difficult to dewater and pour concrete, precast concrete fishways can be installed.

Three styles have been used. A series of reinforced precast concrete troughs are fitted together to form pool and weir fishways. A system of 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; 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.

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 an efficient means of construction as the troughs and is used only when required by lack of access of 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 to be installed. Since the fishway pool volumes are limited, they have an inherent limited use confined to small or spring fed streams with consistent flow.

<u>Laminated Beam Weirs</u> · Narrow bedrock channels often present difficult construction and maintenance problems. They are often remote, difficult to access for crews, materials and equipment and difficult to dewater for construction. Laminated beam weirs are intended for these situations. 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. Twelve weirs of this style have been installed in the last

5 years. Of those, 2 failed; they, and a third that survived, were just upstream of a railroad trestle that was removed in an emergency due to a massive debris jam that formed during the extreme floods of November, 1990.

<u>"Ecology" Blocks</u> Precast rectangular blocks and especially Jersey median barriers are not suitable for fish passage sills. They are difficult to set with enough precision, they scour, settle and roll and gaps open that do not seal. They are generally ugly.

A concept of precast has been designed that would correct the deficiencies of ecology blocks. Precast cantilevered walls could be placed to form an arch structure. The arch shape would prevent differential settling.

<u>Gabions</u> Gabions are not a good fish passage device. 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. With only slight bedload abrasion, I have observed gabion wires to fail in three years in a stream (Chico Creek, Puget Sound trib) that is considered moderately corrosive. Debris easily snags gabions either breaking them or distorting the wire fabric.

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.

The only good use of gabions for fish passage that I am aware of is as a foundation upon which log or timber weirs can be constructed. 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 and Scarlett, 1981 and others). For many species, an upstream juvenile migration strategy is essential for, or enhances survival. Juvenile coho salmon (Oncorhynchus kisutch), chinook salmon (O. tschawytscha), and steelhead trout (O. mykiss) may migrate upstream 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 and Scarlett, 1981).

Coho fry (40 to 60 mm) migrate in Western Washington during May and June and fingerlings (80 to 100 mm) migrate from October through December (King, 1990 and Peterson, 1982). Migration peaks in both seasons coincide with increased flow in the streams that these fish are moving out of. Powers and Saunders (1996) used May in their juvenile fish passage design flow model. They assumed the appropriate design flow for these fish to be the 10% excedeence flow. Chinook move into mainstem tributaries in Eastern Washington in the spring and summer months during high flows in the mainstems.

JUVENILE PASSAGE STRUCTURES

<u>Fishways</u> Steepened rock channels, formal fishways and streambed controls have been constructed specifically for upstream juvenile salmon passage. Juvenile passage is provided through most adult pool and weir fishways if adequate still water is provided in the pools and depth over weirs is limited. 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. The tributary passage conditions are thus enhanced.

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

Most of the fishway styles described in Section 10, <u>Tributary Fish Passage Design</u> are effective for juvenile passage.

<u>Culverts</u> 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. There has been little consideration of turbulence created by the added roughness of baffles or roughness and their effect on fish passage. See the discussion below on boundary layer and turbulence.

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 generally describes plank weirs. Zig-zag and spider weirs are shown in Figure ?. They can span broad channels and are often used for 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 that take advantage of juvenile salmon leaping behavior (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 states. 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; a large number of remote installations are necessary.

The fryway was tested with a prototype installation in April through May, 1987 in Washington State. Two parallel fryways with different test conditions were installed to temporarily replace a pool and weir fishway through which coho fry were known to pass. 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 12-1. 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 and 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% appeared the most practical; it passed 2.7 times as many fry as the 35% slope though only 10% less than the 15% installation.

