DESIGN METHODOLOGY FOR CULVERTS WITH FISH PASSAGE

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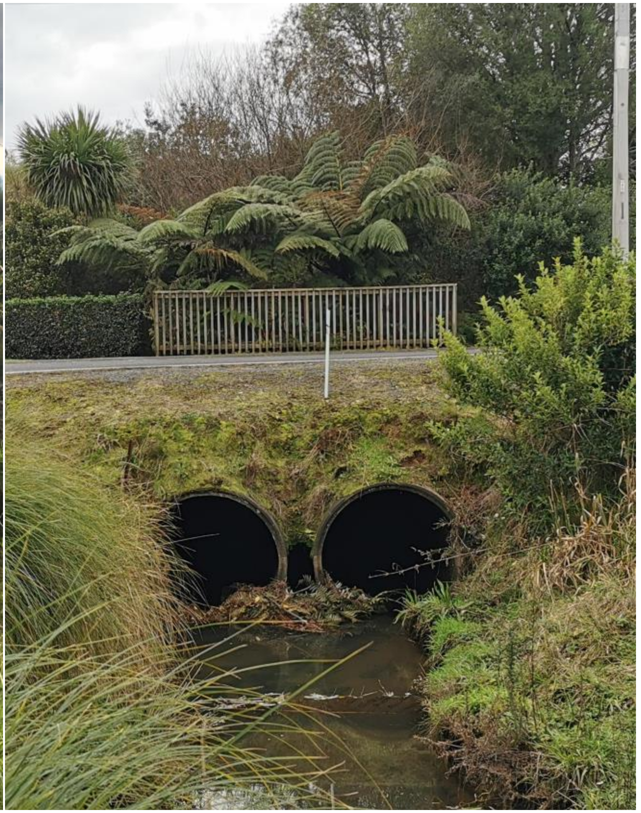

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Water NZ Stormwater 2023

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DESIGN METHODOLOGY FOR CULVERTS WITH FISH PASSAGE

Fish Passage Requirements for Culverts

1983 - Freshwater Fisheries Regulation

- Enforcement by DOC

1991 - Resource Management Act

- Responsible: Regional Councils

2018 - NZ Fish Passage Guidelines (NIWA)

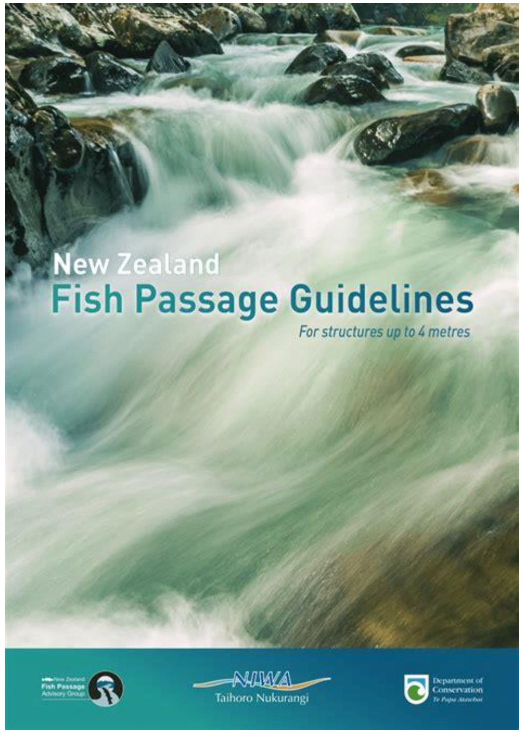
- Approach for obtaining suitable hydraulic design parameters for fish passage

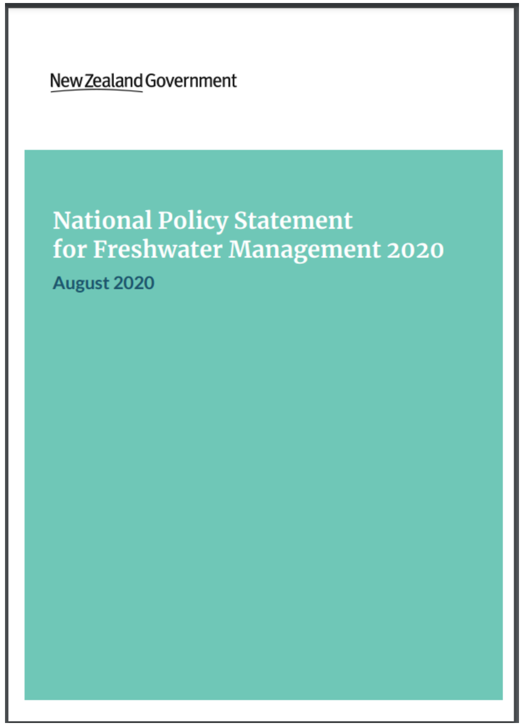
2020 - NES for Freshwater

- Responsible: Regional Councils

Near Future

- Update to NZ Fish Passage Guidelines





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Design Flows for Fish Passage

Fish Passage Design Flows are

- The range is generally intended to include higher rainfall induced stream flows, ranging up to bankfull discharge.
- Bankfull flow would be considered the upper threshold for fish passage.
- The lower threshold would be approximately ½ of the bankfull flow.
- Bankfull flow is very difficult to determine for modified streams, urban streams, or unstable/incised streams.

