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Design of Culvert Fishways

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Water Resources Research Institute
University of Idaho
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16. Abstract
Types of fish migration and typical fish blockage problems associated with culverts are reviewed. Swimming capability of fish as a function of specie, fish length and water temperature are discussed. The hydrologic characteristics of streams and the importance of considering the timing of fish runs and peak discharge is reviewed

A procedure for analyzing cmp and pipe arches for recommended swimming velocities is presented.

Slot orifice fishways for box culverts (slot orifice placed perpendicular to the flow and skewed wing-wall slot orifice) are discussed. Design aids developed for hydraulic analysis are presented. Instream construction in or near prime fish habitat is discussed.

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May 1974

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The opinions, findings and recommendations expressed in this paper are those of the writer and are not necessarily those of the Office of Water Resources Research or the Idaho Department of Fish and Game.

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INTRODUCTION

The purpose of this report is to review the problems associated with the passage of fish through highway culverts and to suggest procedures for the design of culverts to pass fish.

The information presented on the analysis of slot orifice fishways and skewed entrance orifices was developed at the University of Idaho.

The information relating to fish swimming capability and factors which affect fish swimming speeds were obtained from on going studies, existing literature, or from communications with persons knowledgeable in the area. Six significant papers used for source material for this report are, "Fish Versus Culverts", Metsker (1968), "Fish Passage Through Highway Culverts", McClellan (1970), "Passage of Anadromous Fish thru Highway Drainage Structures", Kay and Lewis (1970), "Design of Fishways and Other Fish Facilities", Clay (1961), "Fish Passage & Culvert Installations", Gebhards and Fisher (1972), and "Fisheries Handbook of Engineering Requirements and Biological Criteria", Bell (1973). Other information contained in the report came from personal observations, on going studies, and discussions with fish biologists and engineers experienced in fishway design.

This report covers the following topics:

1. A review of fish passage problems at culverts and a brief description of the types of migration or fish movement which may occur.
2. Swimming capability of fish and a review of variables which affect the swimming speed of fish.
3. Hydrologic characteristics of streams and their influence on

fish migration.

4. Design of culverts for fish passage.
5. Characteristics and design of baffled fishways.
6. Characteristics and design of slot orifice fishways.
7. Instream construction.
8. Concluding remarks.

Fish Passage Through Culverts

Fish Blocks Poorly designed culverts can block or impede upstream fish movements in many ways. If the outlet of the culvert is installed above the streambed elevation or if scour lowers the streambed downstream of the culvert outfall, a dropoff is formed creating a vertical barrier or at best, a high-velocity barrier to upstream fish migration. A more subtle form of blockage can occur within the culvert barrel where a constant cross section has been constructed in place of a natural lined stream section. Because of the relatively smooth walls and floor and the constriction of the section at high flows, the velocity of flow through a culvert barrel is always higher than velocities which would have occurred in the natural channel. Protuberances in a channel, boulders, roots, and consolidated material, and the natural meandering of the thalweg provide zones of quiescent water for resting. Ascent of streams with gradients of 5 to 15 percent is possible in a natural stream. Whenever a rough natural channel is replaced by an artificial channel possessing a uniform cross section, slope and roughness (i.e. culvert), there are no zones of quiescent water; and no discontinuities in the shooting flow regime. Furthermore, the velocity throughout the length of the culvert is nearly uniform along the length of the culvert, is nearly uniform across the entire width of the stream and is greater than that which would have occurred for similar flows in the natural channel. For these reasons upstream fish movements may be obstructed at culvert crossings during periods of high flow unless a remedial culvert design is employed.

Other forms of fish blockage that may occur at culvert crossings include the abrupt drawdown and associated turbulence at the upstream end of the culvert where water accelerates into the culvert, debris barriers (including ice) upstream, within or downstream of the culvert, and shallow depths which occur within the culvert barrel during periods of minimum flow.

Fish Runs There are several types of fish movement that are of concern to the culvert designer. The type which has generated the most public interest and newsprint is the spawning run. These runs are made up of mature fish returning to the area where they were spawned to deposit their eggs. In some species of fish, the mature fish die after spawning, in other instances the fish remain active, migrate downstream and return to spawn on successive years.

For spawning runs, timing is all important. Because the spawning act is probably triggered by a combination of degree days and water temperature and must occur at a particular time, the fish cannot be delayed for any extended period of time during their migration to natural spawning areas without adversely affecting the survival rate of the fry. If mature fish are held up and the time comes to spawn, they will deposit their eggs in undesirable habitat downstream from the blockage. Depending on the type of habitat, the eggs may be washed away, buried in silt or be subjected to improper temperature or flow environment and thus the survival rate may be very low. For this reason, biologists generally specify an allowable delay interval at a culvert crossing from a few hours to six or ten days depending on the species of fish and the relative location of the blockage with respect to the location of the spawning beds. If the culvert is close to the spawning areas, there is a greater urgency on the part of the fish to move upstream thus the allowable delay is generally of a shorter duration.

To design for this type of run it is necessary to select a design hydrograph for the stream, then superimpose the timing of the fish runs on the hydrograph. The species of fish and the estimated performance capability of each specie must be known. In practice the biologist generally specifies the approximate time of the fish runs and the swimming capability of the fish. The engineer then estimates the probable discharges for the time (date) of the runs and designs the structure so that flow velocities within the culvert are appropriate for the design fish.

Spawners are mature fish and are strongly motivated to move upstream. Therefore, velocities of from four to seven body lengths per second are generally tolerable. The passage problem is complicated somewhat by the fact that for some species of fish, fish movement corresponds with the period of maximum flow or near maximum flow. As an example, it is well documented that the Arctic grayling in central Alaska migrate upstream during the period of spring breakup, sometimes moving upstream under the ice or in channels cut in the ice.

Another class of fish which must be accomodated are families of fish that are physically swept out of the steep headwater portions of a stream by high flows. Eventually the stream broadens out to a point where pool sizes and velocities are such that the fish can maintain a position in the stream. As the water level subsides and velocities decrease, these fish make their way back upstream to their home reaches. These fish are not subjected to the same type of stress as spawners. It is not as serious a problem if they are held up for an extended period at a culvert crossing waiting for flows to subside. However, the entire age group - age I through mature fish - must eventually ascend the culvert during low flow periods. The problems associated with providing a channel with velocities ranging from four to six body lengths per second (based on lengths of age I or age II fish) during low flows may place a more stringent requirement on culvert design than the high-flow spawner requirement.

Fish which migrate from one portion of the stream to another for feeding purposes or possibly seeking out regions where water temperatures are more favorable must also be considered. Again it is necessary to design the fishway for the entire run of fish, i.e., all sizes.

A third type of fish migration occurs when streams freeze solid during winter months a common phenomenon in certain small streams in cold climate areas. In most cases the fish are forced out of the channel and move downstream to rivers which are sufficiently deep that they do not freeze to the bottom during the coldest months. When spring breakup occurs, these fish migrate into the small streams for spawning and summer feeding. It is necessary to provide fish passage facilities for the entire age group, age I through mature fish, under these circumstances.

There are many biological and physical variables which effect the ability and/or capability of fish to ascend culverts. The temperature of the water has a marked effect on the swimming capability of fish. Fish swimming speeds are generally low at low temperature, peak at some optimum temperature, then are reduced sharply at higher temperatures, Brett (1958), Watts and MacPhee (1973). The change in light conditions encountered when fish pass from the stream into a culvert then from the culvert into the stream is thought by some researchers to be a serious problem. Swimming capability of fish and significant variables which affect this capability are described in the next section.

Swimming Capability of Fish

Swimming speeds of fish are usually reported in three separate categories; burst speed or darting speed, the speed a fish can swim for a few seconds ranging from eight to twelve body lengths per second; sustained speed, the speed a fish can maintain for a period of several minutes ranging from four to seven body lengths per second; and cruising speed, the speed a fish can swim for an extended period of time, an hour or longer, ranging from two to four body lengths per second.

For the design of long culverts for fish passage, (culvert longer than 150 feet) the cruising swimming velocity of the design fish is compared to the mean velocity of flow through a culvert for an appropriate discharge. When conditions are such that mean flow velocities are in excess of fish capability, a slot orifice fishway, some type of weir fishway, or a separate fish passage facility must be constructed. For some conditions, a bridge or pipe arch may be used in lieu of a culvert.

For moderate length culverts, it appears that sustained speed is appropriate for design, Watts and MacPhee (1973).

The lower range of burst velocity is the appropriate velocity for the design of slot orifice or weir type fishways. In this type of structure the fish darts through the slot (or over the weir) with a burst of speed then has the opportunity to rest in the adjacent pool before passing through the next slot. The pool velocities must be less than the cruising speed capability of the fish.

Paulik and Delacy (1957), reported the cruising velocity capability of Sockeyes as 3.0 L per second (L is the fork length of the fish), Silver Salmon 3.4 L per second, and Steelhead 3.3 L per second. These data were for mature fish. Gray (1953, 1957) reported burst speeds of five feet per second for four inch fish. The burst speed capability of fish was about four times larger than sustained.

Kerr (1953), Bainbridge (1960), Thomas (1964), and Brett, et al (1958) all report that wild fish can swim at a rate about 30 percent higher (at least for short periods of time) than cultured fish raised in a low flow velocity environment. This factor must be considered when trying to compare data obtained from various researchers.

Thomas (1964) also showed that when tests were repeated on a group of fish after rest periods of 24 hours, there was a reduction in the swimming capability of fish when compared to their initial capability. This may imply that as a spawner moves upstream its swimming capability decreases. Thus, the critical location for fish blockage as far as swimming capability is concerned is in the steep headwaters of a stream, the area where culverts are most likely to be built.

Maximum swimming speeds of fish reported by Calhoun (1966), and by Bell (1973) are shown in Table 1 and 2. Some of the velocities reported by Calhoun (1966) appear to be burst velocities rather than sustained velocities and should be used accordingly.

Suggested Design Velocities for Fish For design of culverts of moderate length (60 to 150 feet long), the range of sustained swimming speeds of

Table 1

Maximum Swimming Speeds of Fish by Richard Haley.
From Inland Fisheries Management edited by A. Calhoun, 1966.

Species	Max fps	Experimenter
Brown trout	12.8	Kreitmann (1933)
Brown trout	5.6	Schmassmann (1928)
Brown trout	7.1	Hydrotechnical Research Ins of Leningrad
Sea trout	8.4	Kreitmann (1933)
Sea trout	6.4	Schmassmann (1928)
Sea trout	7.1	H R I of Leningrad
Atlantic salmon	8.4	Kreitmann (1928)
Atlantic salmon	6.4	Schmassmann (1928)
Atlantic salmon	26.5	H R I of Leningrad
Atlantic salmon	12.5	as above but in large numbers
Atlantic salmon	7.8-9.3	H R I of Leningrad
Steelhead	12.0	Paulik and DeLacy (1957)
Steelhead	26.7	Collins and Elling (1960)
Steelhead	26.8	Weaver (1963)
King salmon	14.5	Paulik and Delacy (1957)
King salmon	22.1	Collins and Elling (1960)
King salmon	21.9	Weaver (1963)
Silver salmon	12.2	Paulik and DeLacy (1957)
Silver salmon	17.5	Weaver (1963)
Red salmon	10.3	Paulik and Delacy (1957)
Trout	11.4	Denil (1938)
Grayling	7.1	H R I of Leningrad
Whitefish	4.6	same
Lamprey	6.2	same
Carp	1.2	Kreitmann (1933)
Tench	1.5	same
Pike	1.4	same
Skipjack tuna	19.2	Comm Fish Review (1964)
Yellowfin tuna	16.7	same

Table 2

Swimming Speeds of Average Size Adult Fish as Reported by Bell (1973) in "Fisheries Handbook of Engineering Requirements and Biological Criteria"

Specie	Cruising speed fps	Sustained speed fps	Darting speed fps
Carp	0 to 1.2	1.2 to 4.0	4.0 to 8.4
Suckers	0 to 1.4	1.4 to 5.2	5.2 to 10.3
Lamprey	0 to 1.0	1.0 to 3.0	3.0 to 6.3
Whitefish	0 to 1.3	1.3 to 4.4	4.4 to 9.0
Grayling	0 to 2.5	2.5 to 7.0	7.0 to 14.2
Brown trout	0 to 2.2	2.2 to 6.2	6.2 to 12.7
Trout	0 to 2.0	2.0 to 6.4	6.4 to 13.5
Steelhead	0 to 4.6	4.6 to 13.7	13.7 to 26.5
Sockeye	0.to 3.2	3.2 to 10.2	10.2 to 20.6
Coho	0 to 3.4	3.4 to 10.6	10.6 to 21.5
Chinook	0 to 3.4	3.4 to 10.8	10.8 to 22.4
Shad	0 to 2.4	2.4 to 7.3	7.3 to 15

fish presented by Bell, (1973) and reproduced as Table 2 in this report is recommended. The higher end of the scale is recommended for short culverts, the lower values for long culverts. Based on our experience with Arctic grayling, Watts and MacPhee (1973), the higher end of the sustained speed range would be for large mature fish swimming under optimum conditions; the lower end of the range would be for small adult fish under less than optimum conditions. The average value of sustained speed for mature Arctic grayling from Table 2 (about 5 fps) corresponds to the velocity where 75 percent of 10 inch mature Arctic grayling ascended 60 lineal feet of culvert with water temperatures of 44° F in our studies.

To estimate swimming capability of immature fish, Figure 1 can be used in conjunction with data shown in Table 2. Figure 1 is a plot of relative swimming speed versus relative length of fish. This curve was developed from grayling data, however, the curve should be similar for any specie of fish. An example of how this figure can be used is illustrated on Figure 1.

For long culverts (greater than 150 feet) the higher values of cruising speed presented by Bell (1973) should be used for design. Generally velocities of 3 to 4 body lengths per second is a safe design velocity for fish regardless of culvert length.

It is recommended that velocities less than the lowest range of burst speeds presented in Table 2 be used for designing orifice or weir type fishways. Velocities on the order of 6 to 8 body lengths per second, for the size class of fish which must be accomodated are suggested.

All design velocities suggested are for normal water temperatures. If the fish must move through abnormally high or abnormally low temperatures, the allowable velocities should be reduced by upwards of 35 percent. If pollutants or low dissolved oxygen occur in the system during periods of fish movement, an additional reduction in swimming ability should be anticipated. This is usually not a problem in small headwater streams where culverts are typically used.

Light Factor Early studies on the affect of fish passing from a brightly lighted area into a dark conduit (and from a dark conduit into a brightly lighted environment) indicated that fish tended to pause for a period of time to acclimate themselves to this phenomenon. If this is the case, the extended time required for acclimation to changing light conditions places an additional stress on fish passing through a culvert. The fish, upon entering the culvert, would have to maintain that station for an extended period of time while continuously swimming against the current, then swim the length of the culvert then pause again near the culvert entrance for an additional acclimation period prior to emerging from the culvert. Under these circumstances the fish might swim against the current in the culvert for a period of 20 to 30 minutes as compared to the one to three minutes required to swim the length of a normal culvert.

It is generally believed that the contrast of light conditions at a culvert entrance or exit is insufficient to cause noticeable obstruction to fish movement. For extreme cases such as long culverts (several hundred feet) or culverts on a curved alignment, this may be a problem but in most cases the light constrast is minimal at low or moderate flows.

The writer has observed free movement of fish into and out of culverts during bright days without any noticeable delays. Recent studies by Slatick (1970), Kay and Lewis (1970), and experience with a long dark slot orifice fishway, Gebhards and Fisher (1972), would indicate that light is not a factor. When migration occurs during high turbid flow the light-dark phenomena would be minimized. Upstream movement for some species of fish occurs primarily during the night hours thus the light-dark phenomenon should not be a problem. However, if the designer is unconvinced, the exit and entrance of the culvert can be shaded with bushes thus minimizing the contrast, Metsker (1968).

Minimum Size of Fishways Dimensions commonly specified for fishways appear to be excessive for culvert design. Clay (1961) presented an extensive review of space requirements for migrating fish and suggested a minimum volume requirement of 2 to 4 cubic feet of water per small mature fish (Chinook salmon or Steelhead). Bell (1973) recommended 0.2 cubic feet of water per pound of fish. Fish readily ascend 1 foot of elevation every 3 to 6 minutes, Clay (1961). Thus, assuming volume requirement of 2 cubic feet per fish, 3 feet of vertical ascent, and 5 minutes per foot of ascent, 96 feet of fishway consisting of a series of pools 4 feet wide by 8 feet long by 2 feet deep would accomodate 1,456 fish per hour. Slatick (1970) conducted a fish passage study using a 24 inch diameter pipe 100 feet long and reported that "the two tests conducted did not yield enough data for us to draw dependable conclusions on pipe capacity but it appears that a 24 inch diameter pipe 100 feet long can carry 800 to 900 salmon and trout per hour."

Most agencies specify that weir type baffles for box or circular culverts be a minimum of 4 feet wide. It is apparent that the dimensions cited would accomodate large fish and large hourly runs.

It is recommended that each culvert site be examined in light of probable hourly run size, maximum anticipated size of fish, and the amount of holdup the fish can sustain without detrimental effects. Using this criteria, a fishway of reasonable size should be specified rather than arbitrarily specifying an oversize structure.

