March 2007

Corner Baffle Design Exercise

Fish Passage Retrofit and Culvert Rehabilitation
Highway 128 at John Hatt Creek

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Fish Passage Retrofit and Culvert Rehabilitation
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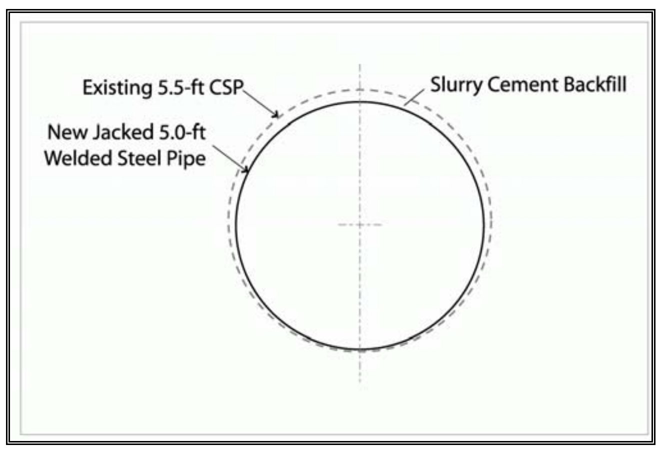
Project Background and Description

John Hatt Creek is a tributary to Rancheria Creek in the Navarro Creek Watershed and supports steelhead trout. A California Department of Transportation (CalTrans) fish passage inventory and assessment in 2003 identified the Highway 128 culvert at John Hatt Creek as a barrier to all age classes of trout, including adult steelhead. The 5.5 feet diameter corrugated steel culvert, 172 feet long and sloping at 2.4%, creates a velocity and depth barrier for all fish. Additionally, there is a 1.3 foot drop at the outlet that requires fish to leap to enter the culvert.

As part of routine maintenance, CalTrans is scheduled to rehabilitate the existing culvert due to its deteriorated condition. The height of the road fill above the culvert makes replacement cost-prohibitive. Instead, they plan to insert a 3/8 inch thick welded steel pipe through the existing culvert and fill the gaps between the two pipes with a concrete slurry (see figure below). The California Department of Fish and Game (CDFG) has requested that the proposed rehabilitation include modifications to allow upstream passage of adult and juvenile steelhead. They have suggested welding corner baffles into the new steel pipe and constructing several concrete weirs downstream of the outlet to backwater the culvert and eliminate the drop.

Existing Culvert Outlet



Proposed Welded Steel Pipe Insert

An engineer has developed preliminary designs for three downstream weirs intended to raise the tailwater at the culvert outlet and reduce the drop heights to allow upstream juvenile and adult steelhead passage.

You have been tasked with developing the size, shape, and configuration of the new baffles and determining if the proposed downstream weirs will create tailwater conditions suitable for fish passage. CDFG requests that the design attempt to satisfy their recommended fish passage criteria as best possible. However, due to limitations associated with retrofitting existing crossings, CDFG staff understands that satisfying all passage criteria at all fish passage flows may not be feasible.

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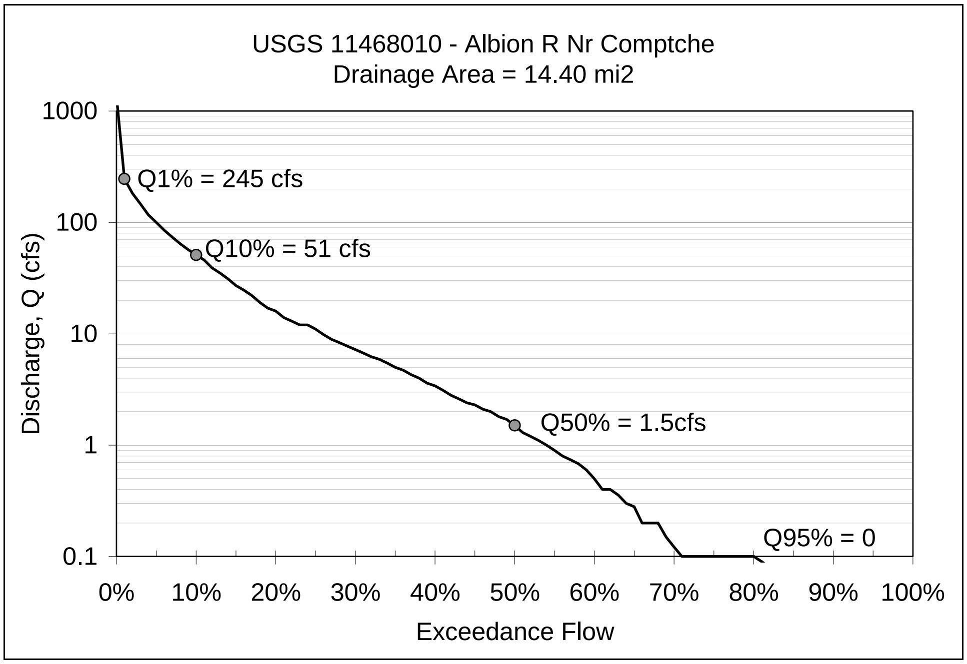
Hydrology, Hydraulics and Preliminary Downstream Weir Design for John Hatt Creek Culvert at Highway 128

