# A PROPOSED CORRECTION OF MIGRATORY FISH PROBLEMS AT BOX CULVERTS

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Upstream passage of migratory fish through culverts long has been a critical fisheries problem in Washington. Many small streams which can be crossed with a culvert rather than a more expensive bridge, account for a significant portion of the state's salmon producing potential. Some species of salmon, particularly silver and chum, seek the smaller streams and tributaries for spawning. Thus, each stream is important for its contribution to the gross production. In past years many of these small streams have been blocked to salmon migration and culverts are one of the principal blocks. Poorly placed or designed culverts present a problem, the correction of which is vital to the maintenance of present spawning areas and the rehabilitation of areas no longer accessible because of past culvert failures.

To facilitate fish passage the Department of Fisheries recently set up simple culvert standards; namely, a culvert grade should not exceed one-half of one percent, and the invert (bottom) of the culvert at the outfall should be one-half foot below the stream bed. In most past construction, state and county specifications have not met present standards since they were fitted to the local topography and grade alignment. Also, fisheries problems were often ignored or not thought of when culverts were proposed and built.

A culvert is normally expected to pass a maximum runoff from its drainage area. The size of a culvert for a particular drainage area is often chosen on the basis of rather inadequate runoff formulae. These empirical formulae are based on the area involved, the maximum intensity of rainfall, and are generally reinforced by some constant intended to compensate for the shape and slope of the drainage area and also for the region in which the drainage area is located. The results obtained are used in other formulae to compensate for the maximum runoff conditions which might occur once in 50 or 100 years. In some cases, however, designers have the benefit of many years of stream gaging records. The drainage area and the 50 or 100-year flood is carefully calculated only when the failure of the culvert to discharge properly would endanger costly structures. Consequently, most of

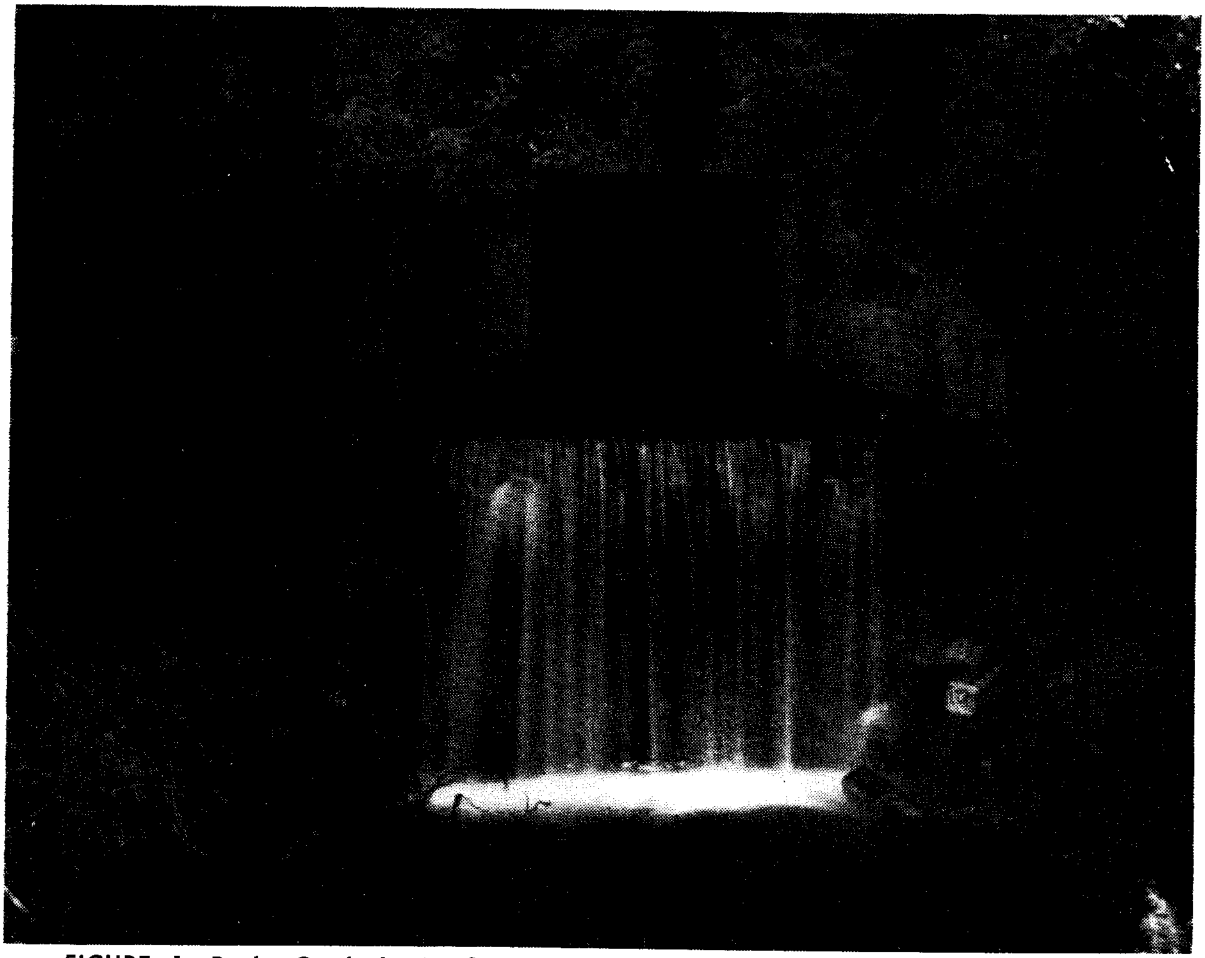


**FIGURE 1—Bagley Creek showing 8-foot stream bed erosion and scouring underneath culvert apron.**

the culverts built are still chosen for size on the basis of these old empirical formulae or by rule of thumb derived from similar drainage areas.