Migrating fish frequently move in schools. When estimating hourly run size, the following information presented by Bell (1973) should be kept in mind: "The movement of fish throughout the day is not uniform and it may be expected that between daylight and 1 p.m. as much as 60 percent of the day's run may pass, and between 1 p.m. and darkness 40 percent. Twenty percent of a day's run has appeared in a single hour." Arctic grayling were observed to move upstream in schools during our studies. However, upstream movement appeared to be in response to water temperature rather than time of day. Peak upstream movement occurred in the afternoon when the stream water was the warmest.

Hydrologic Characteristics of Streams

An important factor of fish passage design is determining a reasonable hydrograph for the crossing site so that the appropriate discharges during periods of fish migration can be determined. The design agency is responsible for specifying appropriate hydrographs for all streams where fish passage structures are necessary.

Factors which influence streamflow and consequently the shape of the hydrograph include the geographic location of the drainage basin and consequent pattern of storms, the general slope, land cover, type and depth of soils, and the season (effect of ground cover). Methods of generating streamflow versus time plots (hydrograph) are well covered in standard texts on hydrology.

Type of Stream When surveying a crossing site, the type of stream must be determined. A brief review of stream types and their characteristics follows:

1. Tributary streams to large lakes - Peak flows for this type of stream are influenced by the lake level. Generally, flow velocities are of a reduced magnitude but peak flows last for extended periods of time. Large scale fish movements are frequently associated with this type of stream.
2. Steep mountain streams where peak flow is the result of melt waters from snow-pack - A typical hydrograph for this type of stream will show pronounced fluctuations of peak flow during a month or so of high runoff followed by an extended period of low flow. Many small streams show a distinct diurnal fluctuation in flow as a function of daytime snowmelt. This type of stream, besides supporting resident fisheries, will frequently be utilized by anadromous spawning fish. The reworking of gravel beds in the riffles during high peak flows combined with extended periods of moderate flow of high quality water are optimum conditions for spawning gravels.
3. Intermittent streams which flow only during extended rainy seasons - Though this type of stream cannot support residence fisheries, it is frequently used for spawning purposes during the wet seasons and may function as a nursery for several months.
4. Groundwater streams - This type of stream is characterized by a very stable discharge with high stages associated with convective precipitation events or by local snow-melt events. This type of stream can support a significant fishery.

Site Data Data which must be assembled for each culvert site include;

a) channel cross section data sufficient to describe the channel one hundred yards upstream and downstream of the crossing,

b) a centerline profile of the channel sufficient in length to estimate normal depths of flow associated with design discharge,

c) an estimate of Mannings n for the reach for both high and low flows,

d) adequate description of bed material so that the potential for scour can be assessed and so that sufficient information is available to design the footings for an appropriate structure, and

e) information describing the drainage basin, general slope, length, cover, aspect, etc. sufficient for a hydrologic analysis (design hydrograph).

Fish Information A regional fisheries biologist must provide information regarding the species of fish which inhabit the stream, the approximate times of migration and the age and size of the migrating fish. Information must be available for the entire fish population of the stream including resident and migratory species.

Design of Culverts for Fish Passage

With crossing site data, hydrologic information, and appropriate information on fish in hand, the design of culverts for fish passage might proceed as follows

Selection of Design Fish

a) The time (approximate date) of fish upstream movements and the swimming capability of the design fish are determined. As an example, assume the adult design fish has a sustained swimming speed capability of 5 fps (FV1) and must ascend the culvert at the time when the stream discharge is equal to 65 percent of the ten year flood (PD1). Juvenile design fish with a sustained swimming speed capability of 3 fps (FV2) must be able to ascend the culvert when the discharge is equal to 20 percent of the ten year flood (PD2). In a stream which supports several species of fish, the most critical specie and age group would establish this criteria.

With this information and appropriate crossing site information, the engineer determines the centerline grade of the structure and selects an appropriate culvert for the maximum design discharge.

The head water (HW) upstream of the culvert generally should be limited to 1 diameter (D) of the culvert, i.e., $HW/D < 1$. This specification might be appropriate for the 25 year event. After sizing the culvert for this condition, the hydraulic engineer should then examine the barrel velocities of the culvert for the two design discharges, PD1 and PD2, and compare them to the swimming capability of the fish, FV1 and FV2 respectively. If either of the culvert barrel velocities exceed fish swimming capability, then an alternate design must be considered. Suggested methods for the hydraulic analysis of conventional or modified culverts and alternate fishway structures are outlined in the following sections.

Hydraulic Analysis of Culvert Fishways

CMP Facility Given the following information, design an appropriate cmp culvert and determine whether or not the culvert will provide for satisfactory fish movement.

Stream slope = 0.004

Discharge expected once in 25 years, Q_{25} = 175 cfs

Discharge expected once in 10 years, Q_{10} = 112 cfs

" " " " 2 years, Q_2 = 55 cfs

Normal summer flow Q_s = 2 - 10 cfs

$\frac{HW}{D} \leq 1$ for 25 year discharge HW = headwater depth in feet.

D = diameter of culvert in feet.

FV1 = 5 fps for 65 percent of the 10 year discharge.

FV2 = 3 fps for 20 percent of 10 year discharge.

PD1 = (0.65)(112) = 73 cfs

PD2 = (0.02)(112) = 22 cfs

For $\frac{HW}{D} \leq 1$ and Q_{25} = 175 cfs;

assume inlet control and a projecting entrance; from information presented in Reference 28, a 72 inch cmp is required but a check on normal depth, Reference 29, indicates that a 72 inch pipe would flow full and therefore HW/D > 1, so an 84 inch cmp is selected for use. Check the velocity in the pipe for PD1 = 73 cfs and PD2 = 22 cfs using Figure 7 in the Appendix. Figures 2 through 8 in the appendix are useful for estimating uniform flow velocities for cmp culverts operating with (or near) entrance control conditions.

For Q = 73 cfs and S = 0.4 percent, from Figure 7 the normal velocity = 5.0 fps, $\leq$ FV1 = 5.0 fps, therefore the design is satisfactory.

For Q = 22 cfs and S = 0.4 percent, from Figure 7, the normal velocity = 3.0 fps $\leq$ FV2 = 3.0 fps. Therefore the design is satisfactory.

In this example an 84" culvert is satisfactory for the site. Tailwater depth must be maintained at an adequate depth. This can be accomplished by constructing a sill 5 to 7 culvert diameters (35 to 50 feet) downstream from the outlet, with the top of the sill set at about the same elevation as the invert of the pipe, see Figure 9. If the channel is stable below the outfall (bed rock outcrop or heavily armored with large boulders) it may not be necessary to construct a sill. However, to be on the safe side, the culvert invert should be set one foot + below the normal grade line of the channel.

If this culvert had been on a 1 percent slope (instead of 0.4 percent) the normal velocity for Q = 73 cfs would have been about 7 fps (> than 5 fps allowable) and about 5 fps (> than 3 fps allowable) for Q = 22 cfs. Under these conditions an alternate design would have to be considered. If it were feasible to construct a tailwater control structure of sufficient height to create backwater in the culvert, the 84" culvert may still be satisfactory for the 1 percent slope. For Q of 73 cfs and a velocity of 5 fps the depth of flow just inside the culvert entrance should be about 2.0 feet. A sill (suitable in itself for fish passage) constructed 35 to 50 feet (5 to 7 pipe diameters) downstream of the culvert at an elevation about one foot lower than the invert elevation at the culvert inlet plus about 2.0 feet (see Figure 10) should be adequate. The culvert invert should be set well below the natural grade line of the channel.

If warranted, the elevation of the sill can be established by a set of backwater computations. The critical depth for Q = 73 cfs (or Q = 22 cfs) can be determined at the crest of the sill. Using this depth as a starting point the water surface profile through the pool and culvert can be estimated with typical trial and error backwater computations. A trial elevation of the weir crest is assumed and the depth at the culvert entrance is obtained by backwater computations. When this computed depth matches the required depth (2.0 feet in this case) the sill is assumed to be set at the proper elevation.

Fish passage over the sill must be possible at minimum flows as well as at design flows. The sill must be constructed with sufficient stability to withstand the design flow for the structure.

The culvert must also be checked for the maximum design discharge taking into account the affect of the sill. In some instances, the downstream control may alter the structure from inlet control to tailwater control. To avoid violating the $HW/D < 1$ criterion, the pipe size may have to be increased.

If a culvert is too long or the slope too steep, it may be impractical to construct a sill. Costs associated with the sill and the difficulty encountered in assurring fish passage over the sill at both high and low flow may rule out this alternative.

<u>Pipe Arches</u> The analysis of fish passage through pipe arches is similar to that for a cmp, however, velocities at low flow are generally somewhat higher (minimum amount of wall friction) and, during low flow periods in the summer, water depths within the pipe arch culvert may be insufficient for fish passage. If tailwater control is possible, oversizing the section and setting the pipe culvert well below streambed elevation may be an adequate solution. The velocities within the pipe arch must be limited to design fish capabilities for appropriate discharges.

<u>Modification of Culvert Barrels with Large Roughness Elements</u> The construction of large scale roughness elements on the floor of culverts has been suggested for the purpose of creating low barrel velocities. If the culvert is on a moderate slope, is significantly oversized, and if the

bed load in the stream is gravel size or smaller such that elements are self-cleaning, significant reduction in flow velocities for small discharges can be achieved. However, if bed load is of such size that it can accumulate in areas adjacent to the elements, the roughened area will fill and elements will have very little effect.

Information presented by Herbich and Shulits (1963) can be used for estimating flow velocities in concrete box culverts or pipes and culverts when rectangular roughness elements are used. Chezy C values ranging from 51 to 6 are reported for various patterns of elements for submergence ratios (depth of water above the floor divided by the height of element above the floor) ranging from 0.5 to about 2. Roberson and Chen (1970) report resistance coefficients for conduits roughened with cubes for a variety of patterns and for submergence ratios ranging from 5 upwards. Sayre and Albertson (1963) also presented friction factors for various combinations of roughness elements.

Rounded Elements Rounded roughness elements exert a much lower drag force per unit frontal area than is exerted by buff shaped bodies. Resistance coefficients for rounded elements can be obtained in a paper prepared by Overton et al (1972). Rounded elements are less effective in reducing barrel velocities in culverts and are also difficult to attach. For these reasons rounded elements are not recommended for reducing flow velocities in culverts.

Structural Plate Arches

A structural plate bottomless arch can sometimes be used where fish passage is required and barrel velocities in a cmp are in excess of fish swimming capability. The stream must be well incised and the bed must be quite stable if this structure is to be satisfactory. Figure 11 illustrates a possible installation and suggests some areas where bed stability may be a problem. The following set of computations illustrates how the hydraulics of a structural plate arch can be analyzed.

Given

Average Stream slope = 0.02

Q_{25} = 755 cfs

Q_{10} = 500 cfs

Q_{2} = 300 cfs

Normal summer slow Q_s = 15-25 cfs

$\frac{HW}{D} \leq 1$ for Q_{25}

FV1 = 5 fps for PD1, PD1 = $(0.65)(Q_{10})$ = 325 cfs

FV2 = 3 fps for PD2, PD2 = $(0.2)(Q_{10})$ = 100 cfs

Assume the cross section is similar to that of a corrugated metal pipe arch culvert.

For $\frac{HW}{D} \leq 1$, projecting entrance, Q = 755 cfs, and entrance control using information presented in reference 28, a 15'-4" x 9'-3" corrugated metal pipe arch culvert is the minimum recommended size. Use a structural plate arch with a similar area, say a 20' span and an 8'-3½" rise.

Check the flow depth in channel for Q = 755 cfs. Mannings n for the channel = 0.035; Mannings n for the culvert = 0.024, use n = 0.035 and assume a flow depth = 4.5 feet. The approximate wetted perimeter, (WP) = 10 + (2)(6.4) = 23 feet. The approximate area (A) = (14.5)(4.5) = 65 square feet. The hydraulic radius (R) $= \frac{A}{WP} = \frac{65}{23} = 2.82$ feet. Using Mannings equation $Q = \frac{1.49}{n} R^{2/3} S^{1/2} A$, $Q = \frac{1.49}{0.035} (2.82)^{2/3} (0.02)^{1/2} (65) = 781$ cfs $>$ 755 cfs therefore the design is satisfactory and flow depth is less than 4.5 feet, well within the normal channel cross section. If the arch spans the original channel (i.e. no change in alignment or modification of original cross section) fish passage should not be impaired by the installation.

The channel is lined with rock and the culvert section is essentially the same width as the natural channel therefore if fish could have migrated upstream under the original channel conditions their movements should not be impared by the installation of this type of culvert. The armor material in the bed will be large enough to provide adequate low velocity zones in the vicinity of the bed and along the edge of the culvert so that fish can make their way upstream. In some cases where the natural stream condition blocks part of a fish run, the design agency may elect to construct a fishway that will allow free passage over the natural obstacle.

The major cause for concern in designing a bottomless arch is the stability of the bed and the material surrounding the footings of the arch. Because of the vena contracta effect at the entrance and a high level of turbulence, a liberal factor of safety must be used when designing structural plate arches. When this type of structure fails it is usually the result of undermining of the footings.

When performing the stability analysis for the bed, the flow conditions associated with the maximum anticipated flood for the life of the structure must be considered. If overbank flow would have occurred under pre-construction conditions, the water-way may be significantly constricted by the arch and therefore higher velocities and deeper flow will result. If significant quantities of bed material are unstable under this severe flow condition, serious degradation within the confines of the arch will occur. This may leave the arch footings in a vulnerable position and may also result in a steeper fish conveyance channel.

The type of stream where an arch type structure may be satisfactory is a stable well incised large bed element stream. The height of the bed elements must be a significant fraction of the mean depth during low flow, so that small fish may move at will during this period.

Design of Baffled Culverts

Early efforts to solve the fish barrier problem centered around the use of a pool and baffle fishway. Vertical baffles spaced at regular intervals were placed on the culvert floor perpendicular to the centerline forming a series of pools and overfall weirs. Two distinct types of flow can occur, "plunging" or "streaming". These regimes are illustrated in Figure 12. When plunging flow occurs, the water drops from pool to pool in a cascading fashion. The kinetic energy is dissipated in each pool, thus affording the fish a relatively quiescent resting area prior to each ascent of a weir. During streaming flow, water skims over the weir tops at a high velocity with little energy dissipation. This type of flow is unsatisfactory for fish passage.

Various tests conducted on pool and weir fishladders, Thompson and Gauley (1965), Gauley and Thompson (1962), Collins et al (1961), with centerline slopes ranging from 5 to 12½ percent, indicated that plunging flow occurs with depths of flow over the weir up to 1.4 feet and streaming flow for any greater depth. If the culvert is to be an effective fishway it must be of sufficient width that flow depth over the weirs does not exceed

1.4 feet for any sustained length of time when fish are migrating upstream. This necessitates a wide shallow culvert.

Structural requirements for the culvert roof and floor are a function of the width of the culvert cubed. The bending moments in the roof (or floor) of a culvert with a span of 10 feet are approximately eight times larger than those for a 5 foot span, thus, doubling the span results in a significantly more expensive structure.

Another factor which limits the effectiveness of baffles is bed load deposition in the pools. The bed material carried in a steep stream may fill the pools between the baffles resulting in streaming flow even at low discharges. It is not economical to clean the pools as the work must be done by hand. Shallow head room and baffles on the floor prohibit any form of mechanical cleaning.

Alternate paired baffles illustrated in Figure 13 have not always proven effective. During low flows, depths in successive pools are below minimum depth for fish passage and extremely turbulent unstable flow patterns unsuitable for fish passage occur during high flows, McKinley and Webb (1956).

The baffle system which has worked most effectively is the offset baffle design shown in Figure 14. Throughout a large range of flow depths a counterclockwise roll of relatively stagnant water forms in the region below the crest of the baffle in the apex between the angled baffle and the wall. This roll affords a resting area for the fish as they make successive advances through the gap between baffles.

Testing of the offset baffles by McKinley and Webb (1956) indicated good cleaning characteristics. Although this may be the case for small sizes of bed material, the strength of circulation required to sweep out material several inches in diameter would surely result in an unsuitable resting area.

Several of these installations in Oregon and Washington have filled with bed material and are no longer completely effective.

Another undesirable feature of any type of floor baffle is the loss of efficiency. For culverts operating with barrel control, efficiency is defined as the ratio of the depth of flow in a culvert operating without baffles divided by the depth of flow for the same discharge and culvert barrel dimensions with baffles in place. Model tests on offset baffles simulating a 10 foot wide culvert with one foot high baffles indicated an efficiency of 69 percent. With 1.4 foot high baffles the efficiency was 57 percent. This is an important consideration when existing culverts are modified. If a six foot high box culvert operating with barrel control proportioned to carry a particular discharge with a headwater of 6 feet is converted to a fishway by installing one foot high baffles, the headwater (backwater) upstream of the culvert would have to be about eight feet in order to drive the same discharge through the culvert. This headwater is about two feet higher than that specified during the original design. In some situations two feet of additional backwater may inundate valuable land or structures, or may overtop the roadway fill resulting in damage to the highway and possible loss of the culvert. This point must be considered when existing structures are modified.

