Hydraulic modeling and upstream fish passage effectiveness evaluation at rock vortex weirs based on field observations

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Abstract

In the Upper Columbia River basin, many streams are diverted for irrigation by diversion dams, some of which are considered to block passage of endangered salmonids to spawning and rearing habitat. In Beaver Creek, a tributary to the Methow River, the U.S. Bureau of Reclamation replaced irrigation diversion dams with a series of rock vortex weirs to provide upstream passage for salmonids and maintain irrigation diversion. A monitoring program was implemented to evaluate the effectiveness of the rock vortex weirs for fish passage. Temperature, discharge, channel topography, and fish movement were monitored. Through a linear decoupled approach, a four-mode hydraulic model was developed to describe flow over the rock vortex weirs as orifice flow, gap flow, weir flow, and rough boundary flow. Using this four-mode model and field observations, rating curves for hydraulic variables important to fish passage were developed and applied to continuous flow records at the study sites, resulting in a chronological record of critical hydraulic parameters. These data were combined with records of fish passage collected by the U.S. Geological Survey's Columbia River Research Laboratory to compare hydraulic conditions to observed fish migration. Hydraulic drops during fish migration periods were estimated from 0.16 to 0.28 m, versus a guideline of 0.24 m, maximum. The ratio of pool depth to hydraulic drop ranged from 1.6 to 20, versus a guideline 1.5, minimum. Energy dissipation factors in the weir pools varied from 63 to 573 W/m^3, versus a guideline of 250 W/m^3, maximum. Cross section averaged velocity at the weir crest varied from 0.14 to 0.94 m/s, versus a guideline of 0.37 m/s, maximum. Based on a hydraulic analysis and recorded fish passage data, the rock vortex weirs demonstrated favorable performance in the first two years following their installation.

Introduction

In the Beaver Creek watershed, located within the Methow River basin, some small irrigation diversion dams for farms and ranches are considered barriers to upstream passage for spawning and rearing habitat for native stocks of summer steelhead (*Oncorhynchus mykiss*) and spring Chinook (*O. tshawytscha*), both listed as endangered under the Endangered Species Act (COE UPA 2004). State and federal agencies have focused on the Methow River basin to improve and increase habitat for these endangered fish. Pilot projects to remove existing diversion barriers and replace them with rock vortex weirs were implemented along Beaver Creek (USFS

33rd IAHR Congress: Water Engineering for a Sustainable Environment

ISBN: 978-94-90365-01-1

1992, BOR 2004). The goals were to provide opportunity for upstream migration of adult and juvenile fish and maintain water diversion for stakeholders. Limited studies have been done on juvenile fish passage at natural and man-made barriers, and more study is needed (Pearson 2005). Specifically, performance of rock vortex weirs for upstream fish passage is relatively unstudied, prompting the U.S Bureau of Reclamation (BOR) to evaluate performance through hydraulic modeling, monitoring fish movement, and assessing upstream fish passage. Selected findings from Ruttenberg (2007) thesis work are presented here, as performed by the University of Idaho, Center for Ecohydraulics Research (CER) in collaboration with the U.S. Geological Survey's Columbia River Research Laboratory (USGS-CRRL).

Description of the Beaver Creek watershed and pilot projects

The Beaver Creek watershed is a 290 km^2 basin located in north-central Washington on the eastern side of the Methow River, which meets the Columbia River upstream of Wells Dam, approximately 843 km from the Columbia River estuary. Average annual rainfall in the Beaver Creek watershed is about 58 cm and run-off in the late spring is rainfall-driven, which is typical for the basins on the eastern side of the Methow River Basin. Temperatures in the Methow River basin range from -29 to +38 °C and topography ranges from elevation 240 m to 2,730 m. Average stream slope is from 1.5 to 2.0 percent within the study reaches on Beaver Creek. Land use in the Beaver Creek basin includes managed forest land in the upper watershed, privately owned cropland and farms in the lower watershed, and recreational uses throughout. Collectively, land use and recreational use have impacted aquatic habitat in much of the Beaver Creek basin (USFS 1992). Sedimentation has embedded cobbles and gravels in the Beaver Creek basin, inhibiting salmonid spawning.