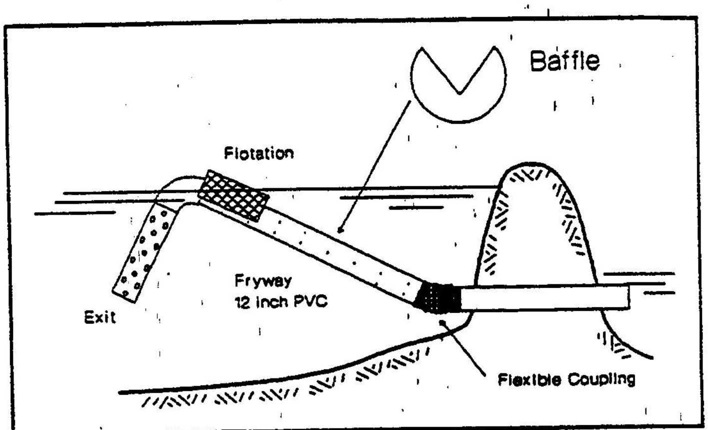


Figure 12-1. WDF fryway cross section.

Adult coho successfully moved upstream through the fryway during the initial testing. There is a risk of these fish being injured or trapped inside the fryway. 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.

BOUNDARY LAYER AND TURBULENCE

It has been observed that week swimming fish and specifically juvenile salmon (Behlke, 1989) use the lower velocity of the boundary layer along the wall to move through culverts (Behlke, 1989; Morsel et al, 1981). The boundary layer is a hydraulic term for the region of fluid near the wall or bed of a conduit that is affected directly by the roughness of the wall. The velocity in the boundary layer is less than the average velocity because of the shear stress of the wall boundary condition (Roberson and Crowe, 1990).

If the velocity and turbulence within the boundary layer of a culvert or channel can be predicted and related to the size and swimming ability of fish, passage design criteria can perhaps be developed. Pipe with a specific corrugation pattern is often specified with the expectation of improving fish passage. Culverts are often fitted with baffles for the purpose creating passage conditions. It is suggested by Bates (1992) that baffles should either be designed as roughness elements to control the velocity for passage or as weirs designed as a pool and weir fishway; either design has specific design criteria.

Morsel et al (1981) proposed the concept of an occupied zone to address fish passage through culverts. It is the region of the flow cross section utilized by fish for upstream passage when they are challenged by higher velocities in the flow cross section. The occupied velocity (V_{occ}) is the velocity in that zone.

A study by WDFW (Bates and Powers, 1996) confirmed that juvenile coho salmon consistently use the low velocity boundary layer to pass upstream when challenged by higher velocities in the culvert barrel, but only when turbulence is low. It is also shown that in general, as culvert wall roughness increased, the required value of V_{occ}, the velocity in the occupied zone, to maintain the same level of passage decreased.

Coho fry were challenged to swim through culverts at various slopes, diameters and corrugation dimensions. Corrugations tested were smooth (PVC pipe; no corrugation), 6.8x1.3, 7.6x2.5, and 15.2x5.1 where 6.8, for example, is a corrugation spacing and 1.3 is a corrugation depth in centimeters.

For 55-65 mm coho, V_{occ} values for 80 percent passage success ranged from 4.8 cm/s for the pipe with the deepest corrugations to 23 cm/s for the smooth pipe. For the 85-95 mm coho V_{occ} values for the 80 percent passage level ranged from 12 cm/s for the deep corrugation culvert to 33 for the smooth pipe.

Table 12-1 Slope (%) for three levels of passage success and five different corrugation types. (nt=not tested)

Culvert Corrugation Type	Slope (%) 60 mm coho				Slope (%) 90 mm coho			
	Passage (%)				Passage (%)			
	80	50	20	r^2	80	50	20	r^2
0	.02	.06	.11	.73	.06	.10	1.5	.91
1.3S	.25	.33	.41	.89	.52	.82	1.14	.83
2.5A	nt	nt	nt		0	.30	.71	.59
2.5S	0	.37	.77	.78	.25	.49	.75	.84
5.1A	.14	.39	.66	.78	0	.71	1.44	.54

A simple linear regression analysis was done for each culvert to predict the number of fish that passed as a function of culvert slope and a correlation coefficient determined for each.

