Stream Simulation Culvert Performance Evaluation Tool

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INTRODUCTION

The Chehalis Basin has 2,700 culverts documented as being barriers to fish passage. Hydraulic and geomorphic theories suggest that, if discharges and sediment loads increase, in-stream velocities rise and the channel responds by increasing its BankFull Width (BFW). Hence if (as expected), stream discharges and catchment sediment yields in the Chehalis Basin increase due to changes in land use and climate, the possibility exists that culverts which currently meet fish passage requirements may cease to do so within their service lives.

These considerations have led the Washington Department of Fish & Wildlife (WDFW) to investigate how existing culvert designs might be adapted to allow for the possibility that in the future they will need to safely convey higher stream flows and sediment loads in wider channels, while continuing to meet requirements for fish passage.

Environmental Science Associates (ESA) collaborated with WDFW and Natural Systems Design Group to model existing culverts that were designed according to WDFW stream simulation design standards in the Chehalis Basin, Washington. The models illustrated the need to account for uncertainty in both our understanding of current flow and geomorphic processes at culverts and how these may respond to climate change. The aim of the project was to develop a relatively simple culvert performance evaluation tool based on first principles.

Rapid Culvert Performance Evaluation Tool of Fluvial Processes and Fish Passage

To inform design adaptation, engineers need to know whether existing culvert designs (e.g. no-slope, stream simulation) meet performance objectives under current and forecast future conditions and, with respect to any aspects in which they do not, how current designs need to be enhanced so that they meet performance objectives throughout the service life of the culvert.

The aim of the project was to develop a relatively simple (reduced complexity) pilot culvert performance evaluation tool, while exploring options for further developing and refining the tool as the field monitoring program continues and additional culvert parameters and fluvial performance data become available.

The performance evaluation tool has only been applied to five of the WDFW observed culverts. Field data and data output by River Flow 2D were used to evaluate the performance of the existing culvert under discharges representing flows with return periods of 2, 10, 25, 100 and 500 years (i.e. the current Q2, Q10, Q25, Q100 and Q500 events). Culvert performance with respect to stream simulation was then re-evaluated with all these discharges increased by 22%, to represent future flows with the specified return periods. Output from the Nays 2Dh Model for the 10-year recurrence interval (existing and future flows) were also evaluated with the performance evaluation tool for Comfort Creek. In this study, the performance of three culvert configurations were evaluated to investigate the sensitivity of the tool to changes in culvert width and channel shape.

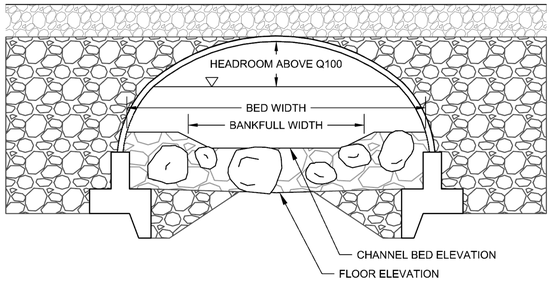
Project Data

Project Name: Chehalis Basin Sediment Transport
Client: Washington Department of Fish & Wildlife
Location: Thurston County, WA

CULVERT PERFORMANCE EVALUATION TOOL

Culvert Performance Metrics

- **Average Velocity** – equal velocity in culvert and stream
- **Headroom** – water surface elevation at Q100 < culvert crown elevation
- **Bankfull Width** – equal BFW in culvert and stream
- **Long-stream bed profile** – no bed discontinuity > 0.8 ft.
- **Bed Character** – equal median grain size and gradation in culvert and stream
- **Bed Mobility** - equal discharge to mobilize bed in culvert and stream
- **Sediment Connectivity and Continuity** –equal slope of sediment rating curve in culvert and stream
- **Channel Scour** - stream scour prism does not interact with culvert walls, floor, or footings
- **Channel Platform Dynamics** – channel within a long culvert does not find the walls at multiple locations



Typical culvert section showing some of the culvert performance metrics.