For wide baffled box culverts or baffled pipe arches operating with inlet control, the increase in headwater can be estimated using weir formulas. As an example a 6 foot high box culvert operating under entrance control will admit about 42.5 cfs per foot of width of culvert, Reference 28. If a 1 foot high baffle is constructed across the entrance of the culvert and a standard sharp edge weir equation is used for computing discharge, the baffled culvert will admit only 33.5 cfs per foot of width. Thus for the same headwater conditions, the baffled culvert would have to be widened about 27 percent in order to accomodate the same discharge as the original box culvert.

New structures which are intended to function as fishways must be designed to pass a particular discharge at a specified headwater depth. A corresponding increase in both the structures width and cost is inevitable.

Hydraulically, baffles functions as a sharp edged weir when operating in the plunging mode. Approximate overflow velocities can be estimated using the energy equation written from the surface pool upstream of the weir to the water surface elevation downstream of the weir. The overflow velocity must be less than the burst speed capability of the design fish.

Slot Orifice Fishways

A slot orifice fishway is a rectangular shaped channel with a series of full depth vertical slot orifices arranged in a systematic pattern.

The slot orifice fishway is a proven fishway with many advantages. It provides stable low velocity flow conditions for a wide range of headwater and tailwater depths, is self cleaning, and is simple and economical to construct. For a box culvert installation, the fishway exit (at the upstream end of the culvert) can be constructed outside the culvert barrel, as shown in Figure 15. Since the critical cross section for culverts on steep grades is the entrance section, there is no decrease in culvert efficiency. At some distance downstream from the entrance (about two or three times the depth of the box culvert) the fishway may be constructed within the culvert barrel adjacent to the wall. The effect of this is to constrict the flow and raise the water surface in the lower reach of the culvert. However, since the fishway occupies a reach downstream from the contracted entrance section and in the supercritical flow zone, the headwater level upstream from the culvert is not affected by the fishway and the entrance conditions for the culvert still controls the upstream flow depth.

Design of slot orifice fishway with equal tailwater and headwater depths

If the depth of water upstream of a slot orifice fishway exit (H_i, Figure 16) is approximately equal to the tailwater depth (T_1) downstream from fishway, the hydraulic analysis of a slot orifice fishway is rather simple. The total drop in water surface between headwater and tailwater is divided by the number of orifices, then the discharge through the orifice can be estimated using the known tailwater depth and Figure 17.

As an example a fishway is assumed to be one hundred feet long with 6 slot orifices and on a slope of 2 percent. Further, its headwater and tailwater depths are 3 feet, fishway width (B) is 3.00 feet, and the contraction coefficient m = 0.70. Determine the approximate velocity at the throat of the orifice.

$$\Delta H = \frac{\text{drop in elevation of water surface}}{\text{the number of slot orifices}}$$

$$= \frac{(0.02)(100)}{6} = 0.333 \text{ feet}$$

$$\frac{H_i}{T_i} = \frac{3.00 + 0.33}{3.00} = 1.11, \qquad m = 0.70$$

$$\text{From Figure 17,} \qquad \frac{Q}{B\, T_i^{3/2}\, \sqrt{32.2}} = 0.106,$$

$$Q = (0.106)(3)(3)^{1.5}(32.2)^{0.5} = 9.38 \text{ cfs}$$

The approximate throat velocity = $\frac{Q}{T_i\ B(1-m)}$

$$= \frac{9.38}{(3)(3)(1-0.7)} = \underline{3.5\ \text{fps}}$$

This velocity is compared to the burst capability of the design fish and if the orifice velocity exceeds the burst speed capability, the spacing of the orifices must be reduced (i.e. add additional orifices) until the two velocities are compatible. Another alternative is to try a different contraction ratio m and redesign the fishway.

The mean flow velocity in the pool between successive pairs of orifices must be less than the cruising speed of the design fish. The discharge Q divided by the mean cross sectional area (B x $\frac{H_i + T_i}{2}$) will yield the approximate pool velocity.

Many fishway publications suggest that an orifice formula $V = 0.68 \sqrt{2\ g\ (\Delta H)}$ be used for computing the throat velocity of a vertical slot orifice. When this formula is used for $\Delta H = 0.33$ feet, a throat velocity of 3.1 fps (as compared to 3.5 fps computed above) is obtained. The throat velocity is known to be a function of the contraction ratio m and ΔH. For this reason the procedure using Figure 17 is considered by this writer to give a better estimate of throat velocity.

Design of Slot Orifice Fishways with Unequal Tailwater and Headwater Depths

The hydraulic analysis of this type of fishway is rather complex. When tailwater depth and headwater depth are unequal the tailwater depth and ΔH through each orifice must vary in a systematic but unknown manner. Dass (1970) developed a method for analyzing this type of structure. The fishway was divided into two reaches, the fishway entrance weir and the remainder of the fishway. With reference to Figure 18, a momentum equation was developed for the control volume extending from the fishway side of the entrance weir (H_1) to the fishway side of weir i (T_i). This equation contained hydrostatic pressure force terms and momentum flux terms for each end section of the control volume, appropriate drag force terms for the slot orifices and the gravity component of the control volume. Model studies were conducted to develop drag coefficients for slot orifices with m values ranging from 0.6 to 0.85 and for culvert slopes ranging from 0 to 5 percent. Three longitudinal spacings of slot orifices were considered, 4, 5, and 6 times the fishway width. The fishway entrance orifice was considered as a separate entity and a series of rating curves for slot orifices as a function of m and $\frac{H_i}{T_i}$ were developed experimentally. With the aid of these rating curves and experimentally determined drag coefficients the momentum equation can be solved by a trial and error solution and the throat velocity at the fishway entrance can be determined. This solution technique is somewhat cumbersome and sensitive to small computational errors, is difficult to use and is limited to fixed orifice spacing, so the following modified procedure is suggested by the writer.

This modified procedure provides a means of analyzing a slot orifice fishway with variable longitudinal spacing of slots, variable contraction ratio from slot to slot, and provides a means of analyzing a skewed slot orifice entrance (slot orifice constructed in a wing wall of a concrete culvert). The throat velocities obtained using this technique are within ± 6 percent of those obtained using the more complex solution technique proposed by Dass (1970).

The suggested procedure is based on the following assumptions or principles:

1. The rating curve for the fishway entrance orifice developed by Dass (1970) is applicable to each orifice in the fishway.
2. The pool surfaces between each pair of orifices is essentially horizontal.
3. Continuity; after the system is in equilibrium, the discharge through each of the orifices is equal.

The design procedure is as follows:

a) Determine headwater depth H_i and a tailwater depth T_1 for the flow condition in the channel, i.e. H_i and T_1 must be known.

b) Select a trial fishway design, (specify B, m and orifice spacing).

c) Assume a trial discharge (Q) through the fishway.

d) Using a trial discharge Q and T_1 compute the value of the parameter $\frac{Q}{B\,T_1^{3/2}\,\sqrt{32.2}}$, enter Figure 17, obtain the value of $\frac{H_i}{T_i}$, and compute the value of H_1.

e) Using this value of H_1 obtain value of T_2; $T_2 = H_1 - s\ (\Delta L)$, (s = slope of channel, ΔL = longitudinal spacing of slot orifice weirs).

f) Using the value of T_2 and Q compute the value of the parameter $\frac{Q}{B\,T_2^{3/2}\,\sqrt{32.2}}$, enter Figure 17 and obtain the value of $\frac{H_i}{T_i}$ and compute the value of H_2.

g) Repeat procedure for each successive weir until H_i is obtained. Compare this computed value of H_i with known value of H_i for flow conditions in the upstream channel.

h) If H_i computed does not equal H_i known then assume a new value of Q and recycle computations. If H_i computed is larger than H_i

known, the assumed value of Q was too large. If H_i computed is smaller than H_i known the assumed value of Q was too small.

Typical sets of computations for two fishways are shown in the computation charts, Figures 18 and 19.

The maximum H/T ratio should be limited to about 1.7. Depending upon the value of m, the discharge through a slot orifice is not a function of T when the $\frac{H}{T}$ ratio exceeds about 2.0. Also, the turbulence created by the weir nappe falling into the lower pool is quite disruptive and is not conducive to optimum fish movement into the fishway. For these reasons the $\frac{H}{T}$ ratio for any slot should be limited to about 1.7.

Skewed Slot Orifice Fishway Exit

In some installations it may be necessary to install the fishway exit in a skewed wall. A definition sketch for a skewed slot orifice fishway exit is shown in Figure 20. A skewed orifice creates an additional hydraulic problem because the rating curve is a function of the skew angle as well as the contraction ratio m and backwater-tailwater ratio $\frac{H}{T}$. Harrison (1972) developed a series of rating curves for m values ranging from 0.60 to 0.85 for skew angles ranging from 30 to 75 degrees, and $\frac{H}{T}$ ratios ranging from 1.0 to 1.4. The design information is presented in Figures 22 through 25.

The design of a fishway with a skewed slot exit is similar to the design of any other slot orifice except the appropriate rating curve for the skewed slot orifice (Figure 22 through 25) is used in lieu of Figure 17 for the skewed slot orifice at the fishway exit. An example solution is shown in Figure 26.

When a fishway exit is constructed in a skewed abutment wall, an entrance such as shown in Figure 21 is recommended. The slot orifices are essentially perpendicular to the centerline of the fishway so the design procedure illustrated in Figures 18 and 19 is suitable for this fishway. H_i can be assumed to be equal to the headwater depth at the culvert entrance.

A trash rack should be constructed across the opening in the abutment wall to prevent debris from blocking the orifices. The invert of the fishway should be constructed several inches lower than the invert of the culvert entrance so that low flow will be routed through the the fishway. This will provide optimum fish passage conditions during periods of low flow.

Suggested Orifice Type Fishway for cmp or Pipe Arch An appurtenance orifice fish passage structure which can be attached within a cmp or pipe arch structure has been suggested by the writer. A sketch of the proposed structure is shown in Figure 27. This structure has not been tested, however, considering the corrugation roughness and the contraction affect of the orifices, maximum slot velocities of 2 or 3 fps should be attainable for slopes of 5 or 6 percent.

The fishway exit could be specially fabricated as shown in Figure 28 so as to provide a rounded entrance for optimum hydraulic efficiency and so that fish would enter the upstream channel a safe distance above the culvert entrance. There is a possibility of fish being swept back through the culvert if the fish emerge from the fishway into a high velocity zone. The placement of the support bracket down the center of a cmp would divide the flow and provide a deeper trough of water for low flow conditions. The orifice cover must be open at the top to provide light and open at the bottom so that water pressures will be approximately equal on either side of the orifice cover. The slot will also allow fish to move from the high velocity culvert barrel area into the low velocity flow environment of the slot orifice fishway.

All support brackets and attachment hardware should be within the confines of the orifice cover to minimize the opportunity for snagging debris. The units could be fabricated in convenient lengths and would be installed in the barrel after the culvert is constructed.

If an existing culvert is obstructing fish movement, this type of fishway could be installed during low flow periods when low water can be temporarily pumped or piped around the structure. Holes can be drilled through the pipe walls and L bolts used for attachment.

There are structural problems associated with hydrodynamic loadings on the fishway. Also the potential for trapping debris and floating ice must be considered. If a portion of the fishway were to break free and jam within the culvert,the culvert would in all liklihood be washed out. A hydraulic modeling program and a thorough analysis of the loadings on the structure during peak flow should be accomplished prior to the construction of this type of fishway.

The economics of this type of fishway is apparent. Currently long cmp or pipe arch culverts can only be used on grades on the order of 1/2 percent or less if small fish are to ascend the culvert. With an orifice type fishway, cmp or pipe arch culverts could be used for slopes up to 5 or 6 percent with a minimum decrease in hydraulic efficiency.

Instream Construction

Extra care must be exercised when constructing a stream crossing structure in or near prime fish habitat. Construction activity should be limited to the times of year when fish movement through the reach are at a minimum.

Installation of structures should be accomplished with the minimum impact on the stream.

Removal of stream gravel should not be permitted if this gravel is normally used for spawning activity. If material is removed from the stream, the pool riffle combinations should be restored after material removal is completed.

Excavation and backfilling at the site should be accomplished in a manner that minimizes addition of silts to the stream. No explosives should be used where shock can be transferred through the water media.

In so far as possible, construction equipment should be banned from the streambed. Haul roads should not be constructed within the confines of the high water marks of the creek. The primary reason for this is to prevent the contamination of the creek with lubricants and fuel spills.

If a gravel pit must be developed within the confines of a stream, a temporary cofferdam should be used to separate the pit from the free flowing stream. If gravels or sands must be washed during the pit process, all wash water should pass through a settling basin prior to routing the flow to the creek.

Concluding Remarks

This report presents a limited review of fish passage problems associated with culvert installations. Time and space does not permit an exhaustive review of all details. The purpose of this report is to alert the inexperienced designer (or biologist) to some of the common problems associated with culvert crossings.

The significant species of fish, the type, size and timing of fish runs (if any), the hydrologic characteristics of the basin and the physical characteristics of the stream at each culvert site will be unique. For this reason a structure of one type may be more desirable than another. It is the responsibility of the design agency to determine which structures will permit satisfactory fish movement then to make the final selection of structure based on economic considerations. The optimization of the hydraulic efficiency of a culvert and the creation of optimum fish passage conditions within the barrel are mutually exclusive objectives thus a compromise must be affected.

The information which is most difficult to obtain is a description of the fish population in a stream and the life history (location of spawning areas, feeding habits and environment, migration periods, swimming capability, etc.) of the various species of fish. A regional fishery biologist should make this determination. Fish behavior of the same specie may vary significantly from stream to stream or region to region.

With the fish information in hand, the value (both social and economic) of the fishery resource must be established and at this point a managerial decision concerning the preservation of the fishery resource must be made. In many instances agency policy or laws will require that the fishery be maintained and therefore fish passage will be required.

The swimming capability of the design fish is fixed, therefore the hydraulics of the culvert (or fishway) will have to be matched to the fish. Therein lies the challenge to the engineer; the development of the most economical structure which will accommodate both design discharge flows and permit free movement of fish through the structure.

Degradation below the culvert outfall will be a major problem at many culvert sites. Information presented in Reference 23 and Reference 30 are useful for analyzing this problem and for the design of an appropriate sill. Sheet piling sills or gabion structures with appropriate notches for low flow conditions may also be used for the sill.

Another major problem associated with fishway design is estimating the swimming capability of the design fish. Table 2 shows that there is a wide range of swimming capability for any one specie of fish. Most fish swimming velocities for wild fish have been determined by indirect observation, in short open flumes sometimes with artificial stimulation, or by inference from jumping capability. To this writers knowledge the swimming capability studies of Arctic grayling in a 60 foot culvert, Watts and MacPhee (1973) are the only controlled swimming speed studies ever performed in a prototype culvert using the entire population of fish (the entire range of age classes) moving upstream under near natural conditions. Swimming capability of fish as a function of fish length and water temperature were determined where 25, 50 and 75 percent of given size classes of fish successfully ascended the culvert under various slope and velocity conditions. This type of study is needed for all important species of fish so that culverts can be designed to insure adequate fish passage.

Information presented in this report is not meant to imply that a culvert (modified or otherwise) can be used at any crossing. In certain instances good judgement will dictate that the stream be left in its natural channel and the entire waterway be spanned with a bridge. If this is necessary the abutments should be set well back from the normal highwater cross section. The channel should not be constricted with rip rap or gabions constructed to protect the abutments or roadway prism. If this protection is necessary the area to be protected should be excavated then backfilled with rip rap or gabions.

It is hoped that this paper will generate additional studies on fish swimming capabilities and the hydraulic analysis of fish passage structures. Sport fisheries are an important natural resource. Additional design information and field prototype studies are needed so that we can better manage this valuable resource.

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APPENDIX

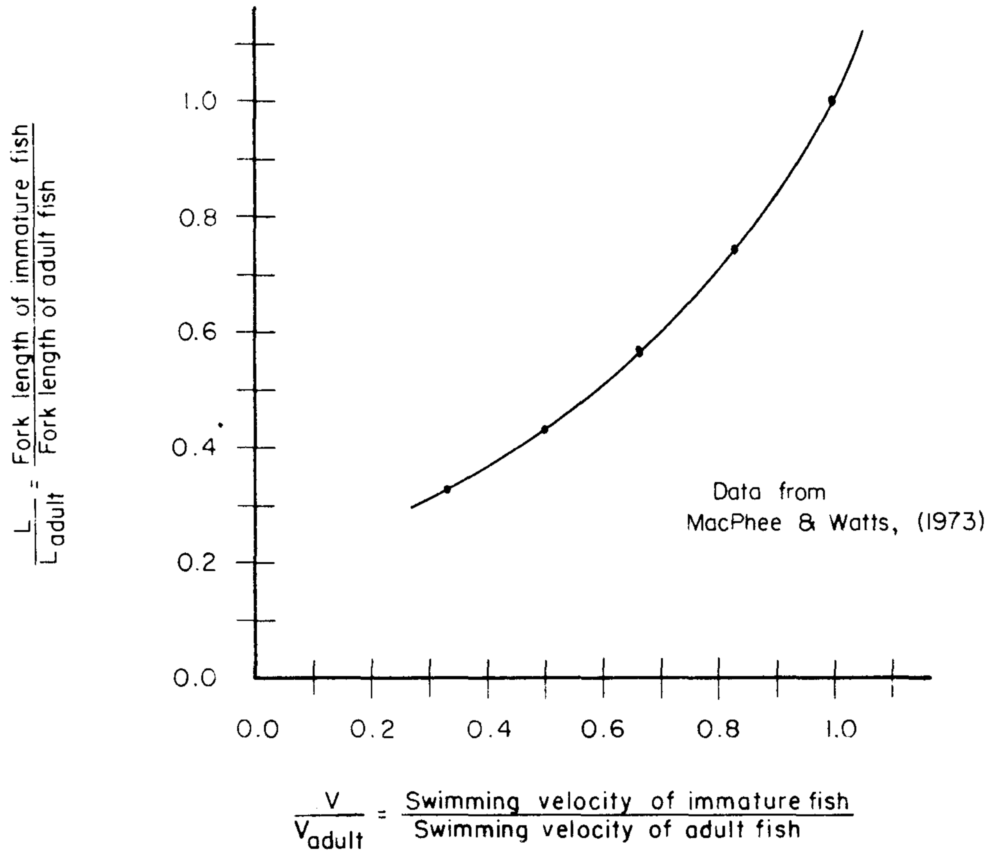


Figure 1 — Relative Swimming Velocity versus Relative Length of Fish

Graph for estimating design swimming capability of immature fish

Determine the sustained swimming speed capability of a trout with a five inch fork length.