A common type of culvert which interferes with fish passage is one which has a steep slope, or one in which the invert at the out-fall is above the stream bed. Steep slopes cause excessive velocities and shallow depths at normal and low flows. An invert above the stream bed soon causes erosion in the stream bed—in certain instances, lowering the stream bed immediately below the culvert by as much as 12 feet. This type of erosion may be seen in Siebert and Bagley creeks, both near Port Angeles (Figures 1 and 2). The excessive velocities created by steep slopes must be dissipated in the area immediately downstream. These higher velocities give a high kinetic energy content to the water which, in part, is expended in the movement of gravel until the velocities decelerate to those of the normal stream. Steep slopes and improperly placed inverts are the direct cause of many culverts being under-cut and the resulting failure of the out-fall or apron of the culvert. When carried to the extreme, these conditions will result in the complete block of migratory fish. Even when not extreme, they may delay the fish and thus interfere with their spawning.

## Previous Attempts at Culvert Correction

Constructing a fish passage device through a culvert essentially opposes the entire basic idea of the culvert. The culvert is made to pass water downstream at the highest possible rate, whereas the fish passage facility built

**FIGURE 2—Siebert Creek showing 12-foot erosion of stream bed below culvert and correctional fish ladder installed in one barrel of the culvert. Bagley and Siebert Creeks are on the Olympic peninsula near Port Angeles.**

into it must afford a relatively easy upstream path for the migrating fish. On the one hand, greater runoff can be discharged through a smaller and less costly culvert if it is as small as possible and is installed at a maximum gradient; on the other, optimum fish passage requires that the culvert be placed at a gradient approaching zero or that velocities be slowed by some type of energy dissipation device.

Two common fish passage devices used for that purpose in the past have not been very successful. One type is a series of low 6 to 8-inch barriers extending across the bottom of the culvert at right angles to its length, in imitation of a pool and weir fishway (Figure 3). It was not successful due to its shallow depth and tendency for the water to go to a streaming flow at a relatively low discharge. A successful pool and weir fishway requires complete dissipation of the kinetic energy content of the water in each pool, and sufficient water depth for the fish to jump the barriers. Neither of these requirements is met by the low barrier fishway. Figure 4 illustrates plunging and streaming flows. Another type is an alternate barrier designed to swing the low flow back and forth across the culvert bottom (Figure 5). The purpose of this device is to increase the length and decrease the slope of the water's path, thereby decreasing the velocity. This fishway is also unsuccessful because it makes a tortuous path for the fish to swim at low flows and soon drowns out when the flow increases slightly.

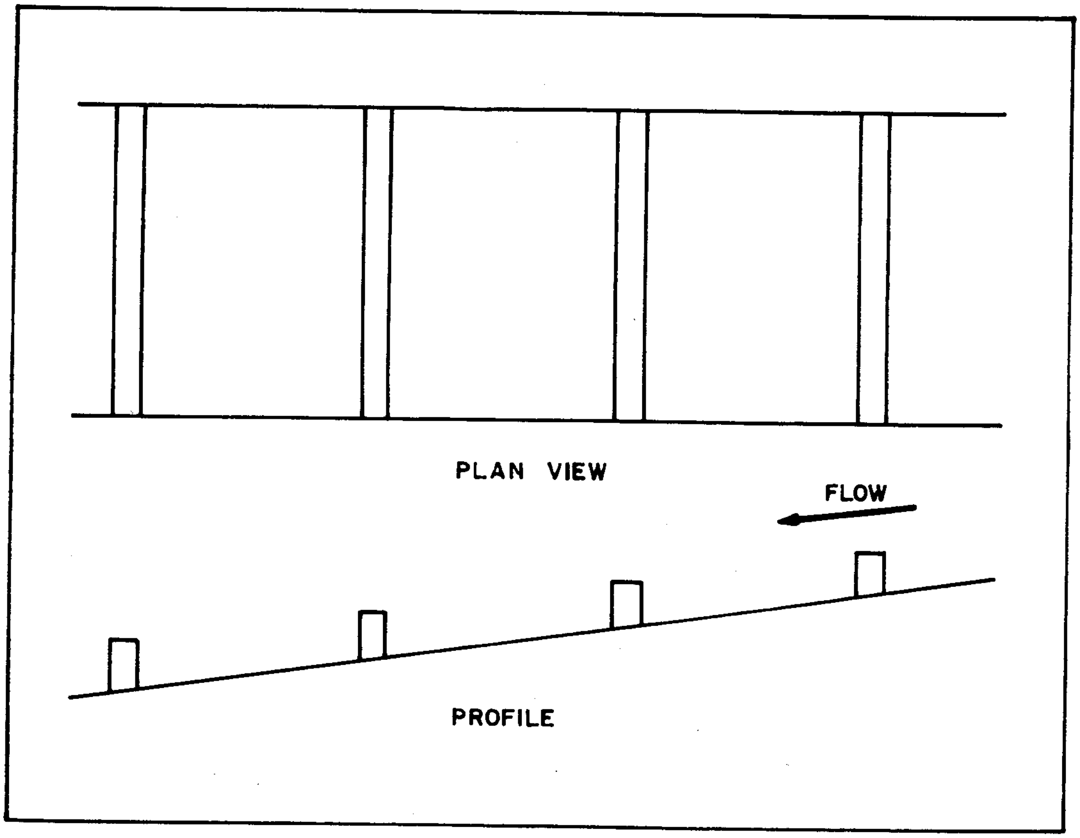



FIGURE 3—Low barrier culvert baffles—ineffective for fish passage.