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Design Flows for Fish Passage

Approach Where Bankfull Flow is Not Identifiable

- Upper Threshold - 0.5 X the 2-year ARI (or 50% AEP) is generally near the 1.5-year ARI flow (Lagassa et al, 2012). Bankfull flow field measurements of several streams have corelated well with ½ of the 2-year design flow.
- Lower Threshold - 0.1 X the 2-year ARI is approximately the 0.5-year ARI, based on hydrology checks for multiple small streams.
- Discussions are on-going regarding the lower fish passage threshold.

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Velocity Threshold for Fish Passage

Three Ranges of Fish Swimming Velocities

- **Sustained Swimming Speed** – Velocities that the fish can sustain for longer than 200 minutes, without muscle fatigue (Beamish 1978).

- **Prolonged Swimming Speed** – Velocities that fish can maintain for 20 to 200 minutes, and ends in fatigue (Beamish 1978).

- **Burst Swimming Speeds** – Highest velocities that fish can achieve, that can only be maintained for less than 20 seconds (Beamish 1978).

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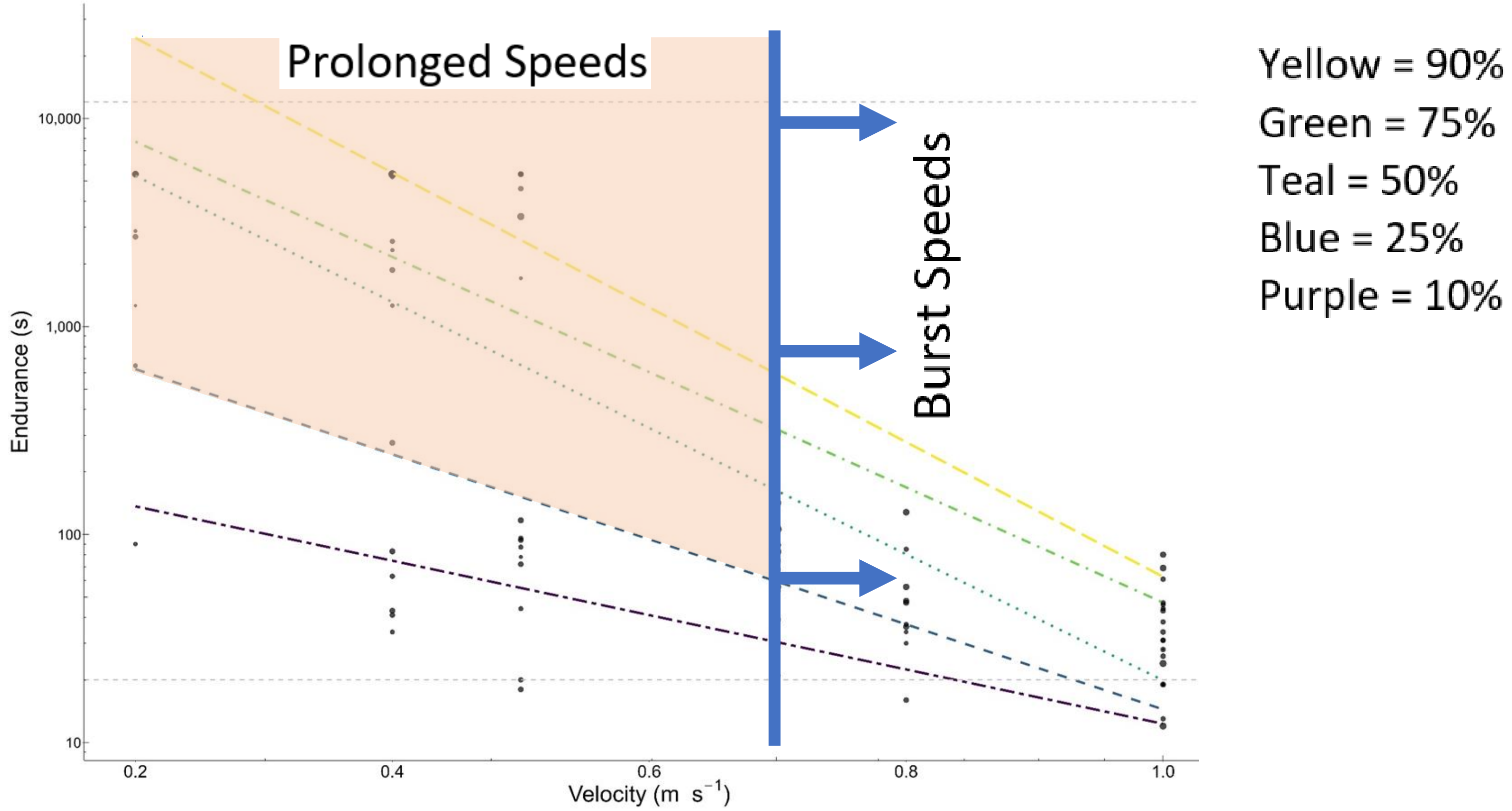
Velocity Threshold for Fish Passage