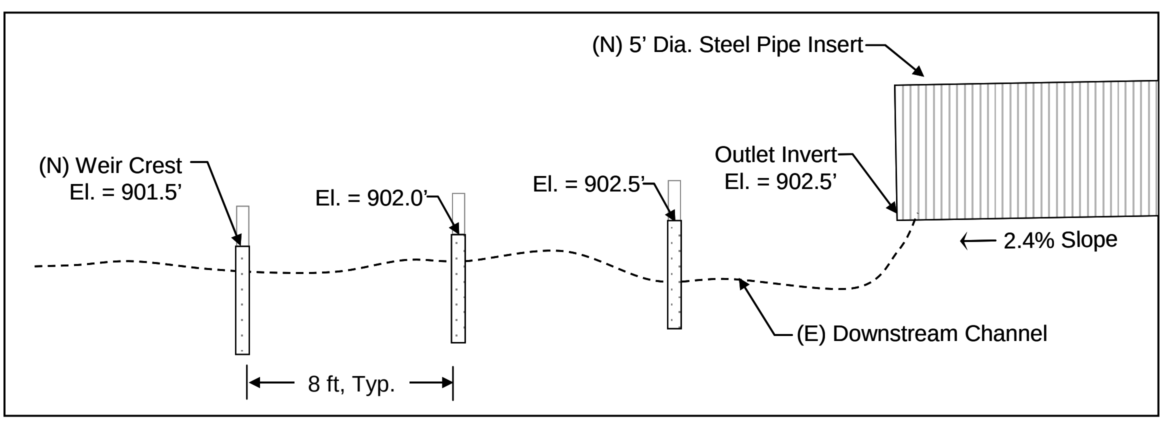
Site Hydrology Information

John Hatt Creek at Highway 128
Drainage area of John Hatt Creek is 1.20 mi^2



Flow duration curve of gaged stream near project site showing the percent of time that a flow is equaled or exceeded.

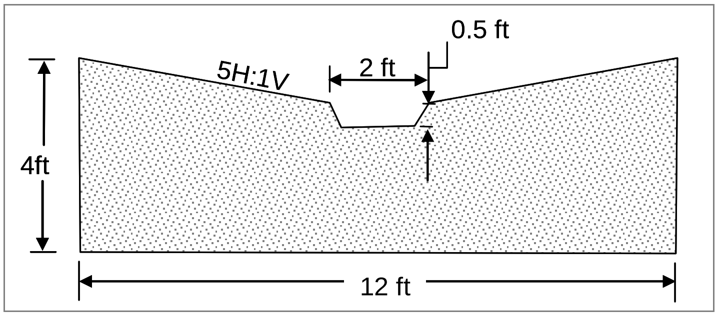
Initial Design for Downstream Concrete Weirs at John Hatt Creek



Channel Profile of Downstream Weirs and Culvert Outlet. See typical section for shape of weir.

Stage-Discharge Rating Table for Weirs

Rating table for proposed weirs downstream of culvert. Discharge calculations assume the compound weir functions as a sharp crested weir. Results account for submergence and assume flow is plunging rather than streaming. Depth over weir crest is measured from the crest of low-flow notch.



Typical Cross Section of Proposed Compound Weirs. Note: portion of weir keyed into channel bank and bed is not shown.

Depth over Weir Crest	Discharge
0.30 ft	1.0 cfs
0.40 ft	1.6 cfs
0.50 ft	2.0 cfs
0.60 ft	2.6 cfs
0.70 ft	3.4 cfs
0.80 ft	4.4 cfs
0.90 ft	5.6 cfs
1.00 ft	7.0 cfs
1.10 ft	8.8 cfs
1.20 ft	10.8 cfs
1.30 ft	13.0 cfs
1.40 ft	15.6 cfs
1.50 ft	22.4 cfs

Weir Flow for Baffles in John Hatt Creek Culvert

Table 2 – Discharge over corner baffles (arrangement WB-1a) in a 5 ft diameter pipe as a function of depth and baffle side-slope (Θ). Calculation assumes plunging flow over a sharp crested weir with partial submergence.

Depth above Baffle*	Discharge (cfs)			
	$\Theta = 5^o$	$\Theta = 10^o$	$\Theta = 15^o$	$\Theta = 20^o$
0.10 ft	0.05	0.02	0.02	0.01
0.20 ft	0.27	0.13	0.09	0.06
0.30 ft	0.70	0.35	0.23	0.17
0.40 ft	1.32	0.67	0.44	0.32
0.50 ft	2.03	1.10	0.73	0.53
0.60 ft	2.79	1.65	1.09	0.80
0.70 ft	3.60	2.31	1.53	1.12

*** Depth is measured from the lowest point on baffle.**

Recommended Design Criteria

DFG has provided the following recommended fish passage criteria for design of the baffles and downstream weirs.

Hydrology and Fish Passage Flows

Fish passage conditions should be suitable between the low and high fish passage design flows.