# Model Culvert Studies

The overall problem of correcting culverts to provide optimum fish passage conditions is a major one from the points of both basic solution and application in the field. Various box culverts in use include a range of gradients up to 3 percent and widths to 10 feet. Because the type of fish-passage barrier now commonly used has not been too successful and better designs are unavailable, a special study to overcome these inadequacies was initiated by the Department of Fisheries. Incorporated in the study were basic criteria which are essential in the design of any fishway.

## Fishway Criteria

The present criteria for fish passage devices require that certain conditions be present in order to pass fish with the least delay and expenditure of energy:

1. When going from a resting area through an area of high velocity to another resting area, a fish should be able to enter the high velocity area with as little change in direction as possible.
2. Resting areas must be large and well placed to allow plenty of room for numbers of fish in each pool.
3. Energy dissipation must be complete in each section so that velocities will remain the same throughout the length of the fish passage device.
4. The minimum depth in each section must be controlled so that fish at all times will be submerged.
5. The flow pattern must be stable.

6. There should be no objectionable whirlpools, hydraulic jumps, standing waves, or other detrimental hydraulic peculiarities.

In addition, when the fishway is placed in the culvert, the design should allow for the highest possible culvert efficiency and present no barrier to bed load and debris.

## Premodel Calibrations

Since most culverts to be baffled already are in place, the difficulty of entering these culverts, placing concrete forms, or anchoring wood baffles requires that a simple fishway design be utilized. An arrangement of baffles must be straight with no change in cross-section, no curves, no re-entrant ends, or other complexities. A straight clear channel through the entire culvert is desirable so that fish do not have to swim a curved, tortuous path. For the model culvert fishway study patterns were selected which satisfied these special demands and seemed to offer the best prospects for easy fish passage, the most effective use of water at low flows, and minimum constriction of the culvert cross-section.

Rough cedar lumber was selected as the model material as best duplicating, in correct ratio, the roughness of the concrete from which culverts are usually constructed. This selection was influenced by discharge measurements made during low flow at the Ennis Creek culvert, near Port Angeles. The roughness coefficient (Kutter's **n**) of the culvert was calculated to be 0.0254 for a flow of 27.5 cfs., a depth of 6 inches and a bottom width of 10 feet. The roughness relation between model and the Ennis Creek prototype, when the effects of friction are included, is expressed by the formula $\frac{\mathbf{n}_m}{\mathbf{n}_p} = \mathbf{L}_r^{1/6}$ where $\mathbf{L}_r$ is the linear ratio of the model to prototype. With the model at 1:10 scale, the required coefficient in the model was calculated to be 0.0173. Tests of the model showed that the roughness coefficient equaled in correct ratio that of the prototype.

## Model Construction

The study required close control of the variable flow, a precise method of varying the slope, and a means whereby the discharge of the model could be measured accurately. The facilities of the University of Washington hydraulics laboratory are well adapted for such a study, since both excellent hydraulic facilities and woodworking equipment are available.

The model culvert was constructed on a unit scale; that is, one foot wide so that it would have a convenient scale ratio to any size prototype. To make the slope easily computable, the effective length between supports was made exactly 10 feet (Figure 6).

The upstream end of the model was attached by means of a specially constructed intake to a stilling pool. The quantity of water flowing into the stilling pool was controlled by a 6-inch valve, and discharge was measured by a rectangular tank placed in a sump below the out-fall of the model. This tank was one regularly used by the hydraulics laboratory for measurement of water, and had an exact horizontal cross-section of 2 by 3 feet. A vertical scale on the inside of the tank measured the discharge by the time required for a unit change in depth in the tank.