Table 12-1 shows the slopes calculated from the regression equation at the 80, 50 and 20 percent passage levels. The "0" slopes in the table are a result of the regression analyses predicting a slope equal to or less than 0%. The culvert labels correspond to the culvert corrugation depths; "A" and "S" are annular and spiral corrugations respectively.

Passage through only the smooth pipe was successful at velocities corresponding to swimming abilities of coho fry reported in the literature from swimming stamina studies (Taylor and McPhail, 1985; Brett, Hollands and Alderdice, 1958; Davis et al, 1963; Glova and McInerney (1977). In fact close to half (60%) of each the fry and fingerlings tested successfully passed at velocities that corresponded to the median swimming ability data reported by those studies.

This confirms that with increasing roughness, a barrier other than velocity is created in the culverts. It is suggested that that barrier is turbulence. Further study is needed to define threshold levels of turbulence and how it affects fish movement. Turbulence may affect fish passage differently depending on the size of fish relative to the magnitude, period and scale of the turbulence.

An indicator of turbulence was measured in the zone fish swam in, the occupied zone. V_{occ} in the 5.1A culvert at a 2.0% slope and a flow of 0.051 cms averaged 32 cm/s, but within about every 10 seconds the actual value commonly varied from 0 to 50 cm/s with a standard deviation of 20 cm/s.

George and Michael Triantafyllou (1995) describe how swimming fish shed vortices from their tail which they then thrust against to increase swimming efficiency. They built a flapping foil (fin) subjected to a field of vortices. The power efficiency of the fin varied by a factor of at least two by merely changing the frequency of the vorticies approaching it. They use a fluid dynamic parameter known as the Strouhal number which compactly indicates how often vortices are created in a wake and how close they are. For swimming fish, they use a Strouhal number definition of the product of the frequency of tail beats and the width of the jet created by the tail, divided by the speed of the fish.

These findings have direct implications on the design of steep roughened channels and culverts for both juvenile and adult fish passage. It is expected that the relative scale of turbulence in the tests of standard corrugated pipe would not hinder adult fish passage. There is likely a corresponding scale of turbulence however that could block larger fish. That scale might be created by culvert baffles or other roughness elements intended to assist passage. Design criteria for open roughened channel designs for juvenile and adult passage should be developed to include turbulence in terms of roughness size and spacing.

Based on this information it is not likely juvenile salmon passage can be provided through a culvert with an appreciable hydraulic slope or flow without the culvert backwatered or a natural channel in the floor of the culvert. Refer to the Culverts section of this paper.

FLAP GATES

A flap gate is a flow control device that in principle, functions as a check valve, allowing water to flow through it in only one direction. It usually consists of a flat plate that is hinged at the top of a culvert outfall. The plate falls into a near vertical position over the face of the culvert opening to close it. A positive head differential against the downstream face will force the flap against the face of the culvert to seal it. A positive head against the upstream face of the gate will force it open to release water.

Flap gates are typically constructed of cast iron. Plastic, fiberglass and aluminum gates are also available. Larger gates are constructed of wood and are often hinged at the sides rather than the top.

They are typically attached to culverts that are placed through tide dikes river flood dikes. They allow the stream to normally drain in its normal direction but prevent high tides or river floods from backing water into the stream channel.

FISH PASSAGE

Flap gates are obviously a barrier to all fish migration when they are closed. Unless specially designed for fish passage, most are also a barrier to migration when they are open.

They can be a barrier due to the head differential across the gate or by the narrow opening available for passage when the gate is open. They are also be a barrier, like any other culvert, by being perched above the downstream channel or water surface.