Species and Lifestage	Low Passage Design Flow	High Passage Design Flow
Juvenile Salmonids	95% Exceedance Flow or 1 cfs (which ever is greater)	10% Exceedance Flow
Adult Steelhead	Largest of 50% Exceedance Flow or 3 cfs(which ever is greater)	1% Exceedance Flow

Depth, Velocity, Water Surface Drop Criteria, and Turbulence

Recommended Design Criteria	Juvenile Steelhead	Adult Steelhead
Minimum Water Depth	6 inches	12 inches
Maximum Water Velocity:		
Culvert Length		
0 - 60 ft	1 ft/s – 2 ft/s	6 ft/s
60 ft – 100 ft	1 ft/s	5 ft/s
100 ft – 200 ft	1 ft/s	4 ft/s
200 ft – 300 ft	1 ft/s	3 ft/s
> 300 ft		2 ft/s
Maximum Water Surface Drop	6 inches	12 inches
Maximum Energy Dissipation Factor (EDF):		
Pools below Drops	NA	4 ft-lb/s/ft^3
Baffles[1]	NA	5 ft-lb/s/ft^3
Roughened Channels	NA	7 to 10 ft-lb/s/ft^3

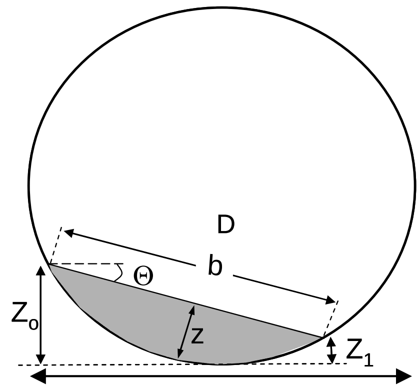
[1] To minimize risk of debris accumulation and sedimentation between baffles, EDF should be greater than 2 to 3 ft-lb/s/ft^3 and baffles should be fully submerged at the adult salmon/steelhead high passage flow.

Corner Baffle Hydraulics

$Q = C(y_o/D)^a\ gS_oD^5)^{1/2}$ *Adapted from Rajaratnam and Katapodis 1990 by WDFW 2003.*

Rearranging to solve for water depth:

$$Y_o = D\left[\frac{Q}{C\sqrt{gS_oD^5}}\right]^{\frac{1}{a}}$$ **Equation 1**



Where:
Y_o = water depth, measured from culvert invert (ft)
Q = discharge (cfs)
D = culvert diameter (ft)
S_o = culvert slope (ft/ft)
z = baffle height as shown (ft)
g = gravitational acceleration (32.2 ft/s^2)
C = coefficient dependent on baffle arrangement
a = coefficient dependent on baffle arrangement

L = spacing between baffles (ft)
Θ = corner baffle side-slope (degrees from horizontal)
Z_o = maximum height of baffle, measured from invert (ft)
Z_1 = minimum height of baffle, measured from invert (ft)
b = length of baffle crest (ft)

TABLE 1 - Baffle arrangements and resulting spacing, height, and hydraulic coefficients as a function of culvert diameter (WDFW, 2003).

Baffle Arrangement	Z	L	C	a	Limits of Experimental Data
WB-2	0.15D	0.6D	5.4	2.43	$0.25 \leq Y_o/D < 0.8$
WB-1a	0.15D	1.2D	6.6	2.62	$0.35 \leq Y_o/D < 0.8$
WB-1b	0.15D	2.4D	8.5	3.00	$0.35 \leq Y_o/D < 0.8$
WB-3	0.10D	0.6D	8.6	2.53	$0.35 \leq Y_o/D < 0.8$
WB4-a	0.10D	1.2D	9.0	2.36	$0.20 \leq Y_o/D < 0.8$
WB-4b	0.10D	2.4D	9.6	2.50	$0.20 \leq Y_o/D < 0.8$

* Coefficients empirically derived using dimensionless analysis.

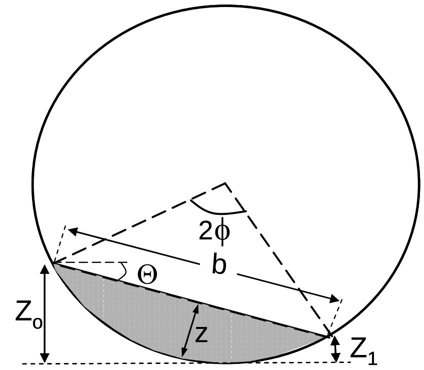
References:

Rajaratnam, N. and C. Katopodis. 1990. Hydraulics of culvert fishways III: weir baffle culvert fishways. Canadian J. of Civil Engineering. Vol. 17:4:558-568.

WDFW (Washington Department of Fish and Wildlife). 2003. Design of Road Culverts for Fish Passage. Olympia, WA. 71 pages.