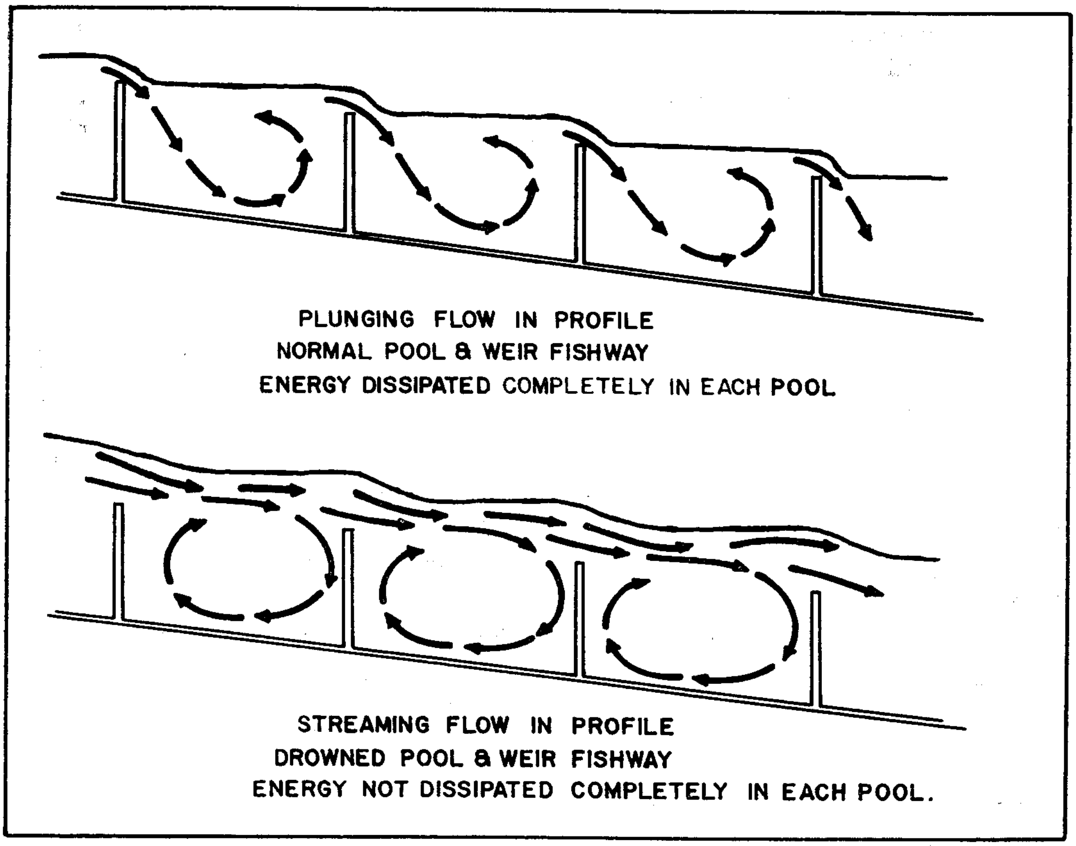



FIGURE 4—Illustrations of plunging and streaming flow in pool and weir fishways.

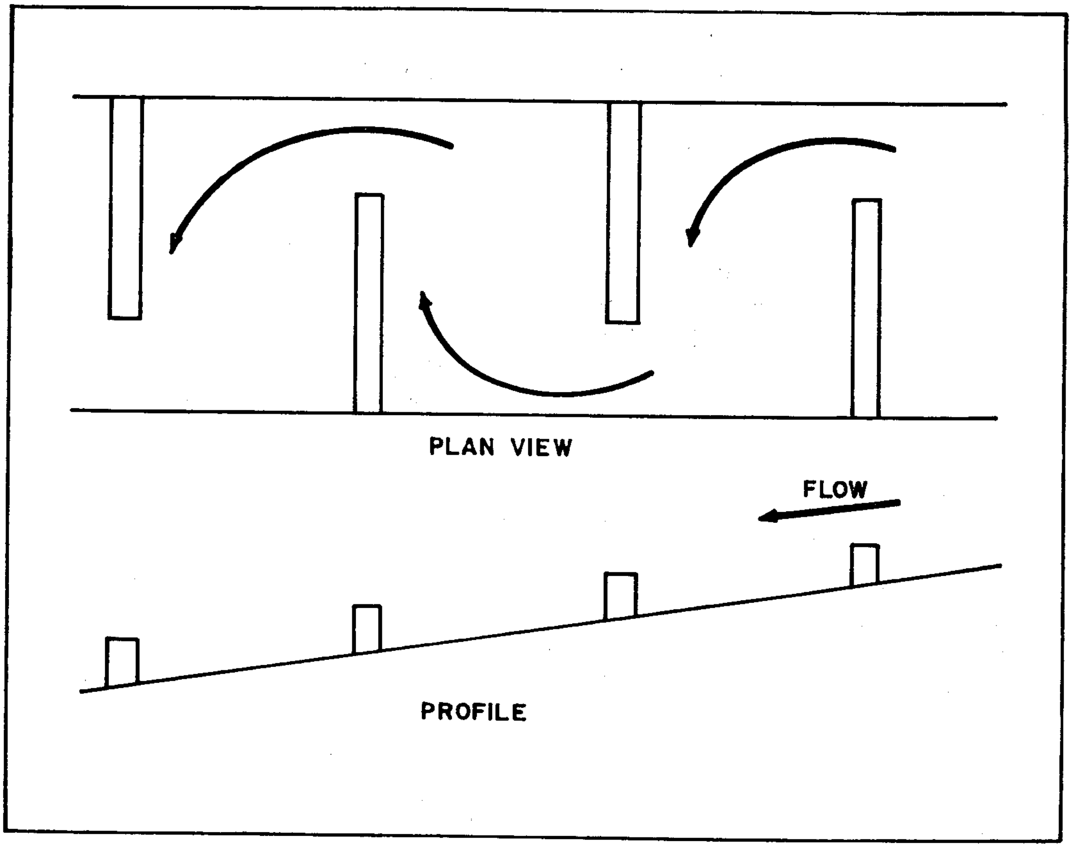



FIGURE 5—Alternate barriers used for culvert baffles have proved ineffective for fish passage.

## Experimental Procedure

Each trial series of a particular arrangement of baffles consisted of three different discharges and three slopes. The first discharge flowed only to the top of the baffles; the second discharge submerged the baffles slightly; and the third discharge overtopped the baffles by several inches. The intervals of slope tested were 1½, 3½, and 5 percent. Thus, for each baffle arrangement, nine tests were made during which flow patterns and any other particulars were observed and an evaluation made. Zero slopes were not examined since a culvert so placed can be made to create one long pool and therefore would not require baffles.