There are several solutions to fish passage barriers through flap gates. A method used in Canada is to modify the gate mounting hardware so the gate is rotated 90° and is hinged on the side. The hardware has to be modified to structurally support the gate, to keep it from opening too far, and to provide a thrust bearing for the weight of the gate. The gate should be mounted at an angle less than 90°. If it is rotated a full 90°, the weight of the gate will not help close it.

A second method is to use a light weight gate such as plastic or aluminum. These lighter weight materials are formed into a thin dome shaped gate by several manufacturers. The gate, being considerable lighter, opens much wider with less head differential. They also therefore have greater outflow capacity.

Figure 13-1 and Figure 13-2 show as an example the difference in hydraulic characteristics of four-foot diameter cast iron and aluminum flap gates. The figures show the maximum opening of the gates (gap) and flow for a range of submergences and head differentials. The gap is the distance the bottom of the flap gate swings away from the frame. The submergence is the depth of the downstream water surface above the bottom of the gate when it is closed. The curves are derived from a theoretical static, hydraulic model that accounts for specific weight and submergence of the gate and pressure head. It does not account for velocity head.

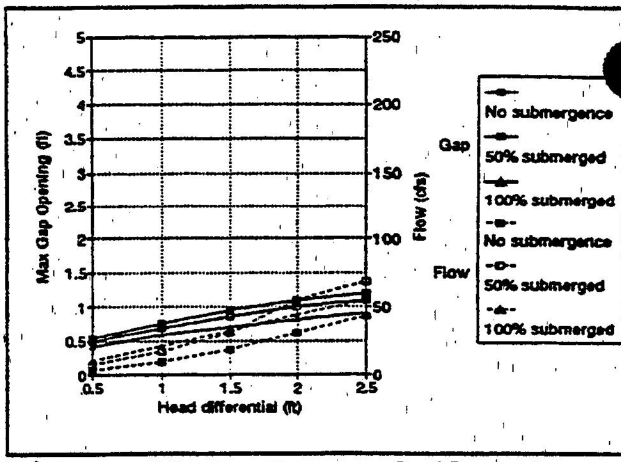


Figure 13-1. Gap and flow for 4-foot cast iron flap gate.

Conditions for upstream fish passage should be less than a foot of head differential and at least a foot of gap opening. Realize that the gap is the opening at the invert of the gate; at the mid point of the culvert, the opening is half the gap measurement. This one foot criteria is the same as standard fishway entrance criteria.

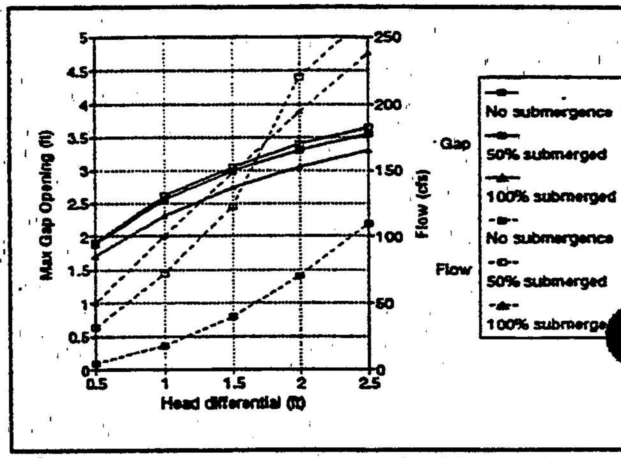


Figure 13-2. Gap and flow for 4-ft aluminum flap gate.

The benefit of lighter weight gates is obvious from the figures. There are no conditions for the cast iron gate in Figure 13-1 that comply with fish passage standards. To create an opening of 1.0 foot, a head differential of 2.0 feet and a submergence of 2.0 feet are required.

For any given gate submergence (downstream water level) and head differential, the aluminum gate is open at least several feet wider than the cast iron gate. For example at a head differential of one foot and no submergence, the aluminum gate is open over 2.5 feet and the cast iron gate is open about 0.5 feet. To open one foot, the cast iron gate requires a head differntial of 1.7 feet. The lighter gate also has much greater flow capacity at any submergence and head. The upstream pool will then drain more rapidly and approach optimum fish passage conditions.