From Table 2, $V_{adult} \approx 4.1$ fps.

Assume adult trout has a 9" fork length.

$$\frac{L}{L_{adult}} = \frac{5}{9} = 0.55$$

$$\frac{V}{V_{adult}} = 0.64, \quad V \text{ of } 5'' \text{ fish} = (0.64)(4.1) \approx 2.6 \text{ fps}$$

Therefore a five inch trout has a sustained swimming capability of 2.6 fps.

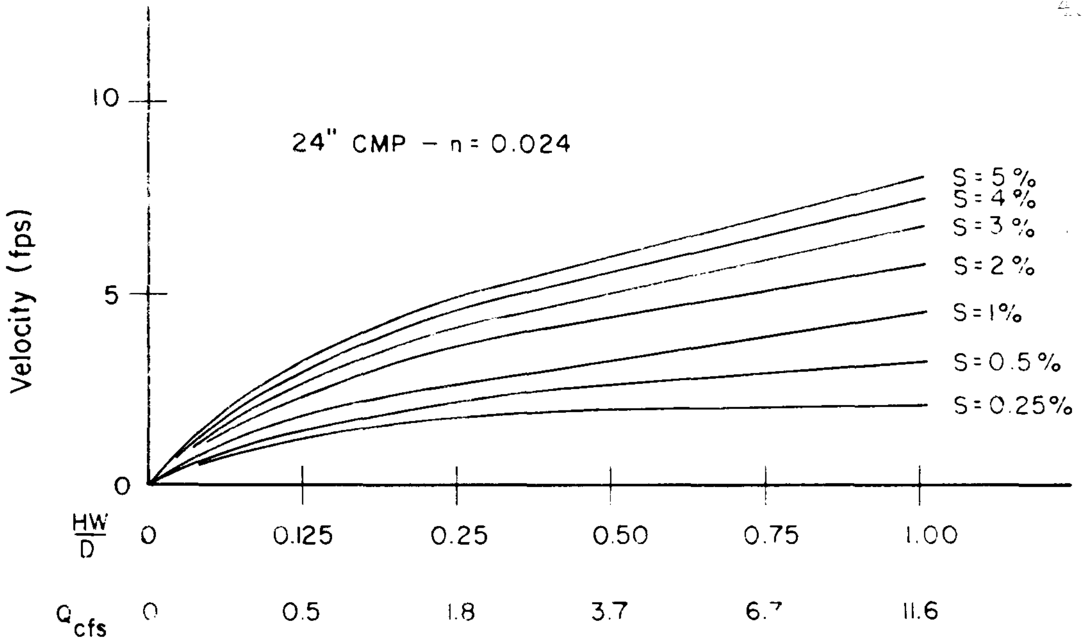


Figure 2 – Uniform Flow Velocity

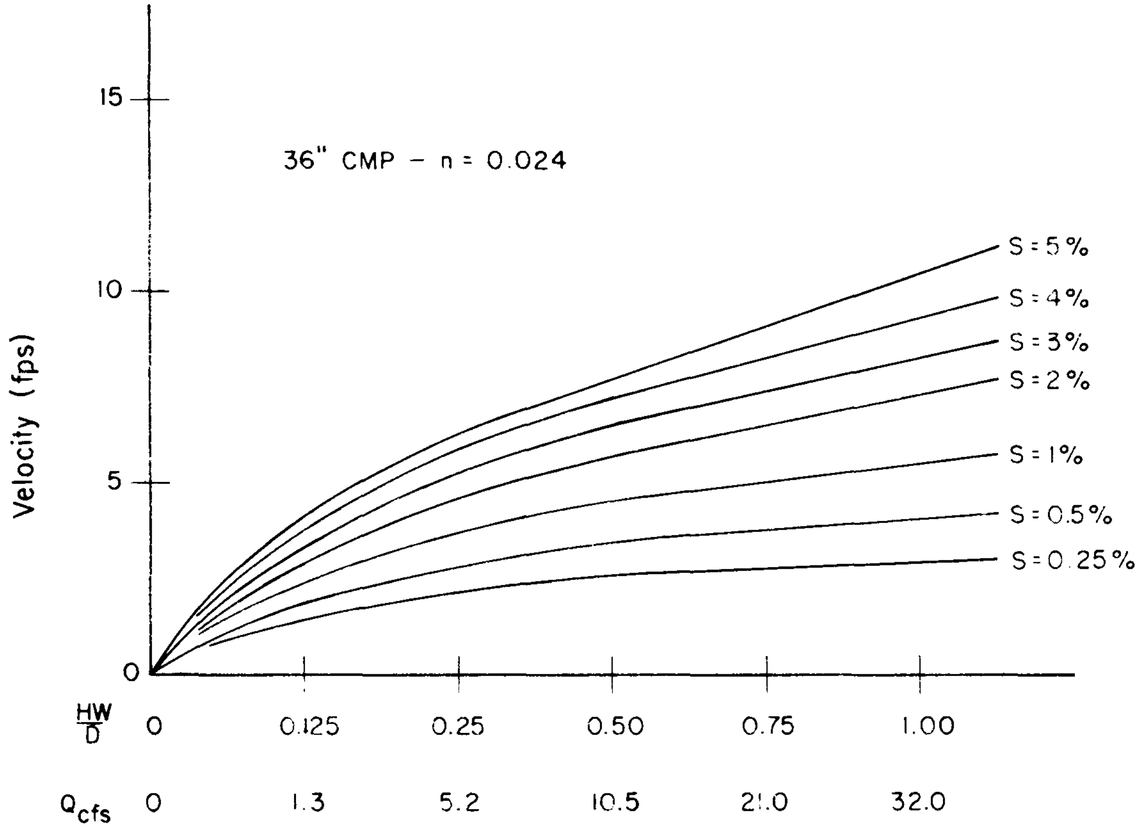


Figure 3 – Uniform Flow Velocity

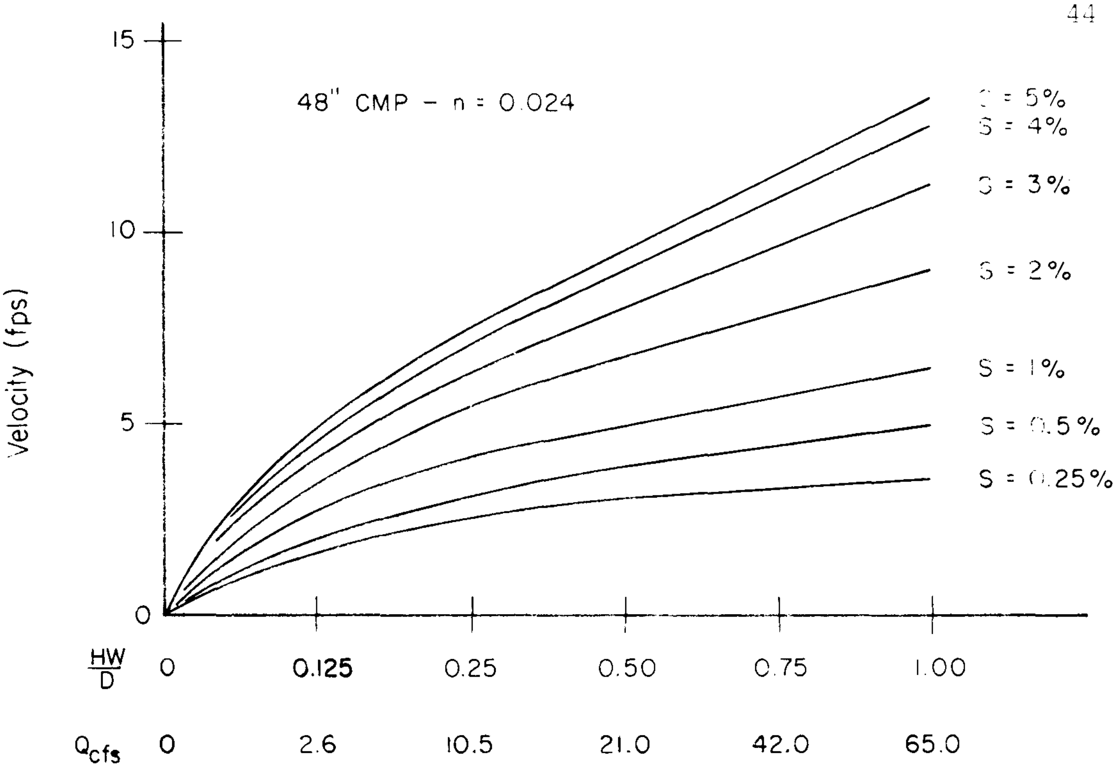


Figure 4 – Uniform Flow Velocity

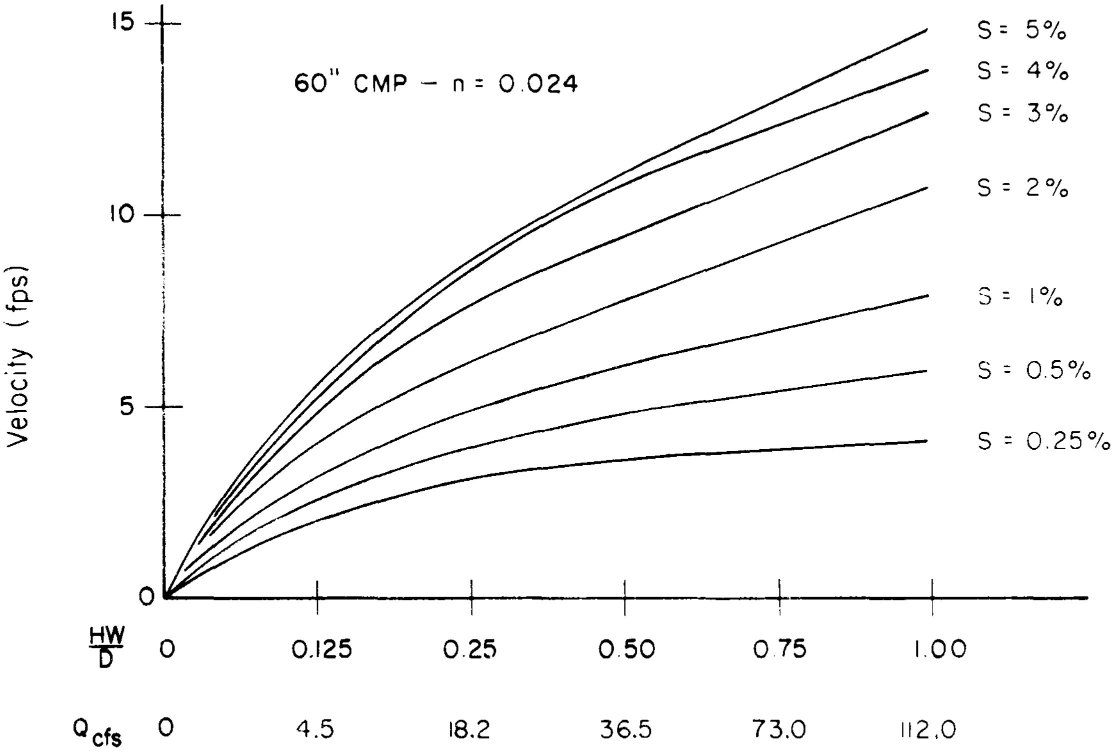


Figure 5 – Uniform Flow Velocity

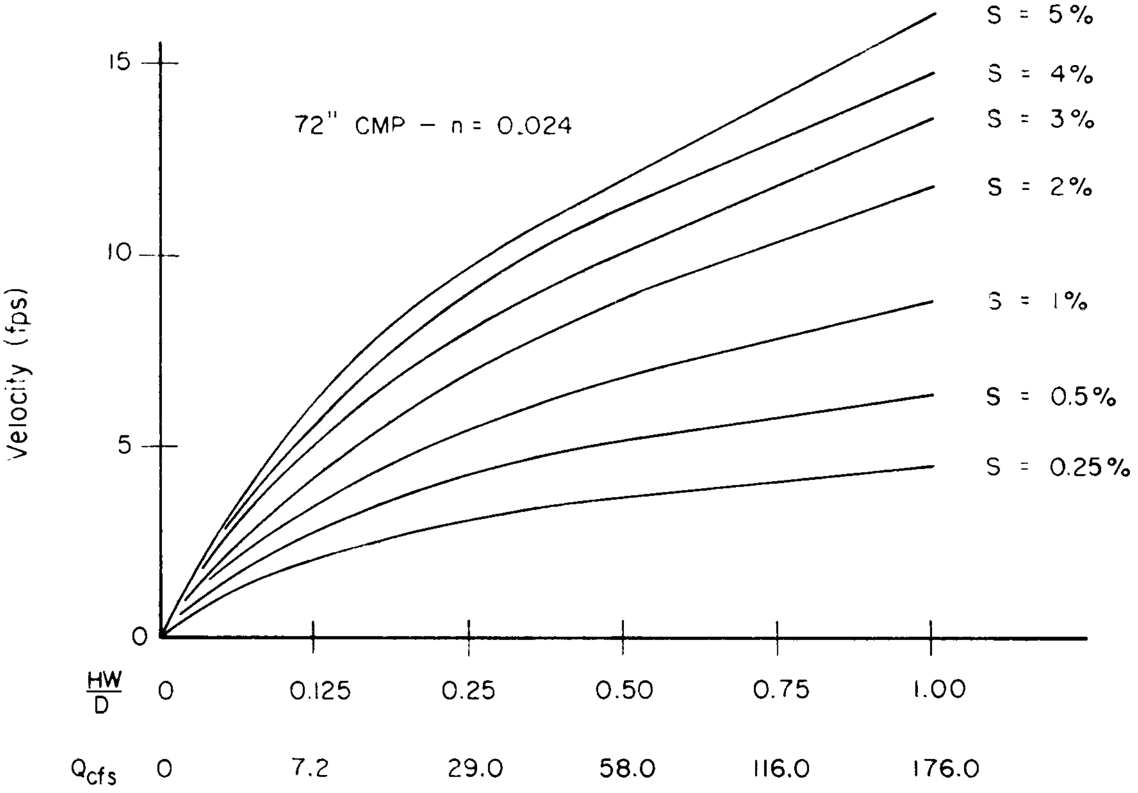


Figure 6 – Uniform Flow Velocity

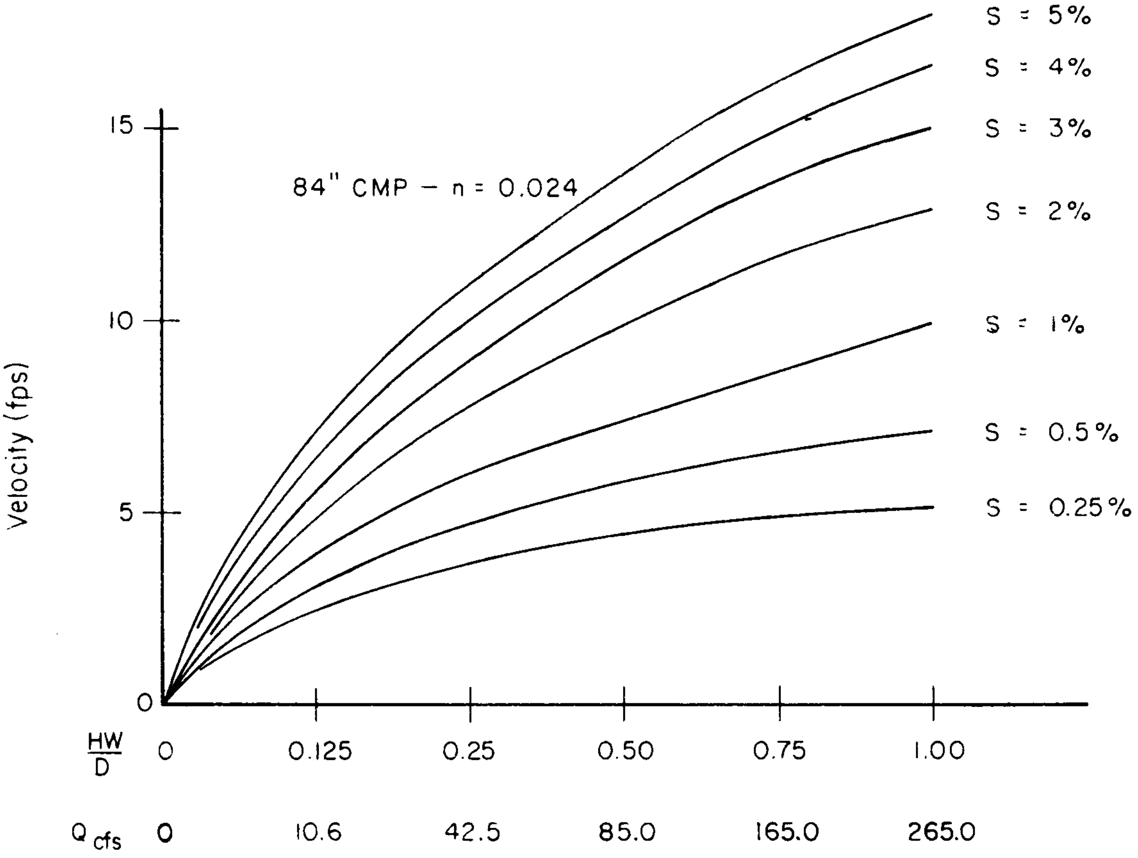