Prolonged Swimming Speeds are Applied for Culverts

- Preliminary plot of prolonged swimming speeds for target species



- (NIWA, Franklin and Crawford):

Velocity Threshold for Fish Passage

General Approach

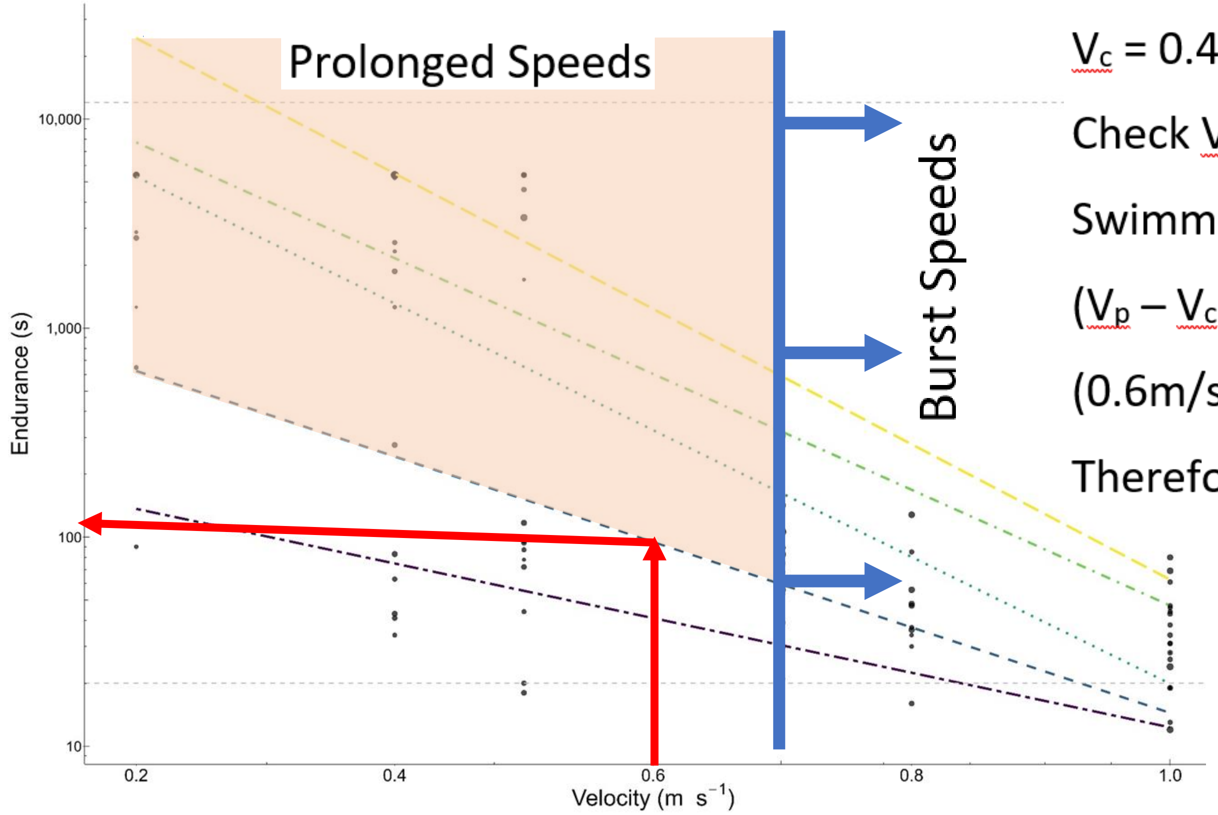
- $\mathbf{V_p} > \mathbf{V_c}$, where $\mathbf{V_p}$ is the prolonged fish velocity of the fish within the culvert and $\mathbf{V_c}$ is the velocity of the water within the culvert.
- Effective velocity ($\mathbf{V_{ef}}$) of the fish through the culvert is $\mathbf{V_p} - \mathbf{V_c}$.
- $\mathbf{T_p}$ is the duration that a fish can maintain a prolonged swimming velocity in seconds.

- $(\mathbf{V_p}\,\text{m/s} - \mathbf{V_c}\,\text{m/s}) \times \mathbf{t_p}\,\text{s} > \mathbf{L}\,\text{m}$ *or* $\mathbf{V_{ef}}\,\text{m/s} \times \mathbf{t_p}\,\text{s} > \mathbf{L}\,\text{m}$

Velocity Threshold for Fish Passage

The solution and the problem

We don't usually design culverts with mean velocities of 0.4m/s.