Corner Baffle Geometry

Using circular geometry and trigonometry, Z_o and Z_1 can be calculated if z and Θ are known:



$$Z_o = \frac{D}{2}\left[1 - \cos(\phi + \theta)\right]$$

(Equations 2 and 3)

$$Z_1 = \frac{D}{2}\left[1 - \cos(\phi - \theta)\right]$$

Where:

$$\phi = \cos^{-1}\frac{(D - 2z)}{D}$$

(Equation 4)

Corner Baffle Design Procedure

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The following is intended to provide general design guidance and process. When retrofitting an existing culvert there are numerous constraints to consider. For example, typically the culvert diameter and slope are predetermined and there is a minimum allowable culvert capacity. As a result, it is frequently not possible to satisfy all of the provided guidelines and criteria. In such cases, it is important to have realistic project objectives, weigh the impact of each decision on passage performance, and document the decision process. In the end, the acceptability of the design relies on the degree to which the project satisfies the objectives.

Recommended maximum culvert slope of 2.5% for corner baffles.

1. Determine the low passage design flows (Q_{lp}) and high passage design flows (Q_{hp}) for each design fish (species and lifestage).

2. Select a baffle arrangement (Table 1) and, using the culvert diameter (D) and slope (S_o), calculate baffle height (z), baffle spacing (L) and the vertical drop between baffles (h), where:

$$h = S_o L$$

Note: *Interpolation may be used to develop baffle arrangements and associated coefficients not provided in Table 1.*

3. Assume the flow (Q) is streaming across the baffles at high passage design flows and the baffles are functioning as large roughness elements. Under this assumption, Equation 1 (provided in following section) can be used to determine water depth and velocity.

a. At the high passage design flow (Q_{hp}) calculate the water depth (Y_o) for the selected baffle arrangement using Equation 1 and the corresponding coefficients in Table 1. Check that the equation and coefficients are being used within their limits of application.

b. Calculate the average cross-sectional water velocity (V) for Q_{hp} using the relationship:

$$V = Q / A$$

Use the wetted cross sectional area between the baffles (A). The wetted area is determined from the geometry of a circular pipe and the calculated water depth (Y_o). Use the attached circular pipe geometry look-up table or the equations for area of a circular segment:

$$A = R^2 \cos^{-1} [(R - Y_o)/R] \quad - (R - Y_o)(2RY_o - Y_o^2)^{0.5}$$

where D = pipe diameter and the pipe radius R = D/2

c. Calculate the Energy Dissipation Factor (EDF) associated with the baffles using the equation:

$$EDF = \lambda Q S_o / A$$

where λ = 62.4 lb/ft^3 (unit water of water).

d. Compare the calculated water velocity and EDF to the velocity and EDF criteria for each design fish.

i. If the velocities or EDF are excessive, return to step 2 and try a baffle arrangement that gives shorter baffle spacing and/or taller baffles.

ii. If the velocities or EDF are much lower than the criteria, sedimentation may occur. Return to step 2 and try a baffle arrangement that results in longer baffle spacing and/or shorter baffles.

iii. If both the velocity and EDF criteria cannot be satisfied with a single baffle arrangement, you must chose an arrangement that provides the best balance between the two.

4. Choose a side-slope for the corner baffles (Θ). The side-slope usually ranges between 10^o and 20^o.

a. Use equations 2-4 to calculate the height of the low (Z_1) and high (Z_o) sides of the sloping baffle, measured from the culvert invert.

b. Check that at the highest Q_{hp} (usually associated with adult salmon or steelhead in anadromous streams or adult trout in resident streams) the water depth is close to the height of the baffle (Z_o).

i. If water depth is much lower than the high-point of the baffle there is an increased risk of debris accumulation on the baffles. Select a lower side-slope (Θ) for the corner baffle and return to step 4a. If the side-slope cannot be decreased further, return to step 2 and select an arrangement with a smaller baffle height (z) and/or larger spacing (L).

ii. If water depth is much higher than the high-point of the baffle there may be insufficient velocity reduction along this side of the culvert. Increase the side-slope (Θ) for the corner baffle and return to step 4a. If the side-slope cannot be increased further, return to step 2 and select an arrangement with a larger baffle height (z) and/or shorter spacing (L).

5. Assume flow is plunging over the baffles and the baffles are functioning as weirs at each low passage design flow (Q_{lp}). In-between each baffle is a pool with a horizontal water surface.

a. Use a sharp crested triangular weir equation with submergence to calculate depth of flow over the baffles (Y_{lp}) at Q_{lp}. Since the baffle functions as half a triangular weir, the predicted weir flow must be divided in half.

b. Calculate the minimum water depth (Y_{min}) within the pools between the baffles at Q_{lp}. The minimum depth occurs at the downstream side of the next upstream baffle:

$$Y_{min} = Z_{1} + Y_{lp} + - L\ S_o$$

where L is the baffle spacing, Z_1 is the baffle height and S_o is the culvert slope.

c. Compare the water depth to the depth criterion for each design fish.

i. If there is insufficient depth at Q_{lp}, return to step 4 and decrease the baffle side-slope (Θ).

ii. If decreasing baffle side-slope fails to sufficiently increase depth, or lowers the high-point of the baffle excessively, return to step 2 and select a baffle arrangement with shorter baffle spacing and/or taller baffles.