Data Input Form and Tool Calculations

Field Observations			
Feature	Parameter	Definition	Units
Culvert	$L_{culvert}$	Length of culvert	ft
	N_{Wall}	Number of times the stream finds culvert wall	--
	$CrownElev_{culvert}$	Elevation of the top of the culvert	ft*
	$FloorElev_{culvert}$	Elevation of the hard culvert floor (if applicable)	ft*
	$FootElev_{culvert}$	Elevation of culvert wall footings (if applicable)	ft*
	$BedElev_{culvert}$	Culvert bed elevation at culvert outfall	ft*
	$BedElev_{stream}$	Stream bed elevation at culvert outfall	ft*
	$D16_{culvert}$	16th percentile bed grain size in culvert	mm
	$D50_{culvert}$	Median bed grain size in culvert	mm
	$D84_{culvert}$	84th percentile bed grain size in culvert	mm
	$\sigma_{culvert}$	Grain gradation of culvert	
	$W_{culvert}$	Width of existing culvert	ft
Stream	BFW_{stream}	BankFull Width of stream	ft
	$D16_{stream}$	16th percentile bed grain size in stream	mm
	$D50_{stream}$	Median bed grain size in stream	mm
	$D84_{stream}$	84th percentile bed grain size in stream	mm
	σ_{stream}	Grain gradation of stream	--
Modeling Results			
Feature	Parameter	Definition	Units
Culvert	$V_{culvert}$	Average velocity in culvert	fps
	$V_{culvert\_SD}$	Standard deviation of velocity in culvert	fps
	$Q_{thculvert}$	Threshold discharge for bed mobilization in culvert	cusecs
	$(\delta Q_s/\delta Q)_{culvert}$	Slope of bed shear vs discharge curve in culvert	--
Stream	V_{stream}	Average velocity in stream	fps
	V_{stream_SD}	Standard deviation of velocity in stream	fps
	WSE_{stream}	Water Surface Elevation approaching culvert entrance	
	$Q_{thstream}$	Threshold discharge for bed mobilization in stream	cusecs
	$(\delta Q_s/\delta Q)_{stream}$	Slope of bed shear vs discharge curve in stream	--

The reduced complexity tool requires existing culvert and stream data in conjunction with modeling results to assess the culvert performance metrics.

To apply the evaluation tool for a selected culvert and stream discharge, the relevant culvert performance parameters are entered into the Field Observations and Modeling Results input tables. Stream Simulation Metrics are then calculated and displayed in the Performance Evaluation Table, together with (1) symbol indicating the outcome of the performance evaluation and (2) a precise comment explaining why the culvert passed, nearly passed, or failed to match stream simulation performance according to that metric. A green tick indicates that the calculated metric falls within the acceptable band for successful stream simulation (i.e. a pass). An orange circle indicates that the metric falls tolerably close to the acceptable band (i.e. a near miss). A red cross indicates that the metric falls outside the tolerable band (i.e. a fail).

Stream Simulation Metric Identity	Metric Value	Stream Simulation Match	Comments
$V_{match} = V_c/V_s$	1.56	✘	Culvert velocity too high
$WSE_{stream} < CrownElev_{culvert}$	8.78	✓	Culvert headroom acceptable
$BFW_{match} = BFWc/BFWs$	1.00	✓	Culvert BFW acceptable
$Bed_{change} = (BedElev_c - BedElev_s) < 0.8$ ft	0.04	✓	Bedchange is acceptable
$D50_{match} = D50_c/D50_s$	2.60	✘	Median grain size is too high
$\sigma_{match} = \sigma_c / \sigma_s$	--		Not enough data
$Qcrit_{match} = Qcrit_c/Qcrit_s$	1.46	✘	Bed mobility too high
$(\delta Q_s/\delta Q)_{match} = (\delta Q_s/\delta Q)_c/(\delta Q_s/\delta Q)_s$	1.29	✘	Sediment connectivity and continuity is too high
$BFW_{culvert} < W_{culvert}$	0.66	✓	Width of culvert is acceptable
$FloorElev_{culvert} < BedElev_{culvert}$	3.92	✓	Culvert bed elevation is acceptable
$FootElev_{culvert} < BedElev_{culvert}$	3.92	✓	Culvert foot elevation is acceptable
$N_{wall} < 3$	--		Not enough data

The existing conditions data and modeling results are used in calculations to evaluate the culvert performance metrics.