The baffle arrangement was changed between each series of tests in an effort to improve the flow pattern. The three baffle arrangements shown in Figure 7 were tested. To judge the merits of each baffle arrangement, a grading system based on the criteria of successful fish passage was needed. An arrangement of baffles that was effective at a certain slope and a certain discharge might, at a different slope or discharge, have entirely different properties. The different trials were then graded individually without reference to previous runs or expected conditions. The properties graded were: Effective energy dissipation, depth encountered by a fish passing through the flow pattern, and its effect upon the path a fish would follow through the entrance conditions from pool to pool; the availability of dead or very slow water for resting purposes; and miscellaneous properties such as objectionable whirlpools, hydraulic jumps, excessive standing waves, high turbulence, or other hydraulic peculiarities. Grading procedure is illustrated in Table 1.

**TABLE 1—Grading procedure used in model studies①**

| | | | | | |
|---|---|---|---|---|---|
| | Bad | | | | Good |
| Energy dissipation | 1 | 2 | 3 | 4 | 5 |
| | ½″ | ¾″ | 1″ | 1¼″ | 1½″ |
| Minimum depth in pool | 1 | 2 | 3 | 4 | 5 |
| Pattern of flow | 1 | 2 | 3 | 4 | 5 |
| | Little | | | | Much |
| Dead or slack water | 1 | 2 | 3 | 4 | 5 |
| | Poor | | | | Good |
| Miscellaneous properties | 1 | 2 | 3 | 4 | 5 |

① Total points determine final grade: 1–5 points, very bad; 6–10, poor; 11–15, fair; 16–20, good; 21–25, excellent.

# Results and Conclusions

An example of this grading system is shown in the following application of a particular trial from actual test data. Energy dissipation was not satisfactory and was given two (out of a possible 5) points because a gain in kinetic energy was observed through the culvert. The minimum depth was

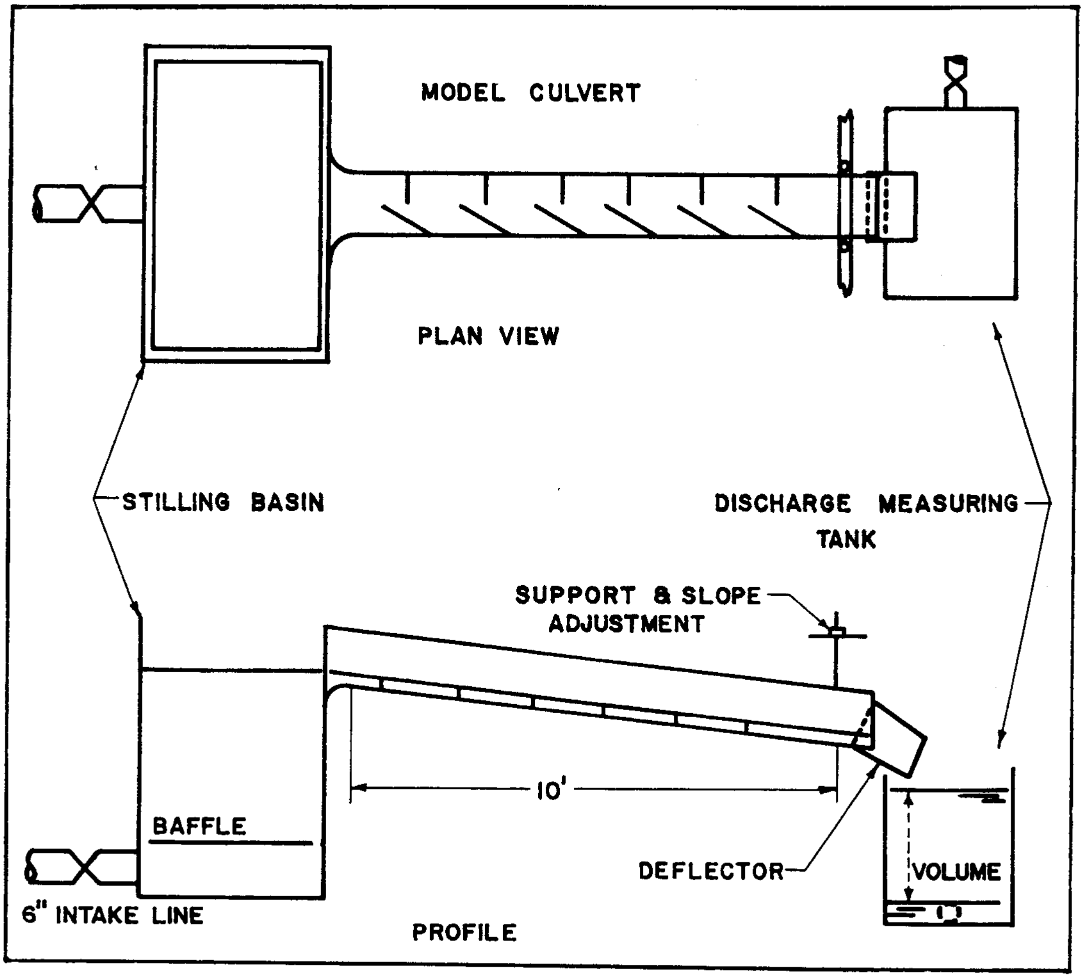



FIGURE 6—Schematic view of test equipment used in modeling culverts.