6. Check the water surface transition at the culvert outlet to ensure that the tailwater depth is equal to or greater than the water depth in the culvert at the low and high fish passage design flows.

a. Calculate a tailwater rating table of discharge (Q) versus tailwater depth (Y_{TW}). Tailwater depth is the depth measured from the culvert outlet invert to the tailwater surface.

b. For each fish passage design flow, compare the predicted water depth (Y_o) from step 3a, to the tailwater depth (Y_{TW}). If $Y_o > Y_{TW}$, there will be a drop in the water surface profile as flow approaches the outlet (M2 curve), causing an increase in water velocity and a decrease in depth.

Downstream weirs are often used to raise the tailwater so that $Y_{TW} \geq Y_o$ at all fish passage flows. If site limitations prevent raising the tailwater to backwater the outlet, it may be acceptable to have a drop in the water surface at the outlet, provided that it does not exceed the maximum drop height criterion.

7. Check hydraulic capacity of the culvert with the addition of baffles and resulting headwater depth at inlet.

a. Using Equation 1 and Table 1. Calculate the water depth at the peak capacity flow, Q_{max}. If the results are not within the limits of the equation ($Y_o/D < 0.8$), use another approach.

b. Calculate critical depth (Y_c) at Q_{max} for the culvert diameter.

c. Compare Y_c to Y_o:

i. If Y_c is greater than Y_o, the culvert is inlet controlled and the baffles have negligible affect on culvert capacity. Use standard methods for calculating headwater depth under inlet controlled conditions.

ii. If Y_c is less than Y_o, the culvert is outlet controlled. Use Y_o at the peak capacity flow (Q_{max}) to calculate the corresponding roughness coefficient (n) from Manning's equation. With the roughness coefficient, calculate the resulting headwater depth using standard methods for outlet controlled conditions.

Design Exercises for John Hatt Creek

Work through the following exercise using the project description and supporting material provided on pages 8 through 16.

1. Determine the low and high passage design flows for juvenile and adult steelhead using the Albion River Near Comptche flow duration curve (attached) by scaling the Albion River's exceedance flows to the drainage area of John Hatt Creek at Highway 128 (1.20 mi^2).

   SOLUTION:

   Exceedance Flows at Albion River gage
   $Q_{95\%}$ = 0 $Q_{10\%}$ = 51 cfs
   $Q_{50\%}$ = 1.5 cfs $Q_{1\%}$ = 245 cfs

   Drainage Area
   Albion River Gaging Station = 14.40 mi^2
   John Hatt Creek at Highway 128 = 1.20 m^2

   Drainage Area Ratio = 1.20 m^2/14.40 mi^2 = 0.083 mi^2/mi^2

   Estimated Exceedance Flows for John Hatt Creek
   Scale using drainage area ratio:
   $Q_{95\%}$ = 0
   $Q_{50\%}$ = (1.5 cfs) (0.083 mi^2/mi^2) = 0.125 cfs
   $Q_{10\%}$ = (51 cfs) (0.083 mi^2/mi^2) = 4.3 cfs
   $Q_{1\%}$ = (245 cfs) (0.083 mi^2/mi^2) = 20.4 cfs

   Juvenile Salmonid Passage Design Flows
   Q_{lp} = 1 cfs ($Q_{95\%}$ or 1 cfs whichever is greater)
   Q_{hp} = 4.3 cfs (10% exceedance flow)

   Adult Steelhead Passage Design Flows
   Q_{lp} = 3 cfs ($Q_{50\%}$ or 3 cfs whichever is greater)
   Q_{hp} = 20.4 cfs (10% exceedance flow)

	Fish Passage Design Flows	
	Low	**High**
Juvenile Salmonids	1 cfs	4.3 cfs
Adult Steelhead	3 cfs	20.4 cfs

2. A series of 3 concrete weirs spaced 8 feet apart, were designed for placement below the culvert outlet to raise the tailwater. The water surface drop over each weir is designed to be 6 inches. Assuming a pool depth of 3 feet, determine if the pool volume is adequate to dissipate the energy associated with the drop at the high passage design flow for adult steelhead. Does the Energy-Dissipation Factor (EDF) exceed the adult steelhead threshold?

SOLUTION:

EDF for Plunging Water into Pools:

EDF = ϑQh / V

Where:
EDF = Energy Dissipation Factor (ft-lb/s/ft^3)
ϑ = 62.4 lb/ft^3 (unit weight of water)
Q = Flow (cfs)
h = water surface drop over into pool (ft)
V = Volume of the water in the pool (ft^3)

Q = Q_{hp} for adult steelhead = 20.4 cfs
h = 0.5 ft (drop between weirs)

Pool Length (spacing between weirs) = 8 ft
Pool Width (width of weirs) = 12 ft
Pool Depth = 3 feet
V (pool volume) = (8 ft)(12 ft)(3 ft) = 288 ft^3

EDF = (62.4 lb/ft^3) (20.4 cfs) (0.5 ft) / (288 ft^3) = 2.2 ft-lb/s/ft^3

$\boxed{\textbf{Pool volume adequate, EDF << 4 ft-lb/s/ft}^3\textbf{ threshold}}$

3. Using baffle arrangement **WB-1a** (Table 1):

   a. Determine the baffle height (z), spacing (L), and the drop between baffles (h).