Results

1.5 x BFW with Benches - Current Flows

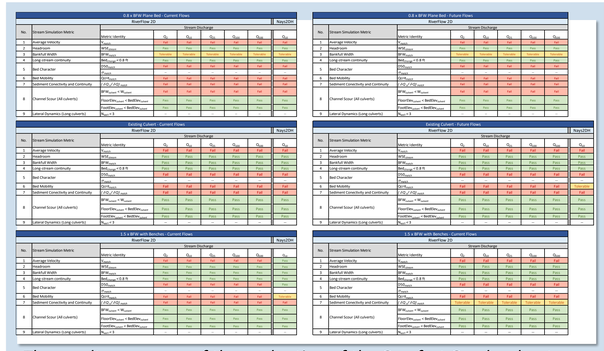
		RiverFlow 2D						Nays2DH
		Stream Discharge						
No.	Stream Simulation Metric	Metric Identity	Q_2	Q_{10}	Q_{25}	Q_{100}	Q_{500}	Q_{10}
1	Average Velocity	V_{match}	Fail	Fail	Fail	Fail	Fail	Pass
2	Headroom	WSE_{stream}	Pass	Pass	Pass	Pass	Pass	Pass
3	Bankfull Width	BFW_{match}	Pass	Pass	Pass	Pass	Pass	Pass
4	Long-stream continuity	$Bed_{change} < 0.8$ ft	Pass	Pass	Pass	Pass	Pass	Pass
5	Bed Character	$D50_{match}$	Fail	Fail	Fail	Fail	Fail	Pass
		σ_{match}	--	--	--	--	--	--
6	Bed Mobility	$Qcrit_{match}$	Fail	Fail	Fail	Fail	Fail	Tolerable
7	Sediment Conectivity and Continuity	$(\delta Q_s/\delta Q)_{match}$	Fail	Fail	Fail	Fail	Fail	Fail
8	Channel Scour (All culverts)	$BFW_{culvert} < W_{culvert}$	Pass	Pass	Pass	Pass	Pass	Pass
		$FloorElev_{culvert} < BedElev_{culvert}$	Pass	Pass	Pass	Pass	Pass	Pass
		$FootElev_{culvert} < BedElev_{culvert}$	Pass	Pass	Pass	Pass	Pass	Pass
9	Lateral Dynamics (Long culverts)	$N_{wall} < 3$	--	--	--	--	--	--

Results table summarizes the results of the performance evaluation calculations for each stream discharge.

Results are summarized in an output patchwork quilt indicating if the culvert is acceptable, tolerable, or unacceptable for each performance metric at each stream discharge. If additional modeling methods were used to evaluate the culvert, the modeling results can be placed adjacent on the results table for comparison. Displaying the results of all culvert model permutations together allows the user to quickly compare culvert geometric permutation performance under various flow events.

CONCLUSIONS

This culvert performance evaluation tool allows the user to easily evaluate the fluvial processes and fish passage performance of a culvert for various stream discharges and configurations. The results are displayed in a summary quilt to allow for quick comparison.



The results summary of the evaluation of the Comfort Creek culvert. Three culvert configurations were evaluated at five flood events at current and future flows.

Based on the tool's evaluation of the culvert crossing Comfort Creek, stream simulation performance was improved by the addition of benches inside the culvert.

Future Goals

This tool is still in the early stages of development. Further testing is recommended to refine the tool and increase performance confidence.

Evaluating additional culverts could improve the accuracy of the tool and possibly improve stream simulation standards of practice.

After thorough testing and evaluation of a variety of culverts, this tool could potentially be released for broad use.

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More on This Project

POSTER: "Futureproofing Stream Simulation – Exploratory Hydraulic Modeling to Investigate the Influence of Stream Simulation Culverts on Stream Process and Sediment Transport Now and In the Future," Steve Winter, Natural Systems Design

POSTER: "2D Morphodynamic Modeling of a Stream Simulation Culvert," Mason Lacy, ESA

PRESENTATION: "Quantifying Performance of Stream Simulation Culverts in the Chehalis Basin," Joe Richards, ESA | Jane Atha, WDFW | Steve Winter, Natural Systems Design | Colin Thorne, ESA