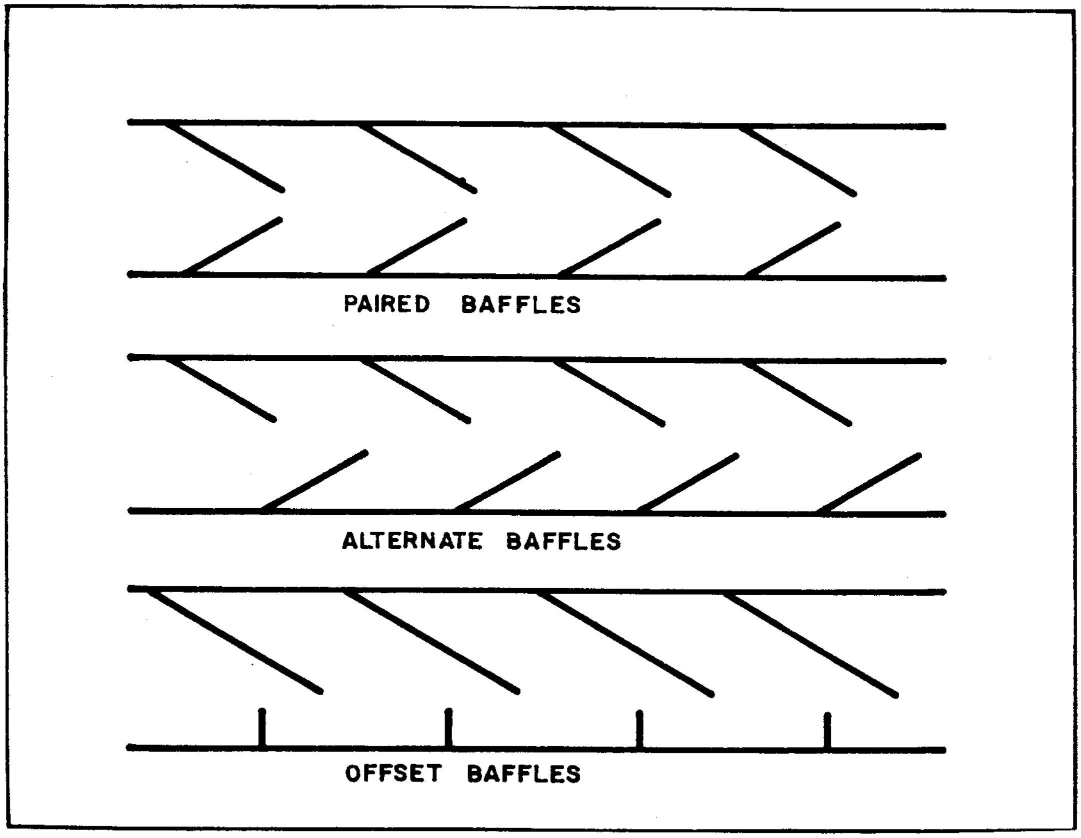



FIGURE 7—Types of baffle arrangements tested in the model study.

above 1½ inches which was worth five points. The flow pattern had little stability and was rated as two points. Very little useful dead water was observed, and was therefore allowed one point. The absence of most of the miscellaneous detrimental properties rated four points. Total number of points received by this trial was 14, which rates it as a three, or in the middle of the grading range. There was definite agreement on the grading between the authors, since the desirable and undesirable factors of each test were quite apparent.

The object of grading each trial was that the different baffle arrangements could be compared at any slope and at any discharge. An arrangement receiving a high grade for all slope and discharge conditions would be the logical choice over one that received a high grade for only one or two conditions.

As an aid to the judgment of flow patterns and paths that fish would follow in proceeding through the baffles, small chinook salmon approximately 3⅜ inches in length were introduced into the lower end of the model culvert during many trials. Baffle arrangements producing a tortuous path for the fish in the model suggested that the same situation would occur in the prototpye. Conversely, when the fish swam through easily with little weaving or darting, it was assumed that the same conditions would prevail in the prototype. As the model was small and it was impossible to obtain a quantitative measurement of velocities, the fish were used to find, by their movements, a qualitative measure of velocities and flow patterns.

The paired baffle was very unsatisfactory at low flows and ineffectively dissipated energy at high flows. The alternate baffle created depths in successive pools that were below minimum at low flows and created completely unstable flow patterns at high flows. These two baffle patterns were found to be completely unsatisfactory. All further mention of baffles or baffle arrangements in this report will refer to the off-set baffles (Figure 7).

During the tests of off-set baffles an unanticipated condition was found during higher flows when using a 30-degree angle between baffle and wall. Along the right wall from which the long baffles project, a counter-clockwise roll was observed (observations taken looking downstream). This roll formed due to the deflection of water by the upstream side of the baffle against the corner filet and the right wall of the culvert, and was continuous along the wall and extended approximately one-third of the width. This roll tended to maintain the flow pattern below the baffle tops after the baffles were well overtopped (observations taken by means of threads a few inches long placed over the entire bottom of three successive pools). The circular motion of this roll appeared to effectively reduce the direct downstream velocities within the roll as more energy was dissipated by this circular motion. In three instances, small chinook were introduced into the culvert and were observed to swim its complete length within the roll.