   SOLUTION:

   Diameter, D = 5.0 ft
   Culvert Slope, S_o = 0.024 ft/ft

   Baffle Type WB-1a (Table 1)
   z = 0.15D= 0.15 (5 ft) = **0.75 ft**
   L = 1.2D =1.2 (5.0 ft) = **6.0 ft**
   h = LS_o = 6 ft (0.024 ft/ft) = **0.144 ft**

b. Use Equation 1 to calculate the water depth (Y_o), average water velocity, and EDF (measure of turbulence) at the high passage design flow for adult steelhead. When calculating velocity and EDF, use the wetted area of the culvert between the baffles.

SOLUTION:
Coefficients from Table 1 for Arrangement WB-1a:
$C = 6.6$
$a = 2.62$

Water Depth at Q_{hp} for Adult Steelhead (using Equation 1):

Y_o = (5 ft)[20.4 cfs/6.6{(32.2 ft/s^2)(0.024 ft/ft)(5 ft)^5}$^{0.5}$]$^{1/a}$ = 1.74 ft

$\boxed{Y_o = 1.74 \text{ ft}}$

Velocity and EDF at Q_{hp} for Adult Steelhead:

Wetted Area (A):

$A = R^2 \cos^{-1} [(R - Y_o)/R] - (R - Y_o)(2RY_o - Y_o^2)^{0.5}$

$A = (2.5 \text{ ft})^2 \cos^{-1}[(2.5 \text{ ft} - 1.74 \text{ ft})/2.5 \text{ ft}] - [2.5 \text{ ft} - 1.74 \text{ ft}]*[2 (2.5 \text{ ft}) (1.74 \text{ ft}) - (1.74 \text{ ft})^2]^{0.5}$

$A = 6.08 \text{ ft}^2$

Water Velocity (V):
V = Q/A = 20.4 cfs/6.08 ft^2

$\boxed{V = 3.36 \text{ ft/s}}$

Energy Dissipation Factor:
EDF **=** $\vartheta Q S_o/A$ = (62.4 lb/ft^3)(20.4 cfs)(0.024ft/ft)/6.08 ft^2

$\boxed{EDF = 5.0 \text{ ft-lb/s/ft}^3}$

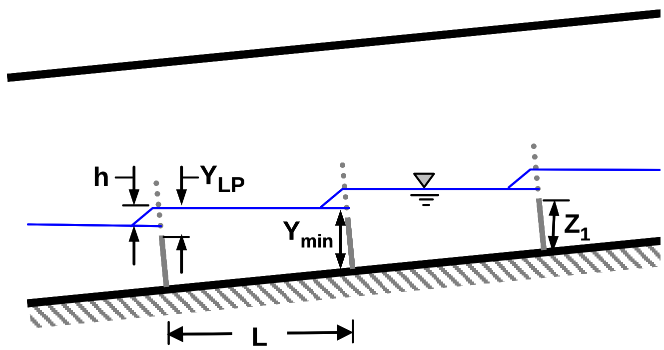
c. Does this baffle arrangement satisfy velocity and EDF criteria for adult steelhead?

Yes, velocity and EDF passage criteria satisfied for adult steelhead at high passage design flow:

Water Velocity $\leq$ 4 ft/s
EDF $\leq$ 5 ft-lb/s/ft^3

4. At the juvenile low passage design flow, assume flow is plunging rather than streaming. For plunging flow, a sharp-crested partially-submerged weir equation can be applied.

   Continuing with baffle arrangement **WB-1a**, use a baffle side-slope (Θ) of 15°. This slope results in Z_1 = 0.35 feet and Z_0 = 1.27 feet.



   a. For the selected baffle slope (Θ), what is the minimum depth in the culvert when flow approaches zero?

      SOLUTION:

      At Q = 0 cfs

      $Y_{min} = Z_1 - h = 0.35\text{ ft} - 0.14\text{ ft}$

      $\boxed{Y_{min} = 0.21\text{ ft}}$

   b. Use Table 2 (weir flow over baffle arrangement **WB-1a** for the John Hatt Creek culvert) to determine if the baffles will provide sufficient depth at the juvenile low passage design flow. What are the depths on the upstream (Y_o) and downstream (Y_{min}) sides of the baffle at this flow? Is the minimum depth criteria for juvenile salmonids satisfied?

      SOLUTION:

      Water Depth at Juvenile Low Passage Design Flow, Q_{LP} = 1 cfs
      Interpolation from Table 2: $Y_{LP} \simeq 0.57$ ft
      (**Note:** Y_{LP} is measured from water surface to low-point on baffle)

      $Y_o = Y_{LP} + Z_1 = 0.57\text{ ft} + 0.35\text{ ft} = \underline{\underline{0.92\text{ ft}}}$

      $Y_{min} = Y_o - h = 0.92\text{ ft} - 0.14\text{ ft} = \underline{\underline{0.78\text{ ft}}}$

      Minimum depth criteria for Juvenile Salmonids are satisfied.
      $Y_{min} > 0.5$ ft

      Also, each baffle is partially submerged by the downstream water surface ($Y_{min} > Z_1$), allowing juvenile fish to swim through the water surface drop across the baffle rather than leap.

c. What is the resulting maximum water velocity at the juvenile low passage design flow for the selected baffle slope?