Figure 7 – Uniform Flow Velocity

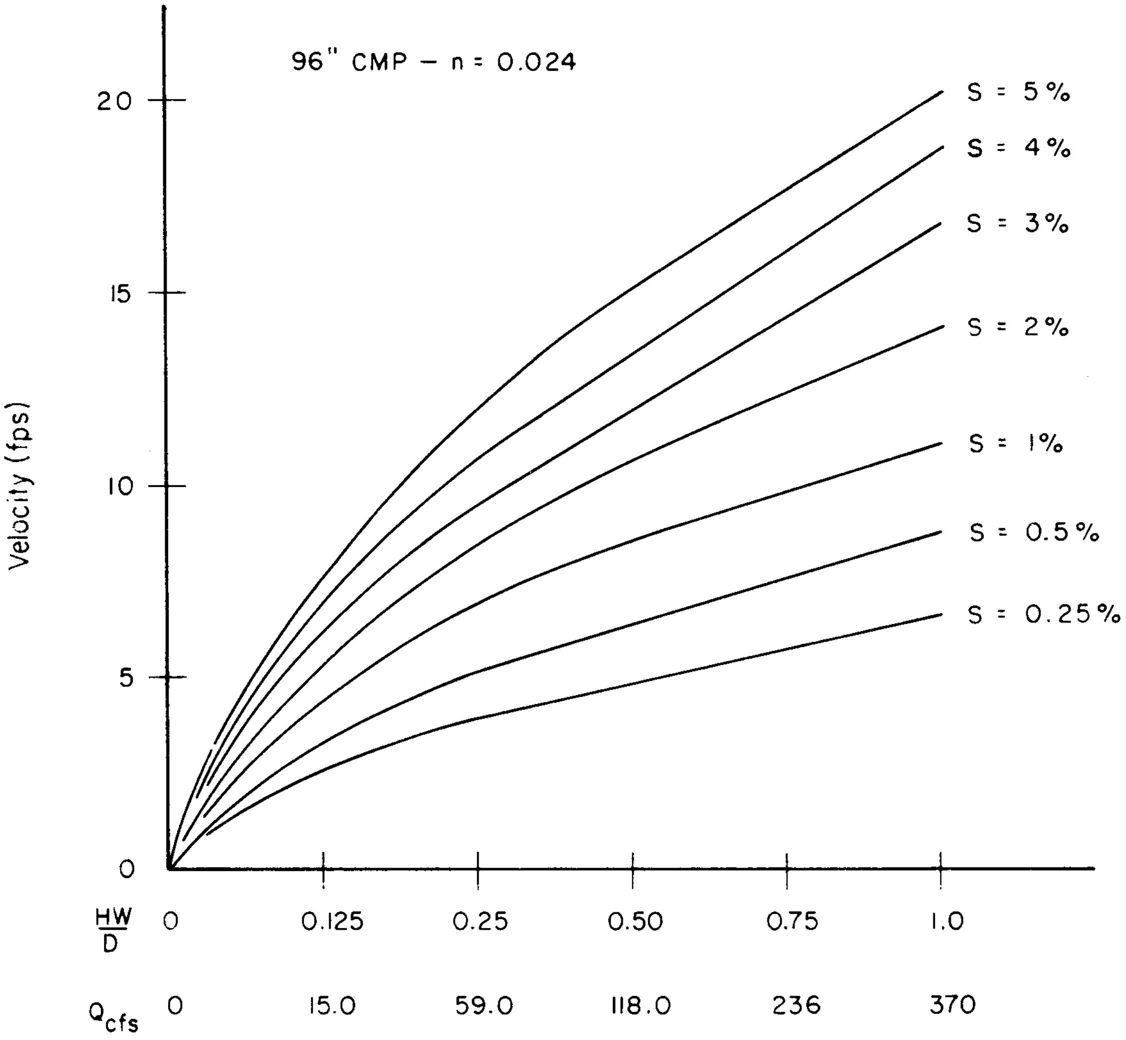
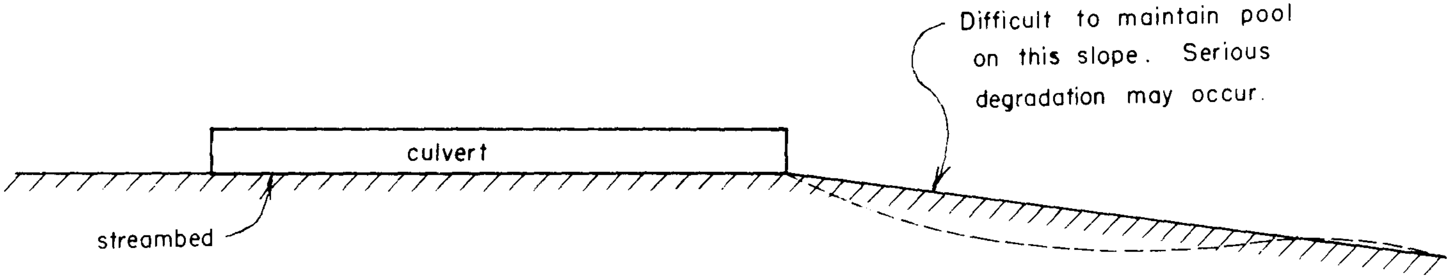
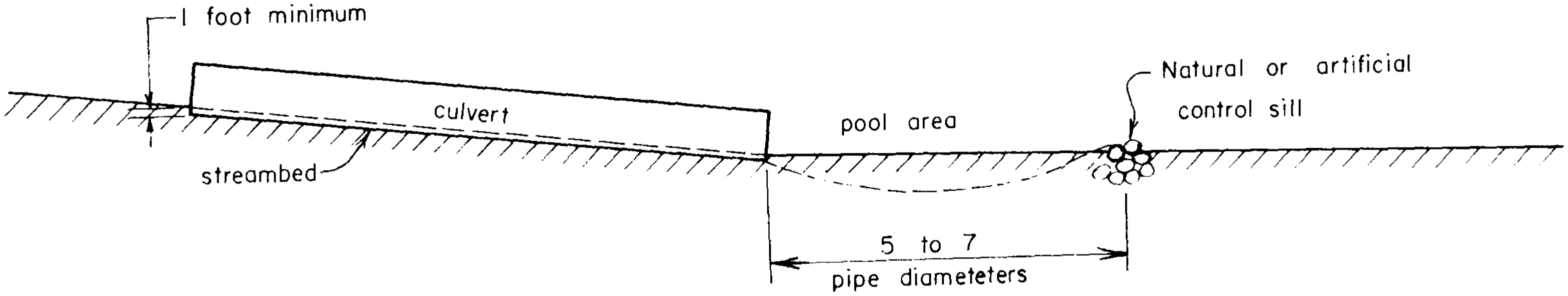


Figure 8 — Uniform Flow Velocity

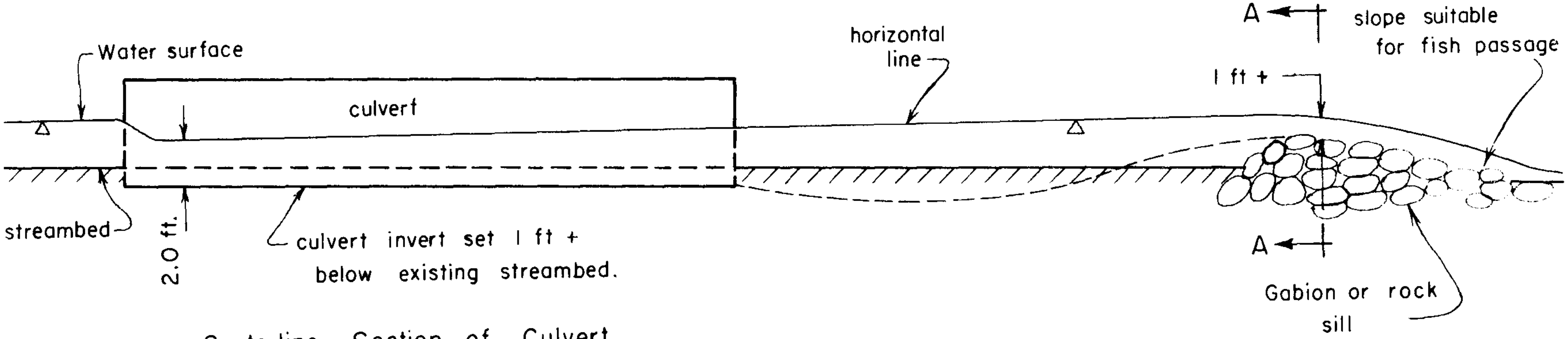


Unsatisfactory Location

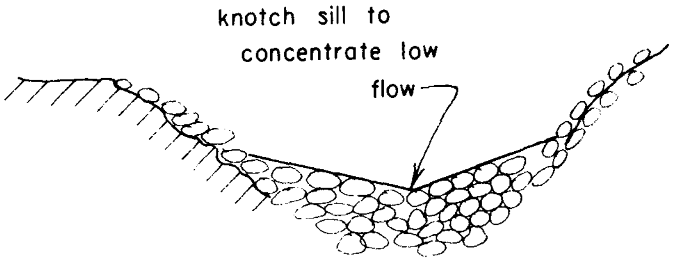


Satisfactory Location

Figure 9 — View Showing Culvert and Sill Details

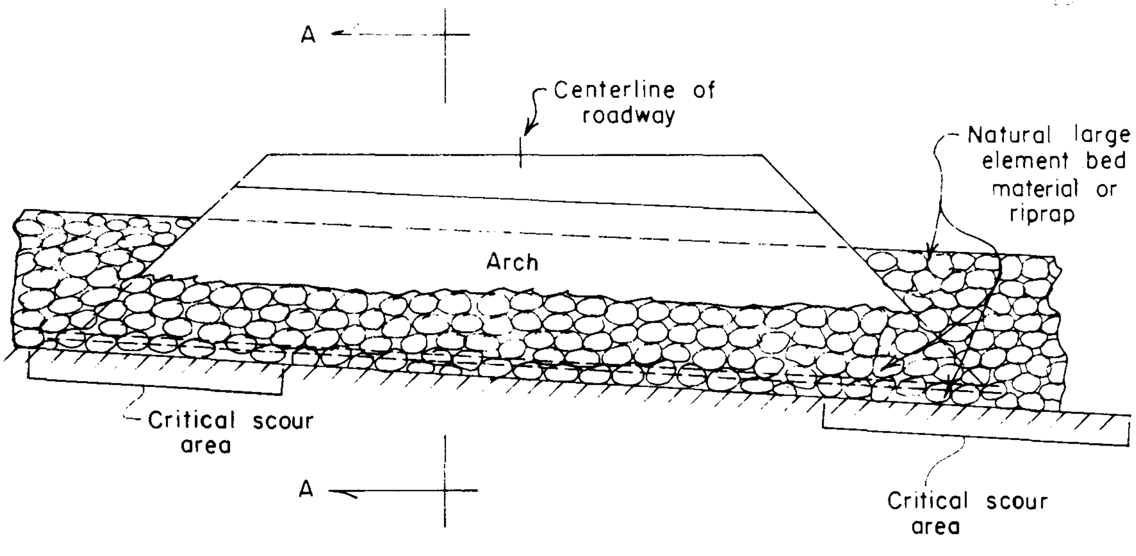


Centerline Section of Culvert

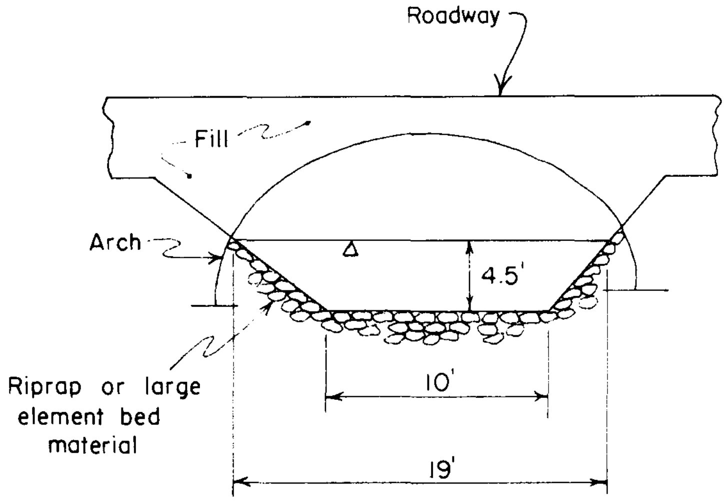


Section A-A

Figure 10 — Details for Backwater Sill at Culvert Site

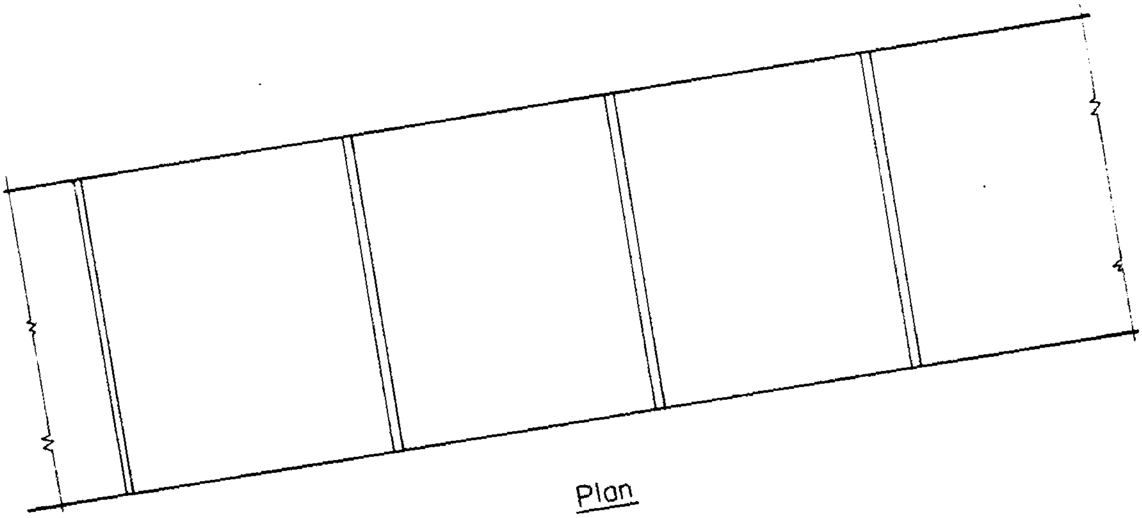


Centerline Section

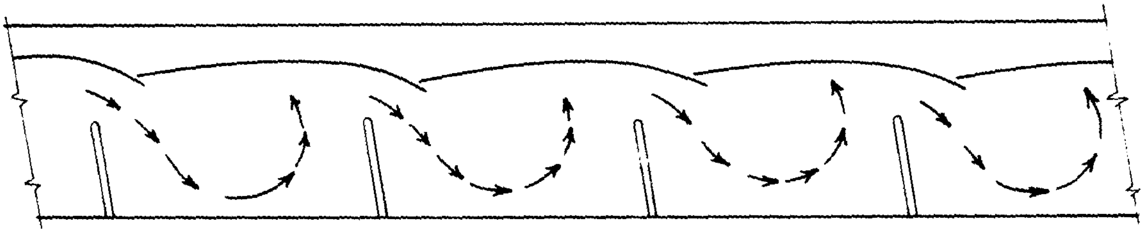


Sec. A–A

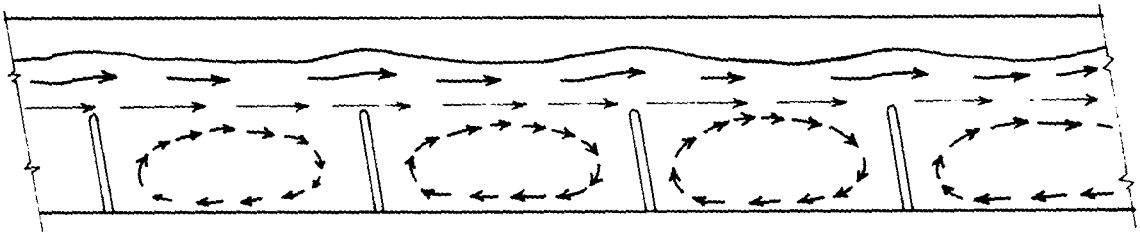
Figure 11 — Arch Culvert Designed for Fish Passage