A third solution to flap gate passage is the use of gate operators or latches. Operators and latches have been designed to prevent the flap gate from closing until the water surface rises to a critical elevation. One design is equipped with float mechanisms that trip a latch allowing the gate to swing shut. To my knowledge, this concept has not yet been constructed. Another design uses an electrically powered gate to close and open in response to the water surface. This concept is obviously the most expensive and has the greater risk of mechanical and electrical failure.

When a number of flap gates are placed on parallel culverts, often no more than one should be equipped with a light weight gate. If all gates in a group are light weight, they will compete for flow and may still not open sufficiently for fish passage. When just a single or a few gates are intended for fish passage, they open wider at low flow.

OTHER FISH PROTECTION CONSIDERATIONS

The ecological impact of tidegates in estuaries is much more than solely a migration barrier. Their influence on water quality may be substantial. These considerations are speculation; I am not aware of them being documented.

In addition to creating migration barriers, tidegates have three other significant impacts:

- Block Salinity,
- Block temperature mixing,
- Control water level,
- Upstream channel filling.

Since tidegates block inflow, in estuaries they block the movement of salt water upstream. A natural estuary with a salinity gradient is then converted to a freshwater pond with an instantaneous change to high salinity at the tidegate outfall.

The same action of blocking inflow also prevents temperature mixing in the estuary. If the stream is any different temperature than the receiving water, the entire change becomes concentrated at the tidegate outlet instead of dispersed through the estuary.

Because of their hydraulic control, tidegates minimize the upstream water level fluctuation. In Puget Sound, the upstream water surface is controlled to within a few feet instead of the natural 5 to 15 feet tidal fluctuation.

The upstream channel is altered by the change in hydraulic conditions caused by the tidegate impoundment. A natural estuary is characterized by tidal surge channels created by the rush of tide waters in and out. A tidegate essentially eliminates the tidal flow and therefore fills with sediment.

By these four actions, the basic chemistry, tidal characteristics and ecology of the upstream area is drastically altered. These changes likely work cumulatively with the migration barrier impact to further affect fish production. The salinity and temperature impacts are concentrated at the tidegate itself. If fish cannot move upstream through the tidegate they cannot willfully select their preferred temperature and salinity conditions. When they pass through the tidegate, they are instantly dropped into a radically new water quality environment with no opportunity to move out of it.

These impacts can be mitigated to an extent. The usual objective of tidegates is to control the upstream water surface. It is important to establish the specific upstream water surface that is allowable. Tidegates, when installed, are usually intended to protect only from extreme high tide flooding. In that case they don't need to be closed more than a few times a year. They are closed during a majority of the time however. To prevent its closure except when needed a tidegate can be equipped with an automatic latching mechanism. Another option is to include an orifice in the tidegate or a small culvert be placed next to the culvert with the tidegate. Either orifice assures a controlled amount of sea water passes upstream at every tide cycle. With a good design, the volume of water that flows in during an extreme tide will not exceed the allowable storage volume and flood elevation above the culvert.

To make these mitigation options work, the surface water hydrology of the upstream contributing basin must be well understood. The hydraulics of the gate must be modelled to assure the intended upstream protection is adequate. This is not a difficult task.

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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 and thereby reduce 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 Fish swimming mode that can only be sustained for a short period of time; about 7 seconds; also called darting speed.

DIFFUSER An open grating or perforated plate that distributes auxiliary flow to a fishway but precludes passage of adult fish. 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 high elevation. It is part 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; proportional to the product of velocity and flow of water.

TRAVEL SWIMMING SPEED The swimming speed of a fish relative to the ground; the actual speed of passage. (or passage speed)

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. (or relative speed)

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.