SOLUTION:

Wetted Area for Y_{min} (A):

$A = R^2 \cos^{-1} [(R - Y_{min})/R] - (R - Y_{min})(2RY_{min} - Y_{min}^2)^{0.5}$

$A = (2.5\ ft)^2 \cos^{-1}[(2.5\ ft - 0.78\ ft)/2.5\ ft] - [2.5\ ft - 0.78\ ft]*[2\ (2.5\ ft)\ (0.78\ ft) - (0.78\ ft)^2]^{0.5}$

$\underline{A = 1.95\ ft^2}$

Water Velocity (V):

$V = Q/A = 1.0\ cfs/1.95\ ft^2$

$\boxed{V = 0.51\ ft/s}$

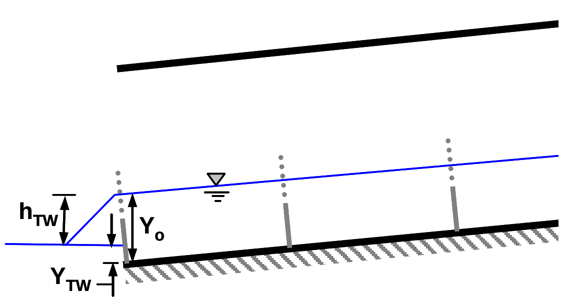
d. What other factors should be considered when selecting a baffle slope?

The water depth at the adult steelhead high passage design flow should be approximately equal to height of the baffle high-point. Lower depth can increase risk of debris plugging and higher depth can result in excessive water velocities for fish passage along the side of the baffle high-point.

In this example the water depth at Q_{hp} is 1.74 ft, which is 0.47 ft above the high-point of the baffle. Using a baffle side-slope of 20° would reduce the depth over the baffle high-point to 0.27 ft while still meeting minimum water depth criteria for juvenile salmonids at Q_{lp}.

5. Using the attached stage-discharge rating table developed for the downstream weirs, assess the hydraulics of the transition as water flows from the culvert outlet into the tailwater pool.

a. Compare the water depth in the culvert outlet to the tailwater elevation below the outlet at the adult high passage design flow and juvenile low passage design flow. Is the tailwater as high, or higher, than the depth in the culvert at both flows? If not, what is the water surface drop at the outlet?



SOLUTION:

Note: Crest of weir downstream of culvert outlet is set at same elevation as outlet invert. Therefore, $Y_{weir} = Y_{TW}$.

At Juvenile Salmonid Q_{lp} = 1.0 cfs

From Stage-Discharge Rating Table:

Y_{weir} (depth over weir) = Y_{TW} (depth above outlet invert) = 0.30 ft

Y_o = 0.92 ft (from answer 4b)

$h_{TW} = Y_o - Y_{TW} = 0.92 \text{ ft} - 0.30 \text{ ft}$

$\boxed{h_{TW} = 0.62 \text{ ft}}$

At Adult Steelhead Q_{hp} = 20.4 cfs

Interpolation from Stage-Discharge Rating Table:

Y_{weir} (depth over weir) = Y_{TW} (depth above outlet invert) = 1.47 ft

Y_o = 1.74 ft (from answer 3b)

$h_{TW} = Y_o - Y_{TW} = 1.74 \text{ ft} - 1.47 \text{ ft}$

$\boxed{h_{TW} = 0.27 \text{ ft}}$

At both flows there is a drop in the water surface at the culvert outlet. Additionally, at the juvenile low passage flow the drop exceeds the maximum drop criteria of 0.5 ft for juvenile salmonids.

b. When the tailwater is lower than the depth in the culvert, what is the impact on fish passage conditions?

A drop in the water surface at the outlet causes the water to accelerate as it approaches the outlet, decreasing depth and possibly creating a velocity barrier. Additionally, if the drop is excessive, it can create a “drop” or “leap” barrier that prevents fish from entering the culvert.

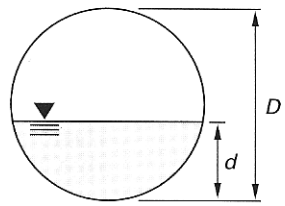
When using baffles, it is best to avoid a drop in the water surface at the outlet at all fish passage flows. If a drop cannot be avoided due to site constraints, the water surface drop should not exceed the maximum drop criteria for the various design fish.

c. What changes could be made to improve the outlet transition?

The downstream weirs should be raised to reduce or eliminate the drop, which would likely require adding a fourth weir to avoid an excessive drop over any individual weir.