V_c = 0.4m/s

Check V_p = 0.6m/s

Swimming Duration (T_p) = 102s

(V_p – V_c) X T_p > L

(0.6m/s - 0.4m/s) X 102s = 20.4m

Therefore L must be less than 20.4m

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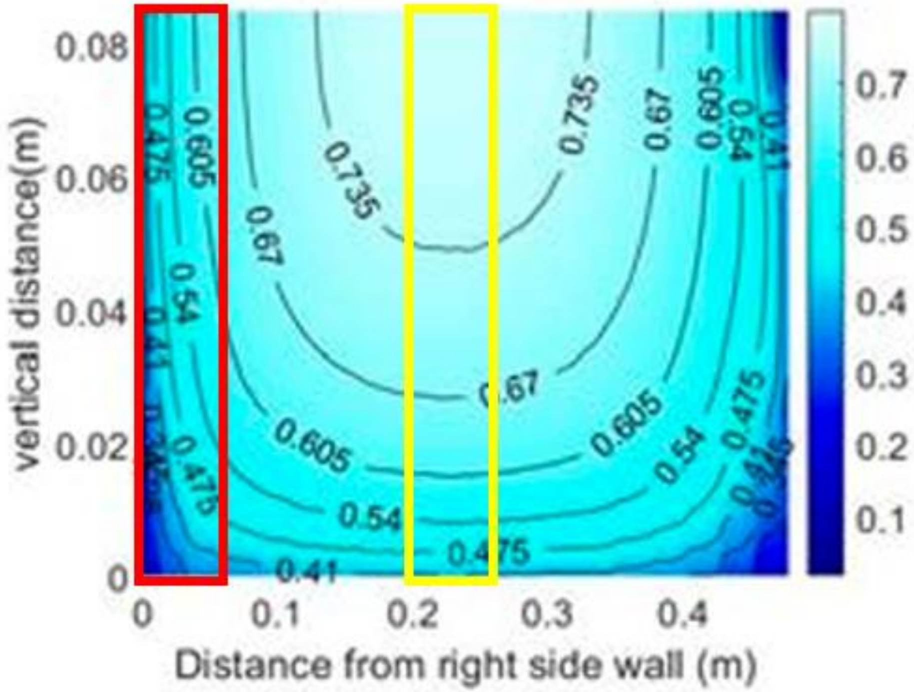
Velocity Threshold for Fish Passage

The solution to the Solution

- Mean culvert velocities generally exceed the sustained and prolonged swimming speeds of NZ native fish species.
- Velocity distribution within the culvert needs to be accounted for, to accommodate NZ fish.
- The best practical way to account for the velocity distribution is look at depth-averaged slices of the design flow within the culvert (Zhai et al).



Velocity Distribution from Zhang and Chanson

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Approach and Methodology

US FHWA Publication number FHWA-HRT-14-064, *Fish Passage in Large Culverts*, by Yuan Zhai et al (2014) provides an empirically derived approach for approximating culvert velocity distribution with depth averaged velocities in vertical slices of the flow within the culvert.

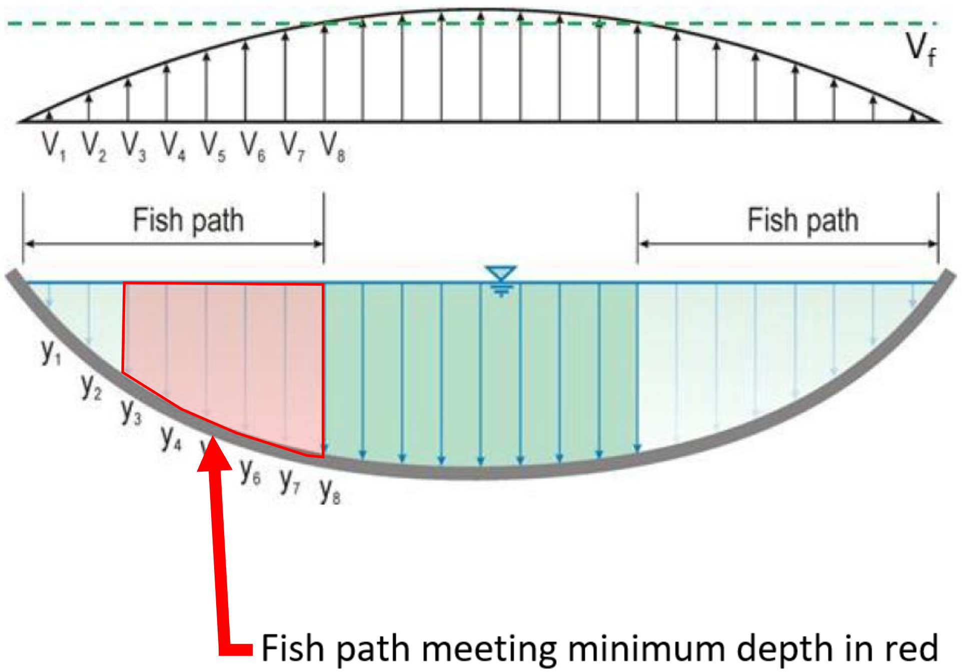
Three simple and readily available approaches for approximating the depth averaged velocity along the culvert walls are:

Approach and Methodology

Culvert Design using HY-8

HY-8 is a culvert design and analysis software published by the US FHWA.