Because one of the design criteria was the establishment of dead, or resting water in line with the slots of the fishway, the preliminary design was evolved with this factor in mind. Changes of the baffle spacing, moving of the slots nearer to the end of the fishway, and varying the angle of the long baffle with respect to the wall, were all tried. Actually, many of these conditions are interdependent and the final aim is effective energy dissipation throughout the length of the culvert and formation of dead water in line with the slots. Dead water allows a fish to swim in short spurts straight through high velocities and enter a resting area which lies nearly parallel to the

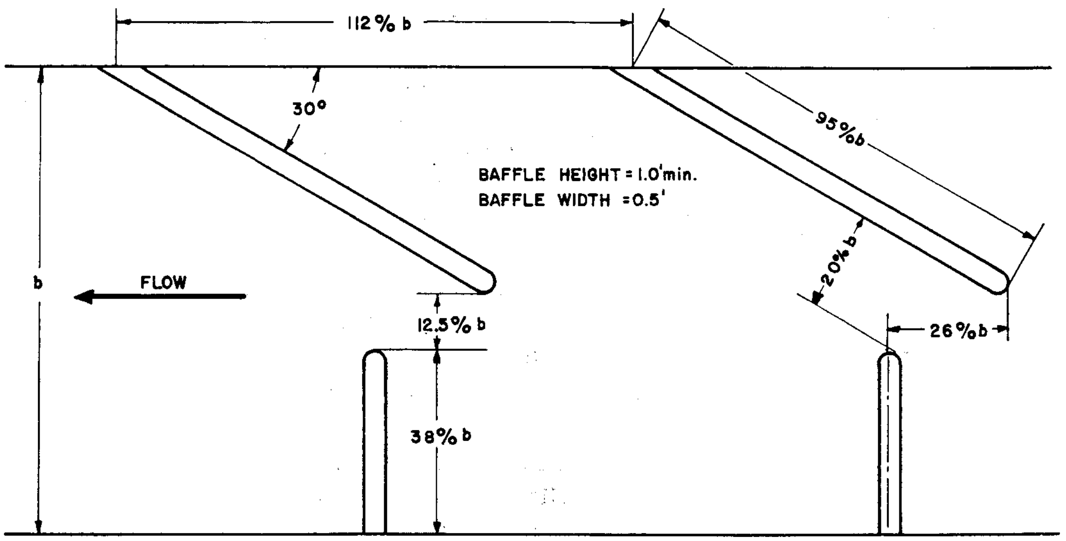
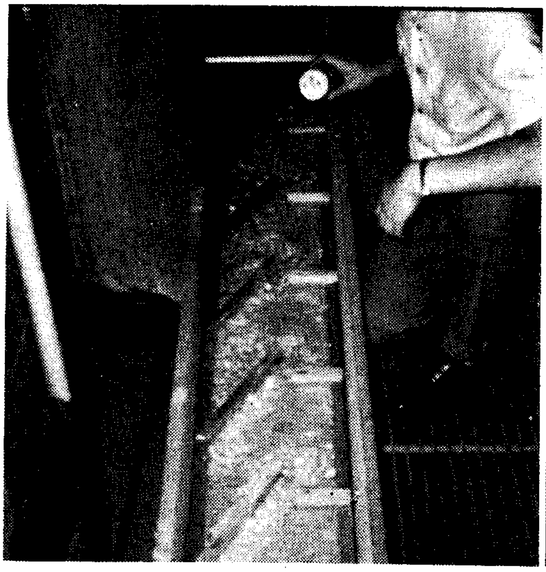



**FIGURE 8—Final offset self-cleaning baffle design which was found to work efficiently over entire range of slopes and discharges.**

jet of higher velocity. Parallelism of the jet and resting area is obtained by varying the angle of the long baffle with respect to the wall. The smaller the angle of the baffle with the wall, the more nearly the line of high velocity is brought directly downstream through the slot. Too small an angle could not be used as this caused the length of the long baffle to increase to keep the slot and resting area in relatively the same position. Increasing the baffle length extended the pools and thereby decreased the depth of water below the slot. Water depth in the pool and in the slot was also a limiting factor. A 30-degree angle was finally chosen for its effectiveness in creating the best combination of conditions.

As a result of the tests, the final design evolved was that shown in Figures 8 and 9. Since culverts are made in a variety of widths, it was thought best to express all baffle dimensions as a percent of the width, exactly as in the results of the model studies. The angle between the wall of the culvert and the long baffle is 30 degrees. The clear opening of the slot is 20 percent of the culvert width and the spacing interval between the long baffles is 112 percent. The distance measured downstream from the nose of the long baffle to the center line of the short baffle is 26 percent. The length of the long baffle is 95 percent. The length of the short baffle is 38 percent. Further limitation of prototype installation is that the minimum height of baffles shall be one foot, and the minimum width of the baffled section shall be 5 feet.

As the ability of the culvert to pass water would be somewhat impaired by the baffles, it was necessary to calculate the relative efficiency of the culvert with and without baffles. Calculation of efficiency is impossible from low flow model data because the roughness factor **n** in the baffled culvert appears to vary significantly with depth or discharge. As a result of the scale agreement in model and prototype **n** previously discussed, efficiency may be calculated at high discharge conditions by scaling model observations to prototype dimensions. To eliminate the chance of error in such calculations, a comparison was made in the model culvert. A high discharge was put through the baffled model and the depth measured. The baffles were then removed and the depth again measured. From data on these comparative tests the roughness in each case was calculated. By assuming the depth in