Plan

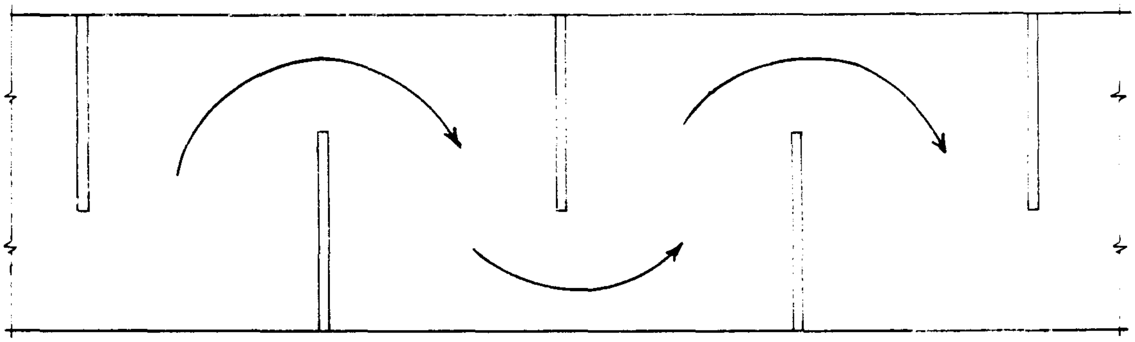


Plunging Flow in Profile

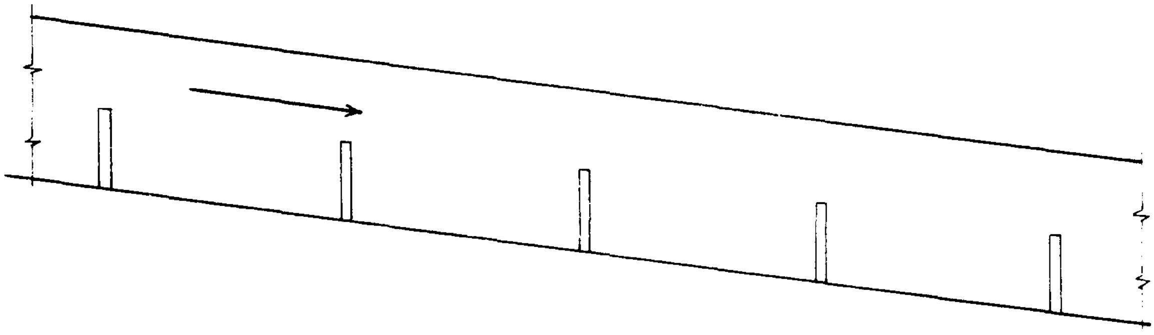


Streaming Flow in Profile

Figure 12 — Pool and Weir Fishway

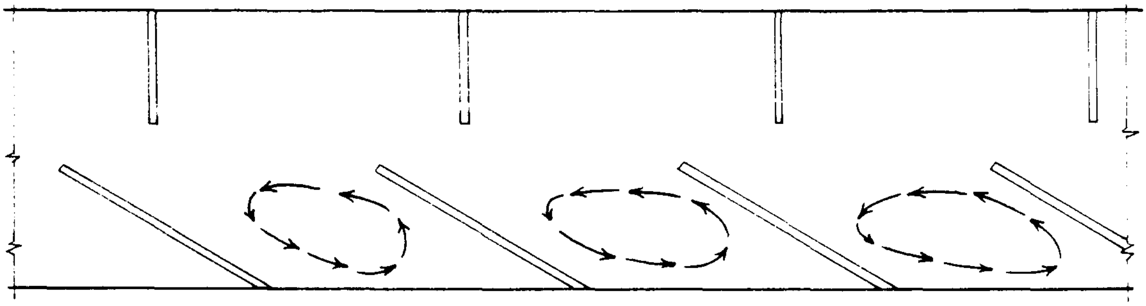


Plan

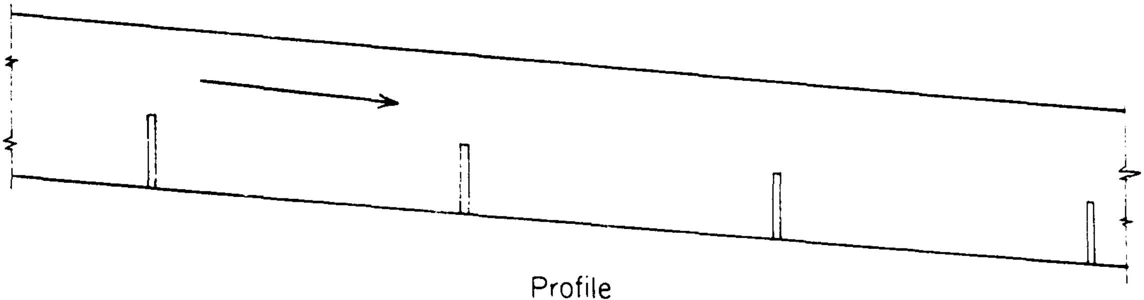


Profile

Figure 13 — Alternate Paired Baffle Spillway



Plan



Profile

Figure 14 — Offset Baffle Spillway

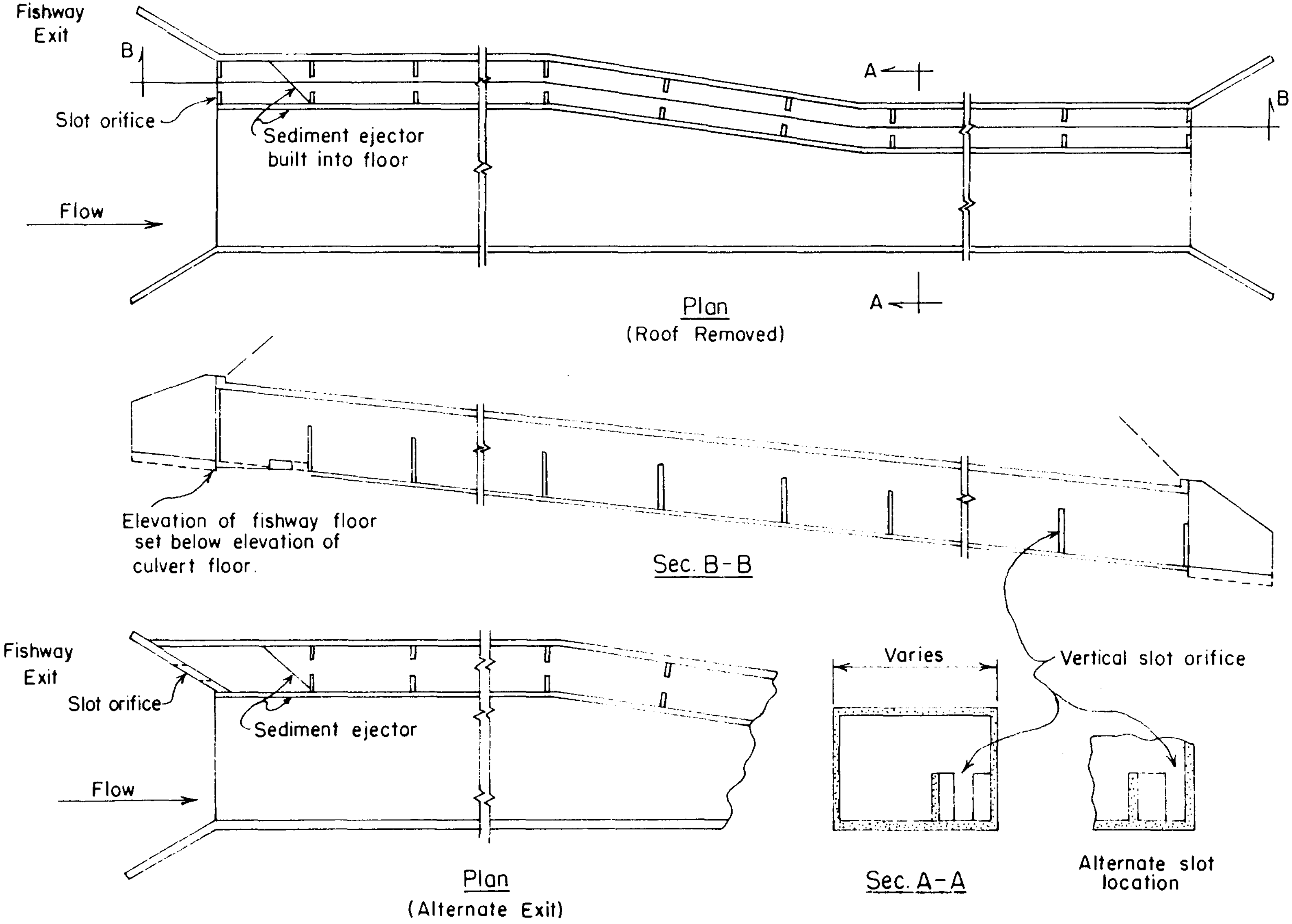
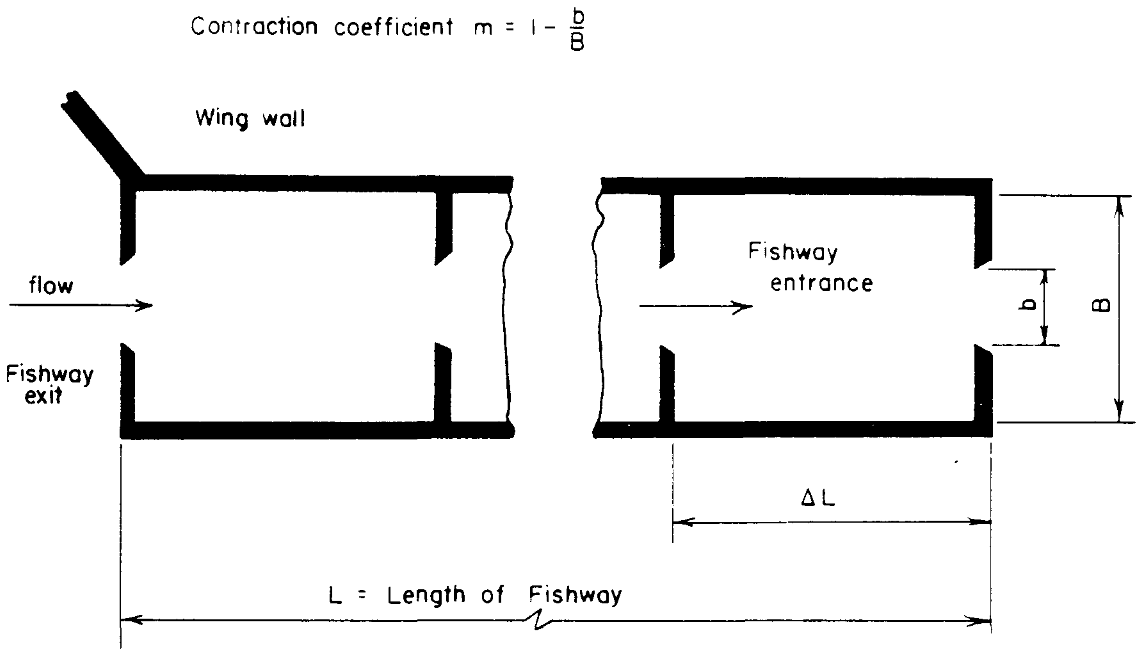
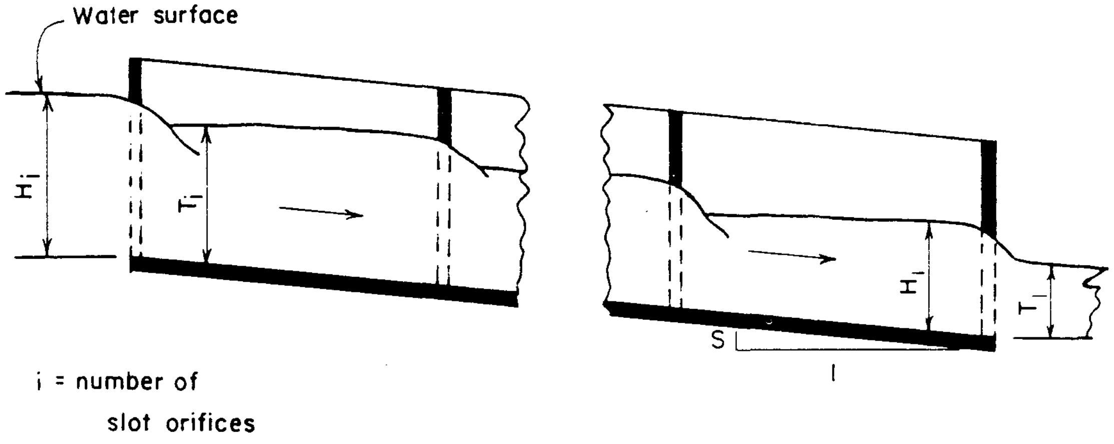


Figure 15 — Box Culvert With Vertical Slot Orifice Fishway



Plan



Centerline Elevation

Figure 16 — Definition Sketch for Slot Orifice Fishway

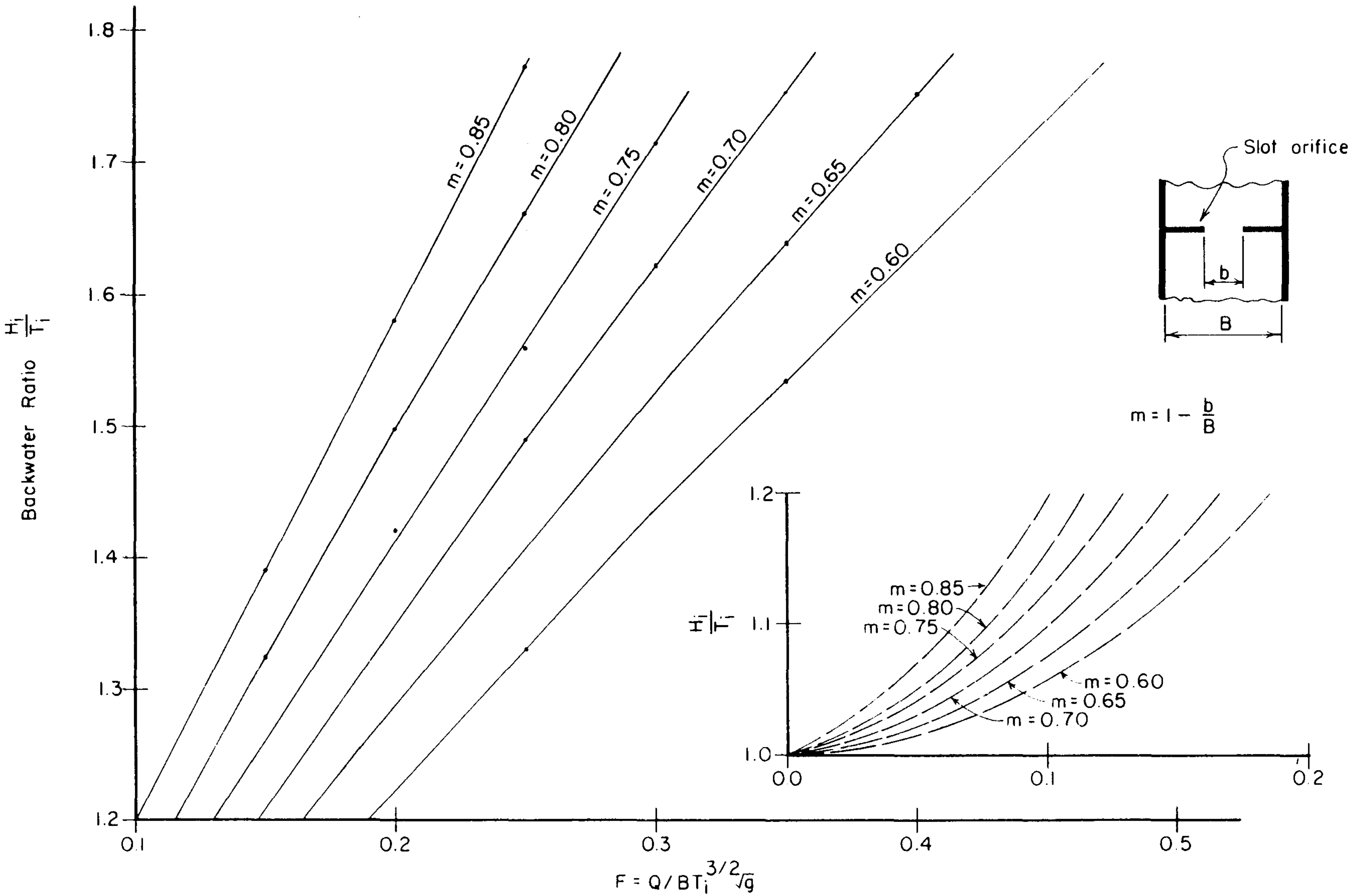
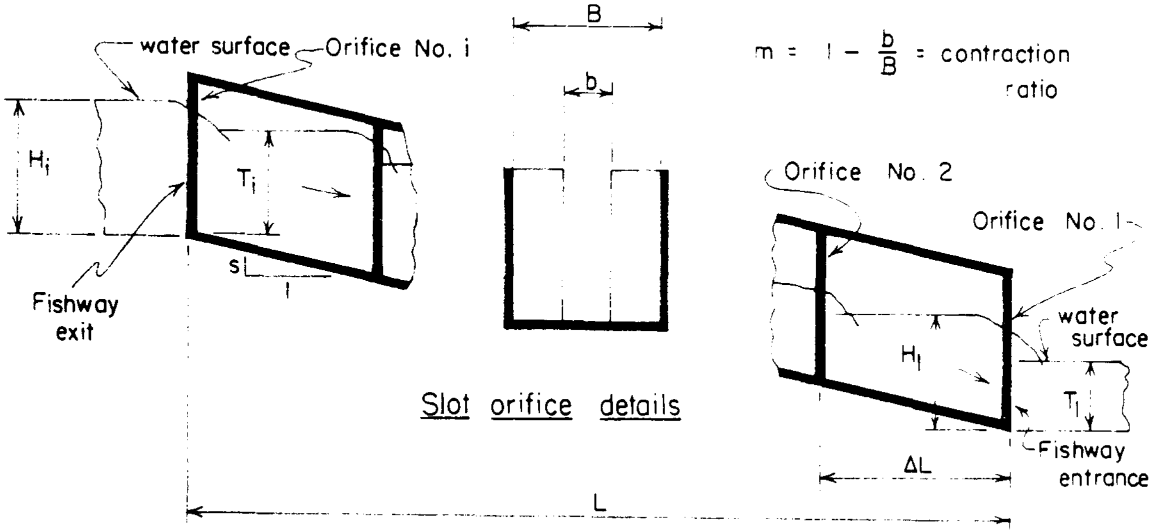