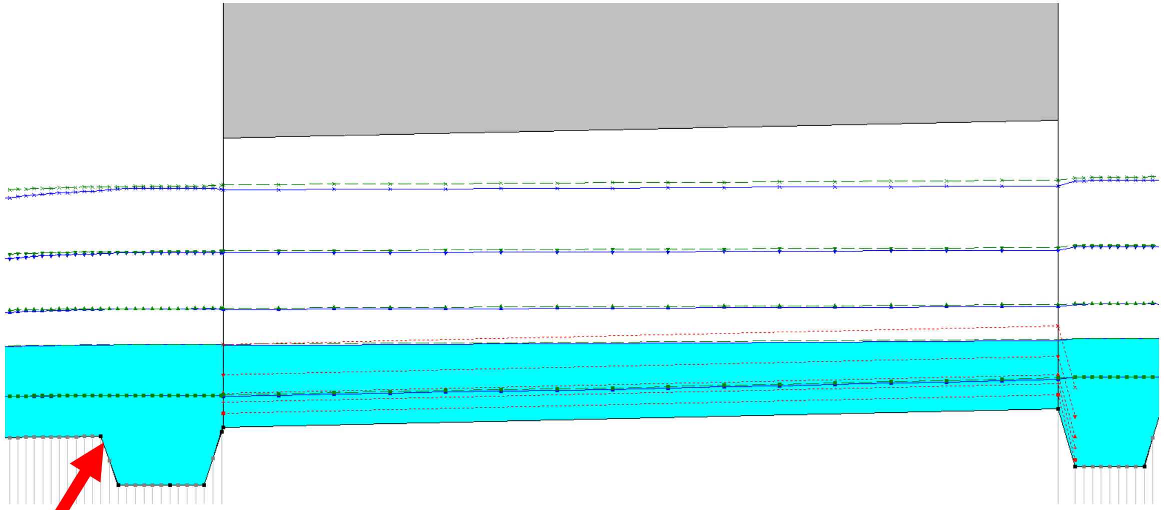
HY-8 directly applies the methods for determining depth averaged velocities in *Fish Passage in Large Culverts*, by Yuan Zhai et al (2014).



Approach and Methodology

Culvert Design using HEC-RAS 1D

HEC-RAS 1D can be used. The mean velocities at the upstream and downstream ends of the culvert can be divided by 3. If V_{mean} /3 is not low enough to allow fish passage, the HEC-Ras input and output can be used to populate the HY-8 input.



Modelling culverts HEC-RAS allows the effects of the stream and aprons to be accounted for.

Culvert Output

File Type Options Help

River: Stream 3 | Profile: 0.5-2 year | Culv Group: Culvert #2

Reach Stream 3 | RS: 192 | Plan: Plan 17

Plan: Plan 17 Stream 3 Stream 3 RS: 192 Culv Group: Culvert #2 Profile: 0.5-2 year

Q Culv Group (m3/s)	1.90	Culv Full Len (m)	
# Barrels	1	Culv Vel US (m/s)	0.54
Q Barrel (m3/s)	1.90	Culv Vel DS (m/s)	0.45
E.G. US. (m)	12.23	Culv Inv El Up (m)	11.62
W.S. US. (m)	12.22	Culv Inv El Dn (m)	11.46
E.G. DS (m)	12.18	Culv Frctn Ls (m)	0.04
W.S. DS (m)	12.17	Culv Exit Loss (m)	0.00
Delta EG (m)	0.05	Culv Entr Loss (m)	0.01
Delta WS (m)	0.05	Q Weir (m3/s)	
E.G. IC (m)	11.95	Weir Sta Lft (m)	
E.G. OC (m)	12.23	Weir Sta Rgt (m)	
Culvert Control	Outlet	Weir Submerg	
Culv WS Inlet (m)	12.21	Weir Max Depth (m)	
Culv WS Outlet (m)	12.17	Weir Avg Depth (m)	
Culv Nml Depth (m)	0.44	Weir Flow Area (m2)	
Culv Crt Depth (m)	0.22	Min El Weir Flow (m)	17.22

Errors, Warnings and Notes

V_{mean} output for each culvert cell is available in standard output tables.

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Approach and Methodology

HEC-RAS 1D Bridge Design for Bottomless Culverts

HEC-RAS 1D flow distribution function can be sued to provide a reasonable velocity distribution within bottomless culverts or culverts with full stream simulation.