Hydraulic Geometry of Circular Pipes

Area, Wetted Perimeter, and Hydraulic Radius
of Partially Filled Circular Pipes



$\frac{d}{D}$	$\frac{\text{area}}{D^2}$	$\frac{\text{wetted perimeter}}{D}$	$\frac{r_h}{D}$	$\frac{d}{D}$	$\frac{\text{area}}{D^2}$	$\frac{\text{wetted perimeter}}{D}$	$\frac{r_h}{D}$
0.01	0.0013	0.2003	0.0066	0.51	0.4027	1.5908	0.2531
0.02	0.0037	0.2838	0.0132	0.52	0.4127	1.6108	0.2561
0.03	0.0069	0.3482	0.0197	0.53	0.4227	1.6308	0.2591
0.04	0.0105	0.4027	0.0262	0.54	0.4327	1.6509	0.2620
0.05	0.0147	0.4510	0.0326	0.55	0.4426	1.6710	0.2649
0.06	0.0192	0.4949	0.0389	0.56	0.4526	1.6911	0.2676
0.07	0.0242	0.5355	0.0451	0.57	0.4625	1.7113	0.2703
0.08	0.0294	0.5735	0.0513	0.58	0.4723	1.7315	0.2728
0.09	0.0350	0.6094	0.0574	0.59	0.4822	1.7518	0.2753
0.10	0.0409	0.6435	0.0635	0.60	0.4920	1.7722	0.2776
0.11	0.0470	0.6761	0.0695	0.61	0.5018	1.7926	0.2797
0.12	0.0534	0.7075	0.0754	0.62	0.5115	1.8132	0.2818
0.13	0.0600	0.7377	0.0813	0.63	0.5212	1.8338	0.2839
0.14	0.0688	0.7670	0.0871	0.64	0.5308	1.8546	0.2860
0.15	0.0739	0.7954	0.0929	0.65	0.5404	1.8755	0.2881
0.16	0.0811	0.8230	0.0986	0.66	0.5499	1.8965	0.2899
0.17	0.0885	0.8500	0.1042	0.67	0.5594	1.9177	0.2917
0.18	0.0961	0.8763	0.1097	0.68	0.5687	1.9391	0.2935
0.19	0.1039	0.9020	0.1152	0.69	0.5780	1.9606	0.2950
0.20	0.1118	0.9273	0.1206	0.70	0.5872	1.9823	0.2962
0.21	0.1199	0.9521	0.1259	0.71	0.5964	2.0042	0.2973
0.22	0.1281	0.9764	0.1312	0.72	0.6054	2.0264	0.2984
0.23	0.1365	1.0003	0.1364	0.73	0.6143	2.0488	0.2995
0.24	0.1449	1.0239	0.1416	0.74	0.6231	2.0714	0.3006
0.25	0.1535	1.0472	0.1466	0.75	0.6318	2.0944	0.3017
0.26	0.1623	1.0701	0.1516	0.76	0.6404	2.1176	0.3025
0.27	0.1711	1.0928	0.1566	0.77	0.6489	2.1412	0.3032
0.28	0.1800	1.1152	0.1614	0.78	0.6573	2.1652	0.3037
0.29	0.1890	1.1373	0.1662	0.79	0.6655	2.1895	0.3040
0.30	0.1982	1.1593	0.1709	0.80	0.6736	2.2143	0.3042
0.31	0.2074	1.1810	0.1755	0.81	0.6815	2.2395	0.3044
0.32	0.2167	1.2025	0.1801	0.82	0.6893	2.2653	0.3043
0.33	0.2260	1.2239	0.1848	0.83	0.6969	2.2916	0.3041
0.34	0.2355	1.2451	0.1891	0.84	0.7043	2.3186	0.3038
0.35	0.2450	1.2661	0.1935	0.85	0.7115	2.3462	0.3033
0.36	0.2546	1.2870	0.1978	0.86	0.7186	2.3746	0.3026
0.37	0.2642	1.3078	0.2020	0.87	0.7254	2.4038	0.3017
0.38	0.2739	1.3284	0.2061	0.88	0.7320	2.4341	0.3008
0.39	0.2836	1.3490	0.2102	0.89	0.7384	2.4655	0.2995
0.40	0.2934	1.3694	0.2142	0.90	0.7445	2.4981	0.2980
0.41	0.3032	1.3898	0.2181	0.91	0.7504	2.5322	0.2963
0.42	0.3130	1.4101	0.2220	0.92	0.7560	2.5681	0.2944
0.43	0.3229	1.4303	0.2257	0.93	0.7612	2.6061	0.2922
0.44	0.3328	1.4505	0.2294	0.94	0.7662	2.6467	0.2896
0.45	0.3428	1.4706	0.2331	0.95	0.7707	2.6906	0.2864
0.46	0.3527	1.4907	0.2366	0.96	0.7749	2.7389	0.2830
0.47	0.3627	1.5108	0.2400	0.97	0.7785	2.7934	0.2787
0.48	0.3727	1.5308	0.2434	0.98	0.7816	2.8578	0.2735
0.49	0.3827	1.5508	0.2467	0.99	0.7841	2.9412	0.2665
0.50	0.3927	1.5708	0.2500	1.00	0.7854	3.1416	0.2500