Figure 17 — Rating Curve for a Slot Orifice



ϕ =

L =

s =

B =

m =

m_s =

i =

ΔL =

T_i =

H_i =

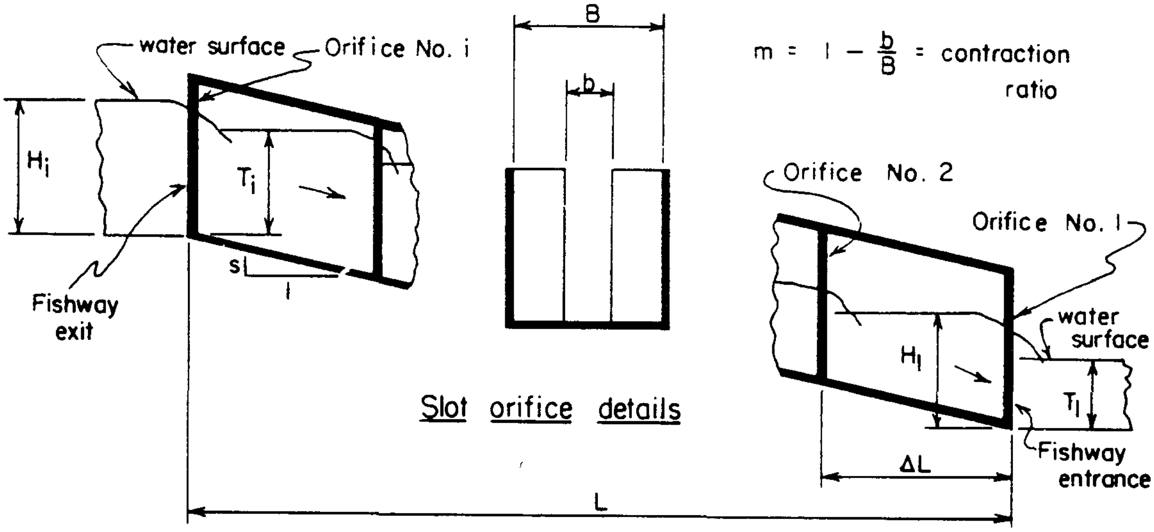
Q =

Q/B(5.67) =

s (ΔL) =

1	2	3	4	5	6	7	8
Orifice	T_i	$T_i^{3/2}$	$\frac{Q}{B\sqrt{g}\,T_i^{3/2}}$	$\frac{H_i}{T_i}$	H_i (computed)	$T_{i+1} = H_i - s(\Delta L)$	$V_i = \frac{Q}{B(1-m)t_i}$
i	ft	$ft^{3/2}$			ft	ft	fps

Figure 18 — Computation Sheet for Slot Orifice Fishway Design



$m = 1 - \frac{b}{B}$ = contraction ratio

ϕ = 90°

L = 50 ft

s = 0.01 ft/ft

B = 3.00 ft

m = 0.70

m_s = NOT APPLICABLE

i = 6

ΔL = 10 ft

T_i = 2.00 ft

H_i = 4.00 ft

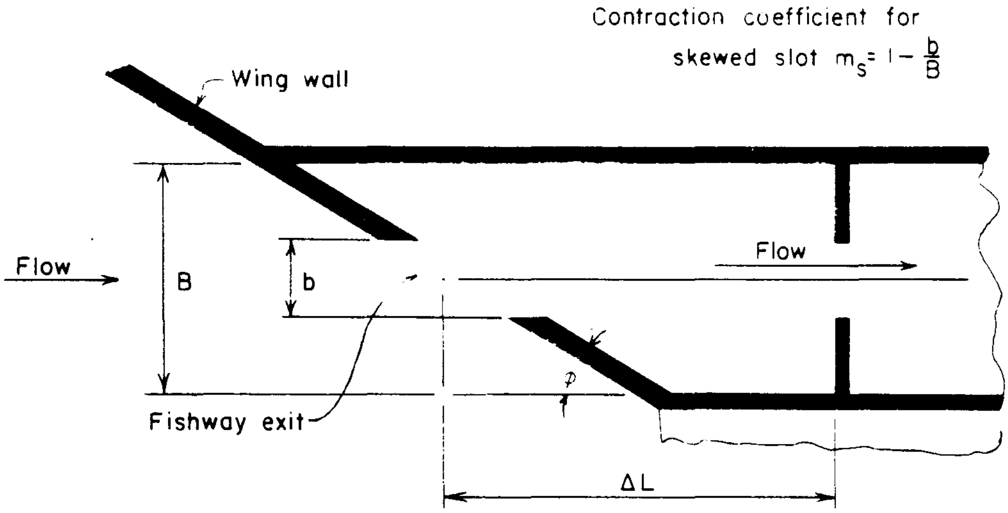
Q = 10.2 cfs

Q/B(5.67) = 0.5996

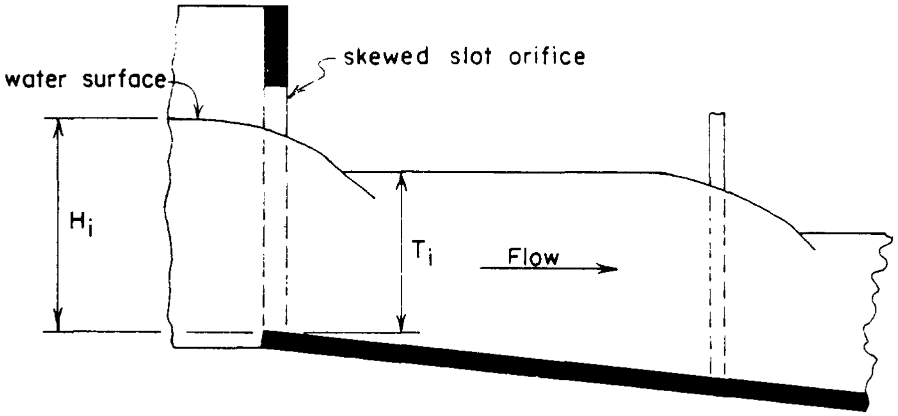
s (ΔL) = 0.10 ft

1	2	3	4	5	6	7	8
Orifice i	T_i ft	$T_i^{3/2}$ $ft^{3/2}$	$\frac{Q}{B\sqrt{g}\,T_i^{3/2}}$	$\frac{H_i}{T_i}$	H_i (computed) ft	$T_{i+1} = H_i - s(\Delta L)$ ft	$V_i = \frac{Q}{B(1-m)t_i}$ fps
						2.00	5.7
1	2.00	2.828	0.2120	1.382	2.764	2.664	4.3
2	2.664	4.348	0.1379	1.180	3.143	3.043	3.7
3	3.043	5.310	0.1129	1.123	3.417	3.317	3.4
4	3.317	6.042	0.0992	1.098	3.642	3.542	3.2
5	3.542	6.666	0.0899	1.080	3.825	3.725	3.0
6	3.725	7.190	0.0833	1.071	3.989		
	3.989	≈ 4.00	∴ Q ≈	10.2 cfs	O.K		

Figure 19 — Computation Sheet for Slot Orifice Fishway Design



Plan



Elevation

Figure 20 — Definition Sketch for Skewed Slot Orifice Fishway Exit

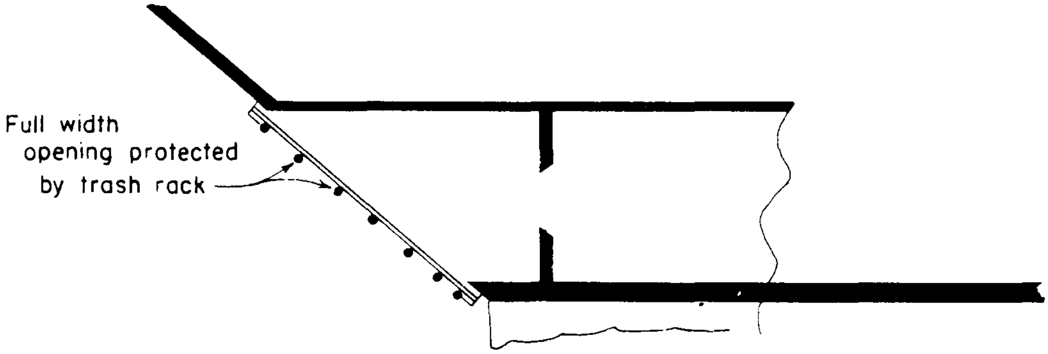


Figure 21 — Preferred Entrance Arrangement for Fishway Exit Constructed in Culvert Wing Wall