Bridge Output

File Type Options Help

River: Stream 3 Profile: 0.5-2 year

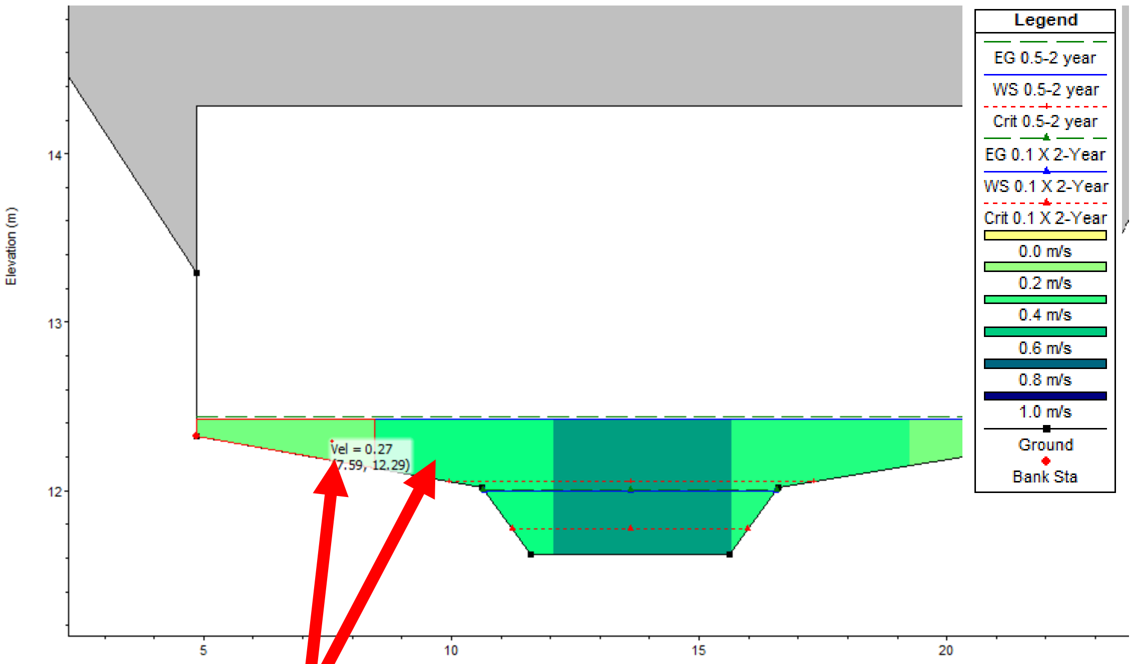
Reach Stream 3 RS: 192 Plan: Plan 16

Plan: Plan 16 Stream 3 Stream 3 RS: 192 Profile: 0.5-2 year

E.G. US. (m)	12.44
W.S. US. (m)	12.43
Q Total (m3/s)	3.84
Q Bridge (m3/s)	3.84
Q Weir (m3/s)	
Weir Sta Lft (m)	
Weir Sta Rgt (m)	
Weir Submerg	
Weir Max Depth (m)	
Min El Weir Flow (m)	17.22
Min El Prs (m)	14.28
Delta EG (m)	0.25
Delta WS (m)	0.26
BR Open Area (m2)	40.88
BR Open Vel (m/s)	0.64
BR Sluice Coef	
BR Sel Method	Energy only

Element	Inside BR US	Inside BR DS
E.G. Elev (m)	12.44	12.20
W.S. Elev (m)	12.43	12.18
Crit W.S. (m)	12.05	11.89
Max Chl Dpth (m)	0.81	0.72
Vel Total (m/s)	0.51	0.64
Flow Area (m2)	7.50	5.95
Froude # Chl	0.18	0.24
Specif Force (m3)	2.31	1.79
Hydr Depth (m)	0.42	0.33
W.P. Total (m)	18.38	18.21
Conv. Total (m3/s)	63.7	43.5
Top Width (m)	18.00	18.00
Frctn Loss (m)	0.24	0.01
C & E Loss (m)	0.00	0.00
Shear Total (N/m2)	14.53	24.98
Power Total (N/m s)	7.44	16.11

Errors, Warnings and Notes



Bottomless culvert with stream simulation showing fish passable zones.

Embedment

Embedment Varies with Application

- Round Culverts – 1/3 X D minimum to ½ D maximum.
- Box Culverts - Minimum 300mm or 1.95 X D_{50}
- Bottomless Culverts or Culverts with full stream simulation – Requires separate methodologies for the main channel bed and the zones along the culvert walls.

Embedment and culvert design must take the natural bedload and sediment transport balance into consideration.

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Embedment

Sizing Ordinary Embedment in Culverts

Apply the Maximum Shear Stress Method

$$\tau_d = \gamma y S$$

τ_d = maximum applied shear stress (N/m^2)

γ = unit weight of water (N/m^3)

y = maximum depth (m)

S = energy slope (m/m)

For pressure flow, use the height of the modelled energy grade line (EGL) above the bed to calculate the maximum Shear stress

$$y = EGL - INV - \frac{V^2}{2g}$$

y = depth (m)

EGL = energy grade line elevation at point of analysis (m)

INV = bed elevation at point of analysis (m)

V = velocity (m/s)

g = acceleration due to gravity (m/s^2)

FHWA-HIF-11-008, Kilgore et al, 2010)

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Embedment

Bottomless Culverts and Stream Simulation

Due to the scour patterns in bottomless culverts and stream simulation, embedment design will vary between maximum applied shear stress for the channel bed and the equation developed by Kerenyi et al, 2007 as shown below:

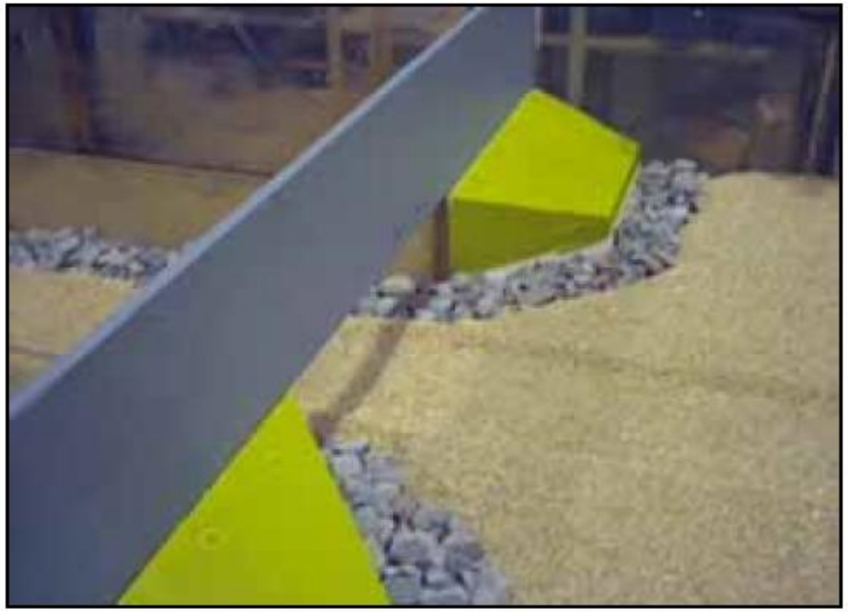

Figure 18.7. Riprap protection at a bottomless culvert with the MDSHA Standard Plan (Kerenyi et al. 2007).

Figure 18.4. Rectangular model with wing walls (Kerenyi et al. 2003).

$$d_{50} = \frac{K_r y_0}{(S_g - 1)} \left(\frac{V_{AC}^2}{g y_0} \right)^{0.33}$$

Figures and Equation from HEC-23 V2, Lagasse et al

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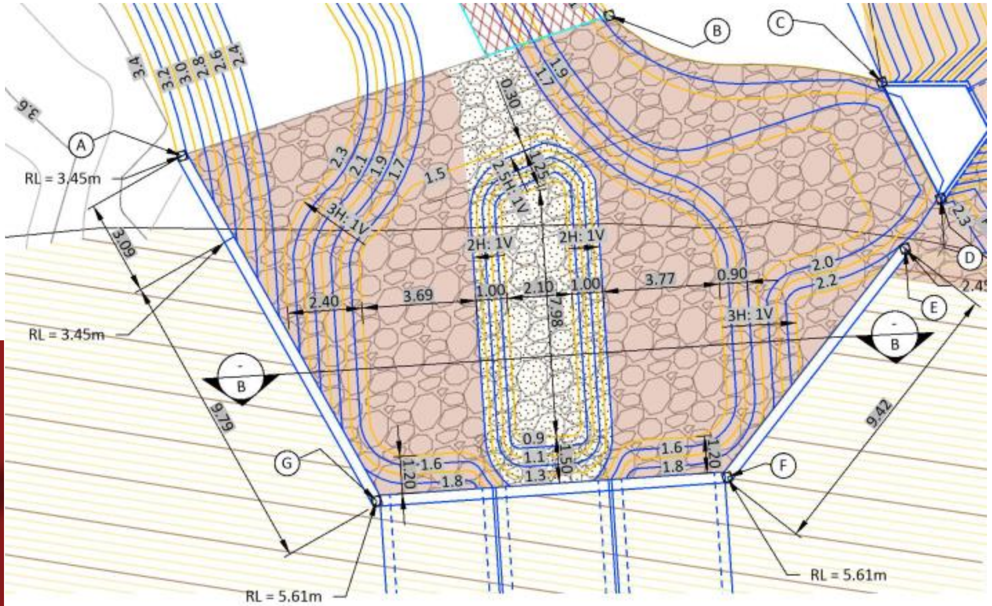
Culvert Aprons

Outlet Aprons

Culvert aprons should be designed to facilitate fish passage into the culvert, in addition to preventing scour.



Outlet aprons can provide resting places for fish prior to working upstream through the culvert.