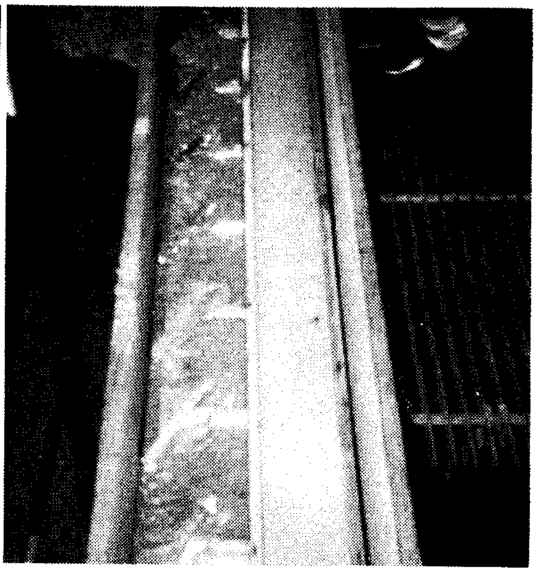


**FIGURE 9 (left)—Model of final fishway design showing introduction of aluminum powder and fine sawdust to show flow patterns. FIGURE 10 (right)—Final fishway design modeled in one-half of culvert. Proposed full width for Ennis Creek.**

the bare culvert equal to that in the baffled culvert, and calculating the discharge required for this new depth, a comparison may be made between the discharge required in bare and baffled culverts to fill the culverts to the same point. Efficiencies tested were made with the model on a slope of 3½ percent. The efficiency resulting from scaling to a 10-foot wide culvert with one-foot high baffles was 69 percent. The efficiency for the same arrangement but with baffles 1.4 feet high was 57 percent.

A further development of the off-set baffle arrangement was considered in the case of very wide culverts. In this type of installation, a vertical wall usually three times the baffle height was run along the center line of the culvert floor. One side of the culvert was then baffled and the other side left open to allow free discharge of the water (Figure 10). This arrangement was tried with baffles one foot high with only half of the culvert width baffled, which resulted in an efficiency of 80.5 percent. Thus it can be seen in the final arrangement with half the culvert baffled that there is a reduction in efficiency from the bare culvert of approximately 20 percent. Since most culverts are overdesigned for the discharge conditions, due to the necessity for a large safety factor, the actual impairment of the culvert's ability to discharge is relatively small.

A further point of interest regarding this type of installation would be the possibility of its becoming filled with silt and washed gravel which would render it useless for fish passage. If the fishway is rendered inoperative due to silting, obviously a possibility exists for further plugging the culvert above the top of the fishway baffles and materially reducing the discharge. The latter part of the study was devoted to examining self-cleaning properties of the various models. Gravel up to 3 inches in diameter, sand, water-logged leaves, sticks and grass, were introduced into the model in quantities that in prototype would be tremendous. Actually in the model itself, the baffles were completely filled with this type of material. The flow of water was then started slowly and allowed to build up to a point considered to be a yearly flood in a prototype culvert. Timing of the cleaning operation which then took place could be measured in seconds, the final result being a very few particles left at the lower end of the pool where the long baffle joins the wall. The rest of the fishway model was completely cleaned of all material. These tests were repeated many times, and in all cases the cleaning action was positive and complete. This effective cleaning action was observed to be due, for the most part, to the rolling action of the water at higher flows. As in other problems of a hydraulic nature, it is impossible to predict the action of water under complex conditions. The model study was undertaken because it offered a quantitative solution to the problem, and the results could be scaled to prototype dimensions by the law of hydraulic similitude. Even though the study did not include round culverts, the authors have, of necessity, extended the results to a prototype round culvert on one small stream in Clark County, Wash.

## Field Application Of Results

Ease of installation is an important consideration in designing the baffles. Access to existing culverts is always difficult, especially if the height of the culvert is under 6 feet. Also, any material used to construct the baffles in existing culverts must be hand placed. The materials for construction of these baffles may be either wood or pre-cast concrete sections which may be easily drilled and grouted into place in any culvert. If the baffles were placed in a new culvert, with its attendant ease of access, the cost and labor of placing them would be lower and would comprise a relatively small part of the overall installation cost.

A proposal has been submitted to the State Highway Department for the correction of five culverts under primary state highways, among them the Ennis Creek culvert under Highway 101. This culvert imposes extreme design conditions. It is an 8 by 10 foot single-barrel box culvert, 164 feet long, laid on a 2.99 degree grade which amounts to a drop of 4.9 feet through the culvert. The resulting velocities through this culvert form an effective block at all water stages from extreme low, when there is insufficient depth for swimming, to higher flood flows. As a result of these high velocities (6 feet per second at a depth of 6 inches), the water has gouged out a drop below the apron at the lower end. This condition made it necessary to design not only the culvert baffles but also a sufficient number of pools to allow the fish to gain access to the level of the culvert floor. To allow the greatest efficiency for passage of high water it was recommended that only half of the culvert (longitudinally) be baffled as half the culvert width would also allow sufficient width for the baffle design (see Figure 10). In addition, the proposed design included controls downstream from the culvert outfall to limit further erosion of the stream bed. Action on this correction is pending by the Highway Department.

## Summary

This study was initiated to provide a low cost, simple, and effective means of passing upstream migrant salmon through culverts. Rectangular culverts to a maximum grade were studied. A model was built which conformed as nearly as possible to prototype conditions, and paired, alternate and offset baffle arrangements were tested for usefulness.

A grading procedure was initiated to evaluate the various arrangements, the most successful of which was the offset baffle fishway (Figure 8). This

arrangement produced a good flow pattern at all slopes and discharges tested.

Special emphasis was placed on ease of installation. The final design is simple and the baffles lend themselves to construction from wood or pre-cast concrete. The baffles may be easily installed in older culverts by drilling and grouting.

At higher flows the self-cleaning qualities of the offset baffle fishway are positive and complete.

The approach in this study was entirely empirical as no mathematical formulae were available to predict flow pattern, energy dissipation, and other hydraulic peculiarities. No attempt was made to investigate other than rectangular culverts as these have presented the greatest problems in the field.

These studies also form a basis for computing the effects of the use of baffles when under unusual conditions the present culvert placement standards of the department cannot be met.