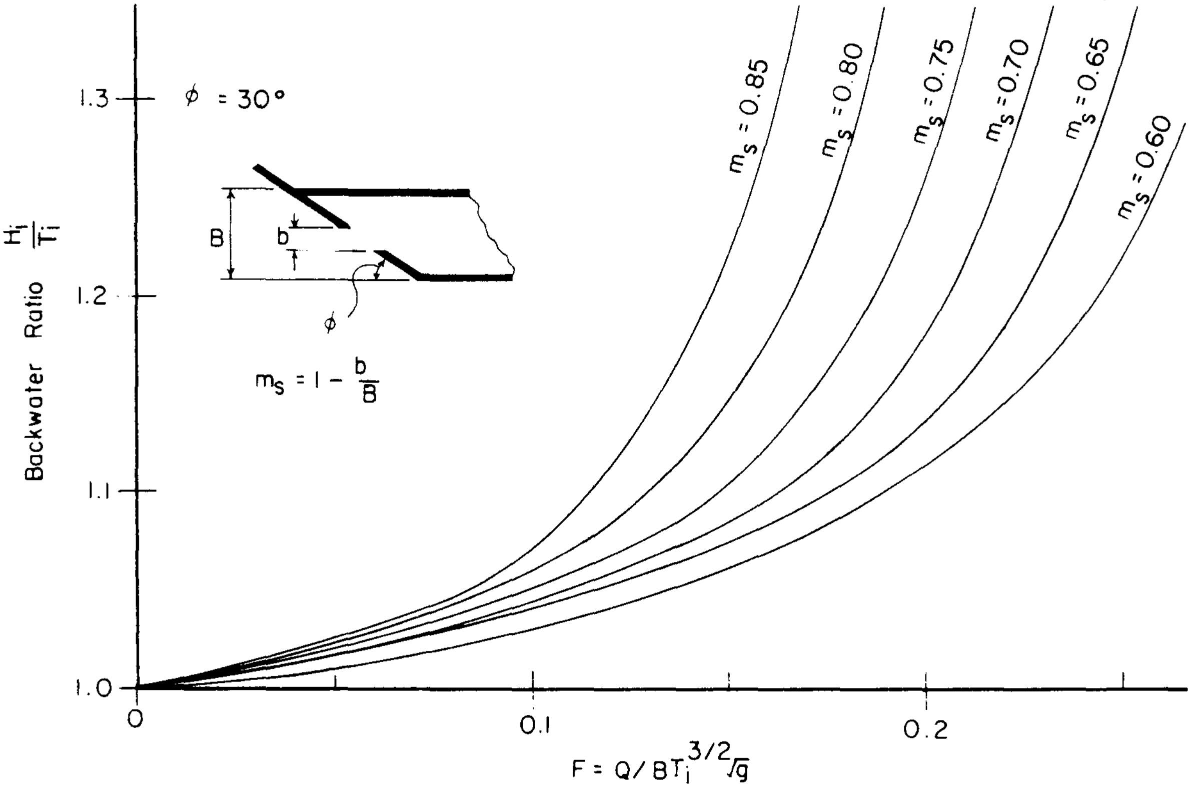


Figure 22 — Rating Curve for Skewed Slot Orifice Fishway

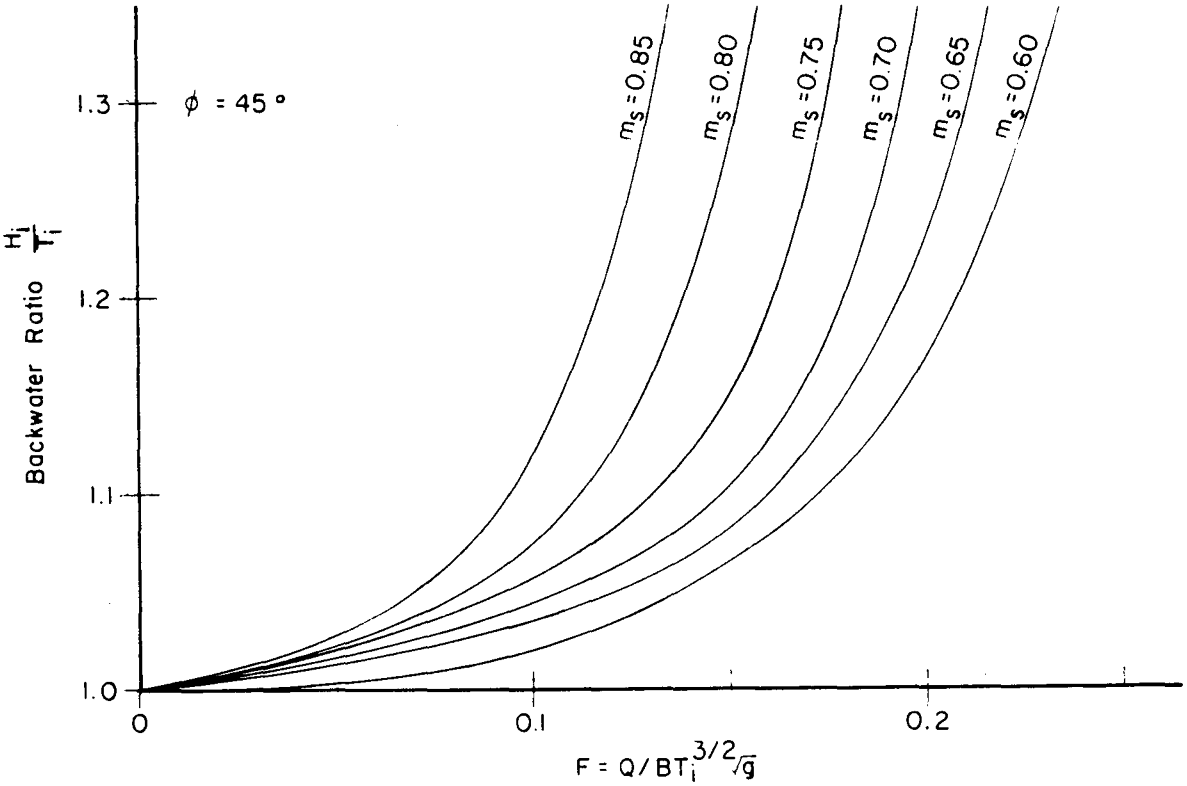


Figure 23 — Rating Curve for Skewed Slot Orifice Fishway

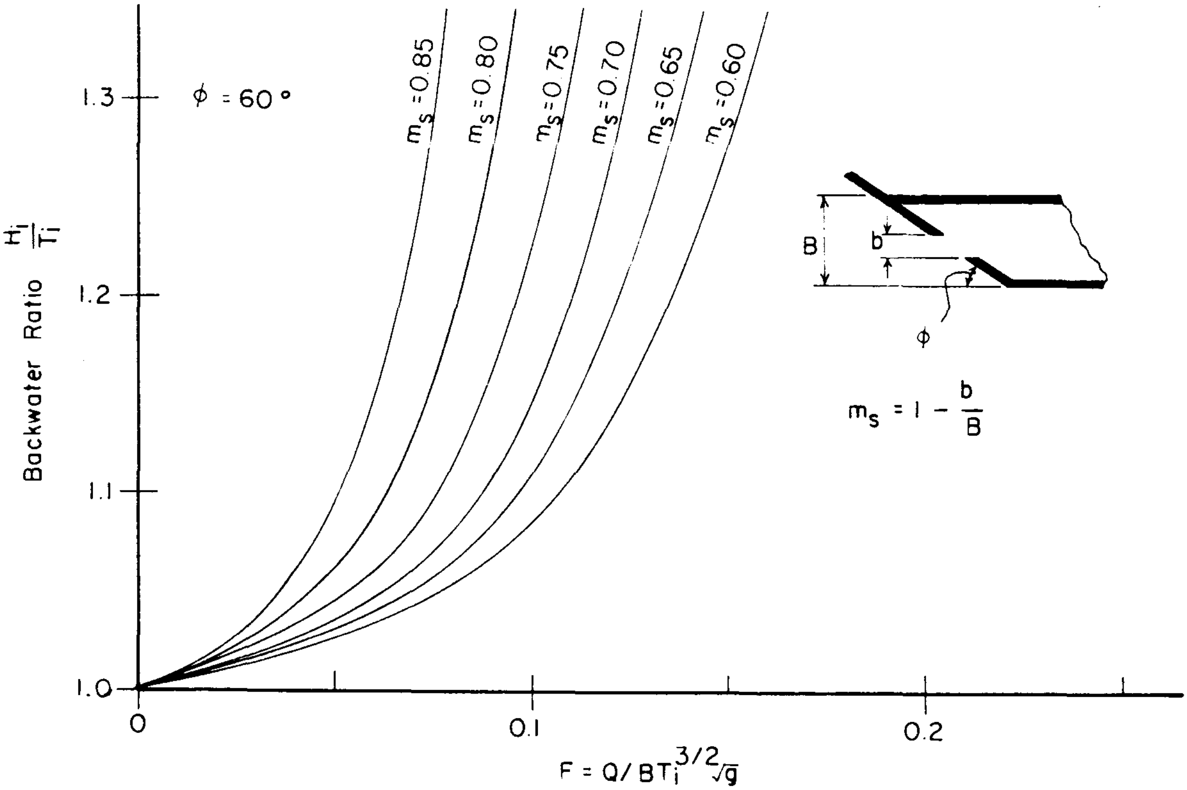


Figure 24 — Rating Curve for Skewed Slot Orifice Fishway

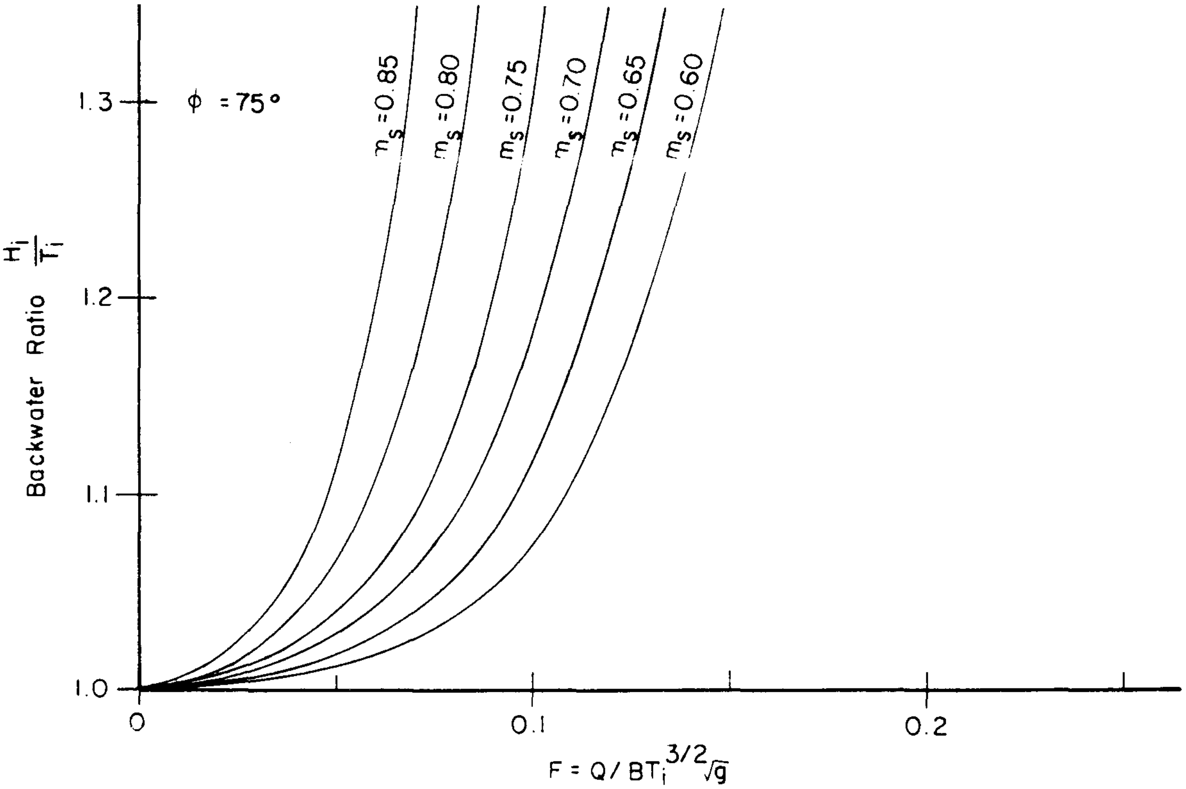
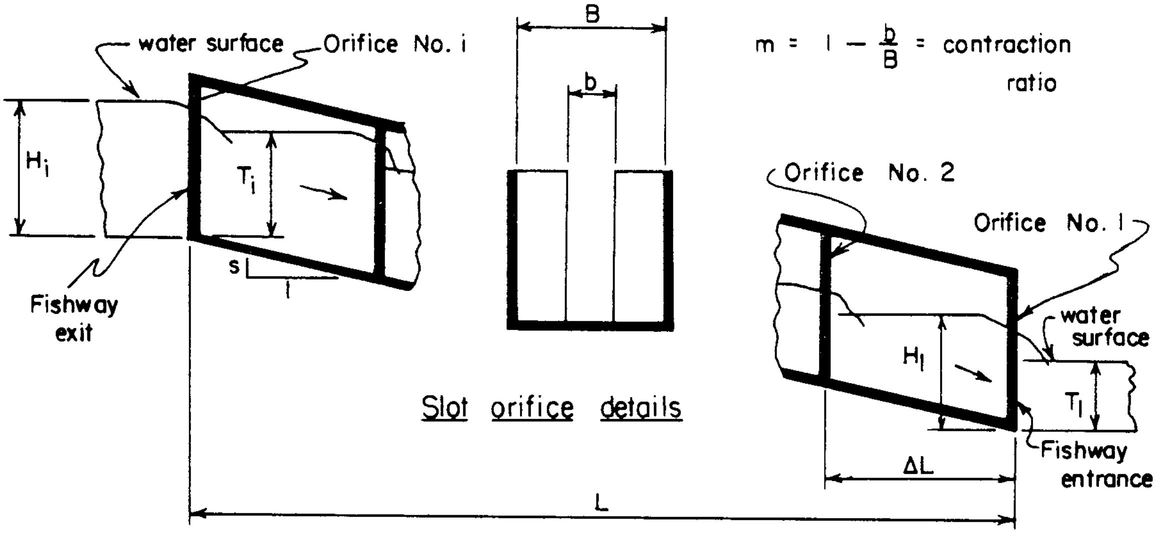


Figure 25 — Rating Curve for Skewed Slot Orifice Fishway



ϕ = 45°

L = 60 ft

s = 0.05 ft/ft

B = 3.00 ft

m = 0.70

m_s = 0.75

i = 7

ΔL = 10 ft

T_i = 2.00 ft

H_i = 3.85 ft

Q = 14.3 cfs ?

Q /B(5.67) = 0.8407

s (ΔL) = 0.5 ft

1	2	3	4	5	6	7	8
Orifice i	T_i ft	$T_i^{3/2}$ ft$^{3/2}$	$\frac{Q}{B\sqrt{g}\,T_i^{3/2}}$	$\frac{H_i}{T_i}$	H_i (computed) ft	$T_{i+1} = H_i - s(\Delta L)$ ft	$V_i = \frac{Q}{B(1-m)t_i}$ fps
						2.00	7.9
1	2.00	2.828	0.2972	1.613	3.225	2.725	5.8
2	2.725	4.498	0.1869	1.312	3.575	3.075	5.2
3	3.075	5.392	0.1559	1.222	3.758	3.258	4.9
4	3.258	5.881	0.1429	1.190	3.877	3.377	4.7
5	3.377	6.206	0.1355	1.170	3.958	3.458	4.6
6	3.458	6.430	0.1307	1.162	4.014	3.514	
7	3.514	6.587	0.1276	1.090	3.830		
		3.83 ≈ 3.85 ∴		Q = 14.3 CFS		O.K.	

Figure 26 – Computation Sheet for Slot Orifice Fishway with Skewed Entrance Slot

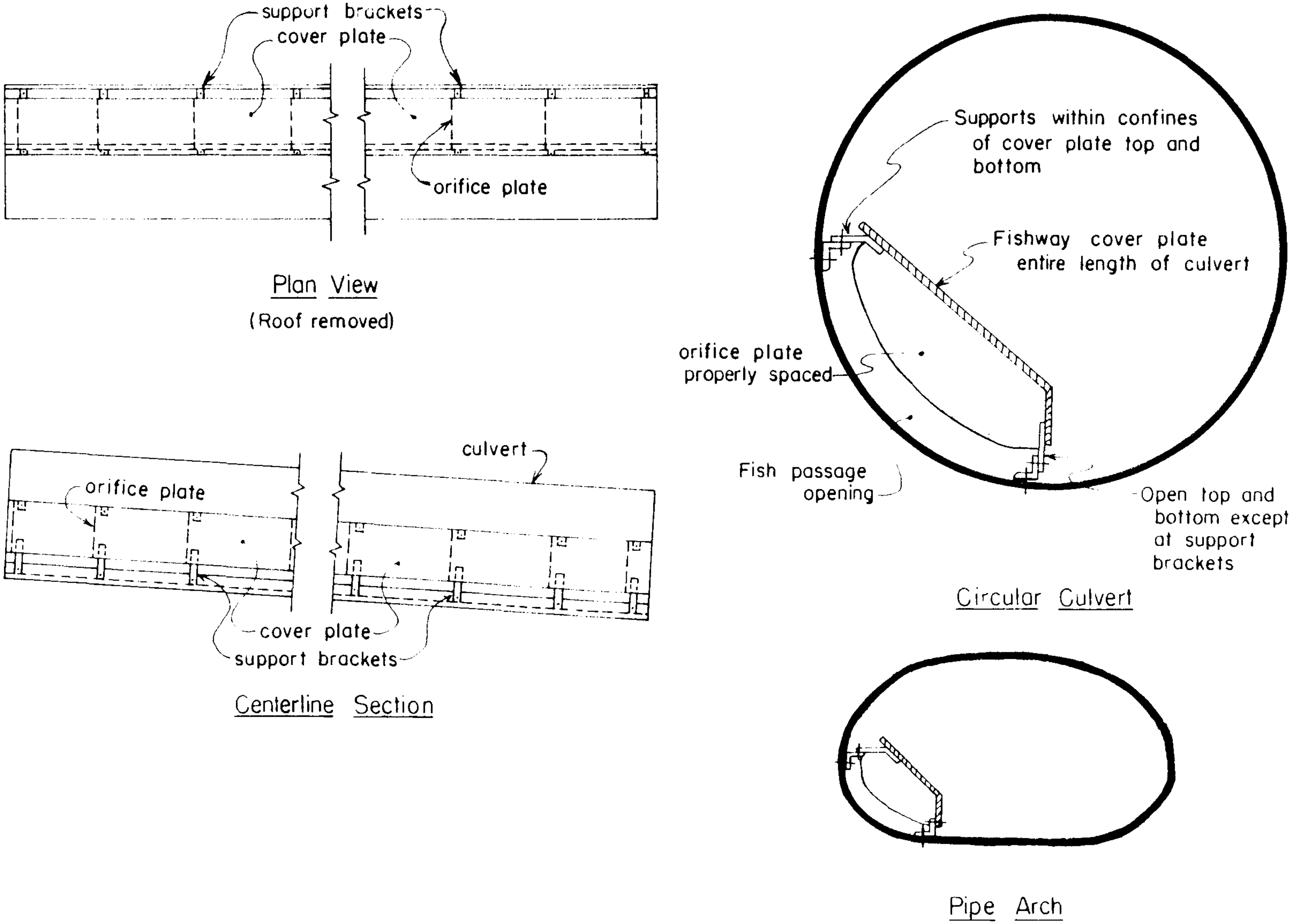
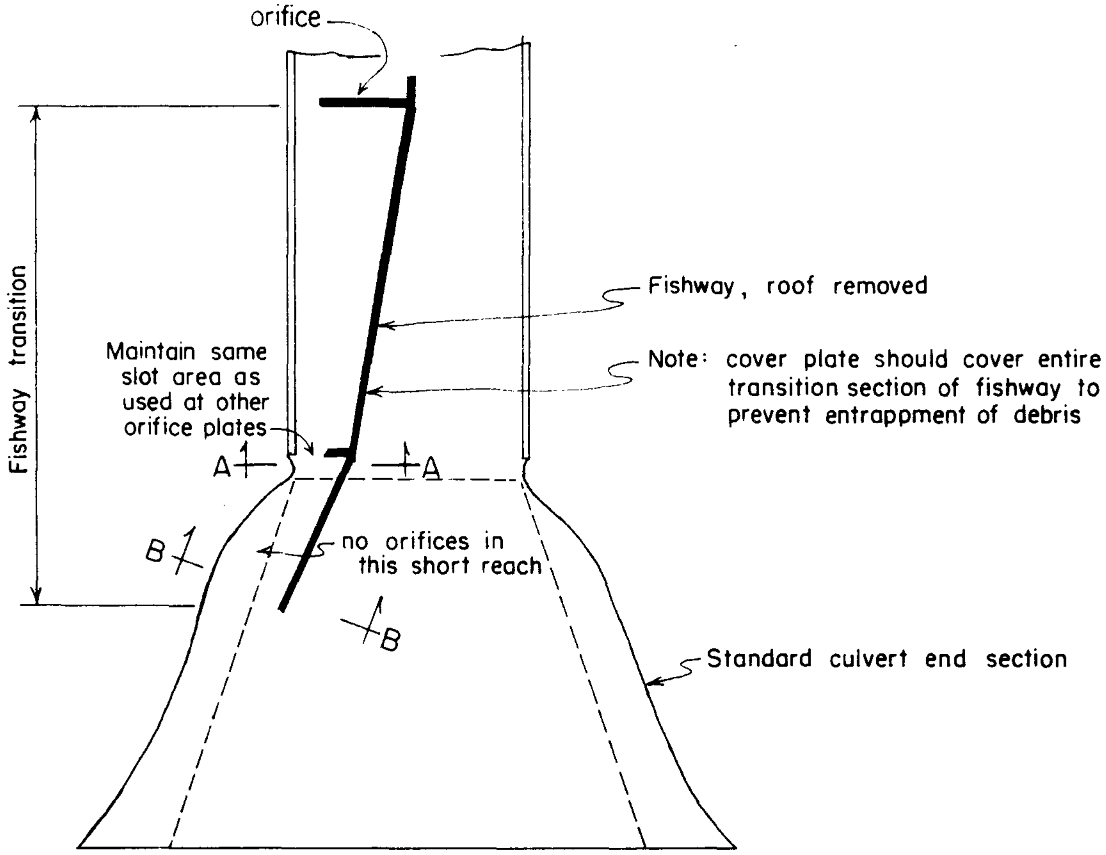
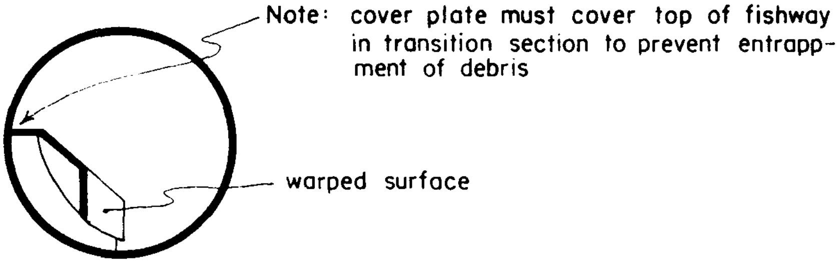


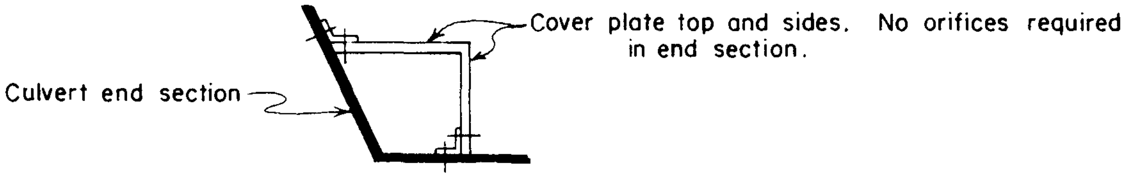
Figure 27 — Proposed Orifice Fishway for Culverts or Pipe Arch



Plan View of Fishway Exit



Section A – A



Section B – B

Figure 28 — Special Fishway Exit for Orifice Fishway