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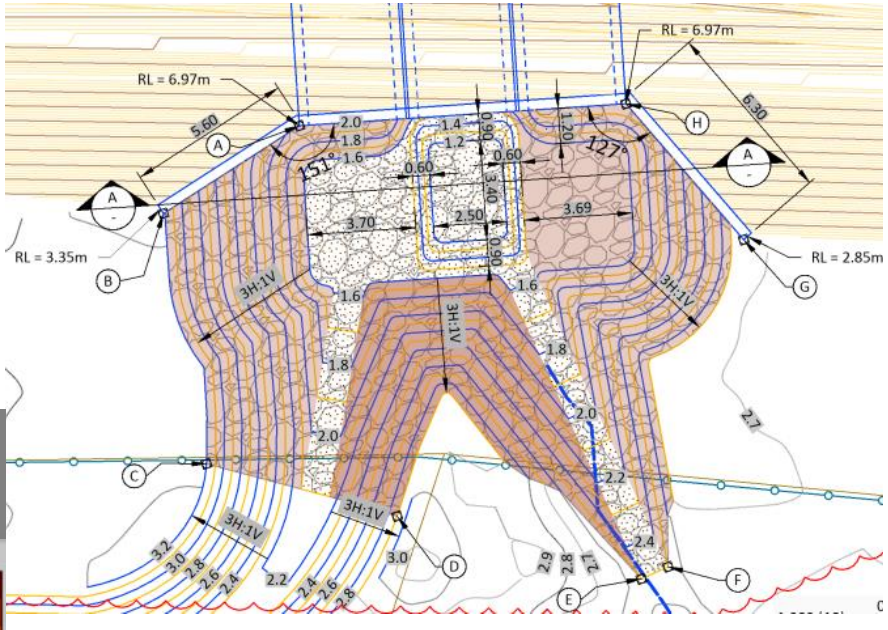
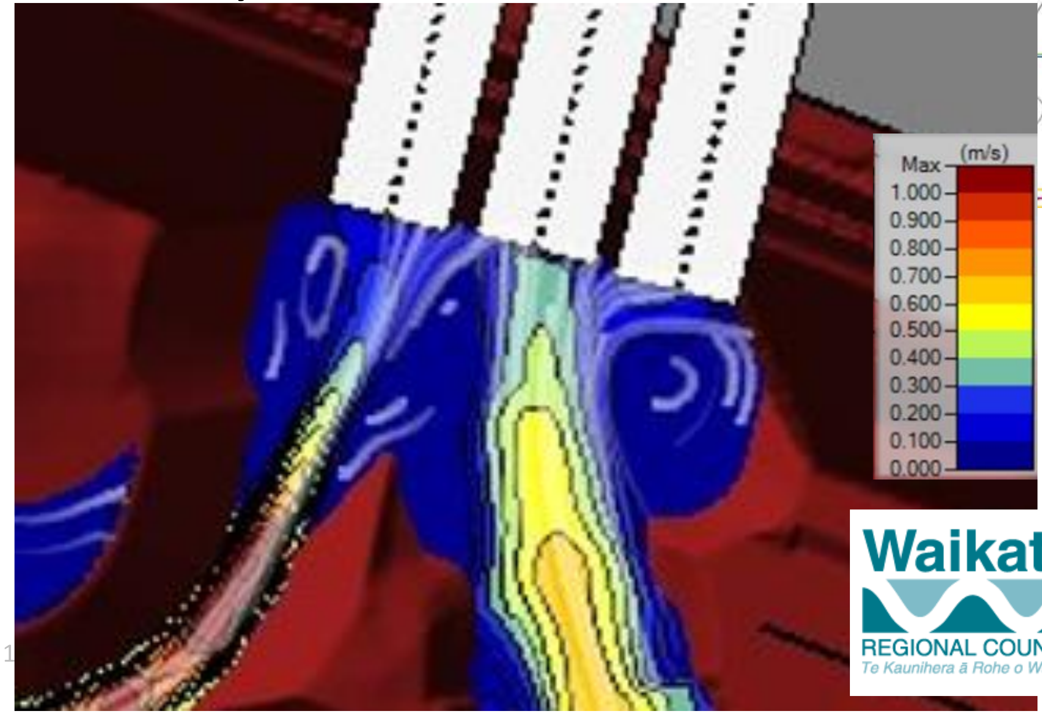
Culvert Aprons

Inlet Aprons

Flow contraction at the culvert inlet can prevent fish from successfully exiting the culvert. The inlet apron can reduce the this effect and provide a low velocity area for refuge and recovery.





Soil Riprap and Void-Filled Riprap

Avoid making a barrier out of riprap

The new guidelines will also cover the use of soil riprap and void-filled riprap to prevent barriers and improve habitat function.

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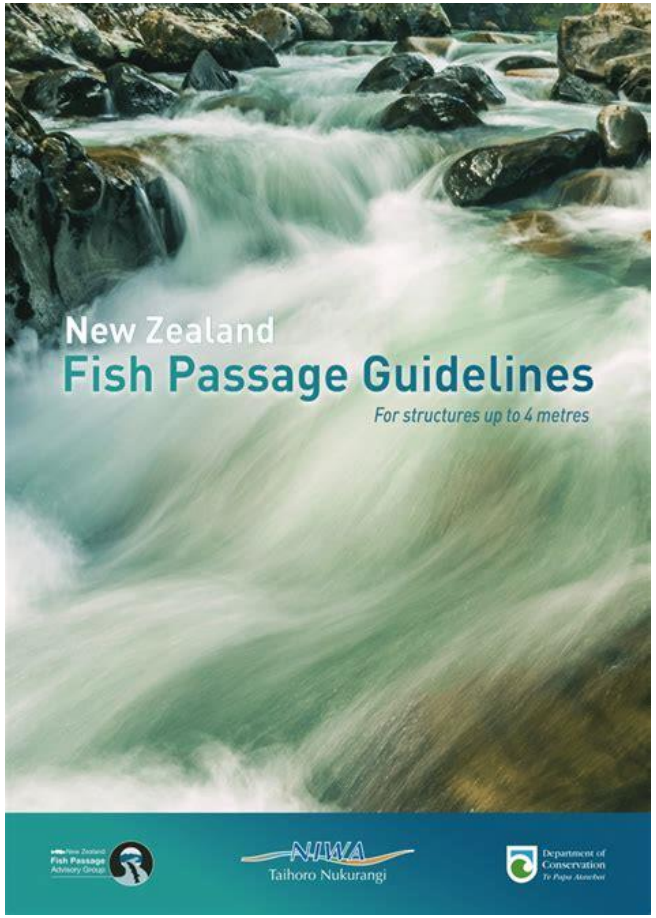
Questions….



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