Utilizing grant funding from the State of Washington's Salmon Recovery Funding Board (SRFB), pilot projects were implemented in Beaver Creek by the BOR in collaboration with the Okanogan Conservation District (OCD), and voluntary efforts of landowners. Three projects implemented on Beaver Creek were studied: Lower Stokes, Thurlow, and Upper Stokes, located 4, 6, and 7 km above the mouth of Beaver Creek, respectively. Typical original diversion dams were composed of stacked logs and plastic sheeting about 1 m tall, which were removed and replaced with a series of trapezoidal rock vortex weirs, designed based on Rosgen (2001). The stream profile was designed for maximum hydraulic drop of 0.24 m at each structure, as required by regulatory authorities. The weirs were strategically placed to provide grade control and maintain backwater for agricultural diversion (BOR 2004). The rock vortex weirs were designed and installed by BOR engineers, in accordance with the National Marine Fisheries Service (NMFS), Washington Department of Fish and Wildlife (WDFW), Endangered Species Act, and COE UPA (2004).

Project collaboration with USGS-CRRL and fish movement data

Concurrent with the CER hydraulic study, monitoring of fish movement was conducted by the USGS-CRRL along Beaver Creek. The USGS-CRRL trapped fish in a weir, PIT-tagged captured fish, and installed a network of interrogation systems for PIT-tagged fish. The weir was located 2 km below Lower Stokes (Site A, about 3 km above the mouth of Beaver Creek). The four PIT tag interrogation systems were located 3 km downstream of Lower Stokes (Site B, just upstream of the fish weir), 20 m downstream of Lower Stokes (Site C), 100 m upstream of Lower Stokes (Site D), and about 5 km upstream of Lower Stokes (Site E). These types of instream PIT tag interrogation systems are further described in Connolly et al. (2008). During 2004 and 2005, about 3,900 juvenile and adult fish were captured, measured, inventoried, and injected with passive integrated transponder tags (PIT-tags) by the USGS-CRRL. Between deployment on 27 September 2004 and end of operation on 22 November 2005, a total of 21 rainbow trout / juvenile steelhead, 4 juvenile brook trout, and 4 adult steelhead were detected moving upstream past the rock vortex weirs at Lower Stokes. Adult steelhead moved upstream past the Lower Stokes rock weirs in late April 2005, and juveniles moved in a group from early June to early July 2005.

Performance criteria from NMFS and WDFW

Existing agency guidelines for fish passage at culverts were adapted to evaluate weir performance for upstream fish passage (NMFS 2000, WDFW 2003). These guidelines specify hydraulic parameters to be satisfied during the primary migration season while the flow is between exceedance flows of 5- and 95-percent. For summer steelhead and spring Chinook, the primary migration period in Beaver Creek for all life stages was considered to be from February 1 to July 7, based on records of fish movement by the USGS-CRRL. The four hydraulic parameters and their threshold values evaluated were maximum hydraulic drop of 0.24 m, minimum ratio of pool depth to hydraulic drop of 1.5, maximum average cross section velocity at the weir crest of 0.37 m/s, and maximum energy dissipation factor (EDF) of 250 W/m^3. A volume-based EDF was calculated as $\gamma \cdot (Q \cdot h_{drop}) / V_p$, where Q is discharge in m^3/s; h_{drop} is hydraulic drop in m, determined from hydraulic modeling; and V_p is pool volume in m^3, calculated from stage-volume relation developed from ground survey.

Modeling approach

The modeling approach determined basin hydrology, developed new techniques to model fish passage hydraulic parameters around rock vortex weirs, simulated continuous records of hydraulic parameters during fish passage at rock vortex weirs, and evaluated performance of rock weirs over a range of flows in meeting existing regulatory fish passage guidelines developed for culverts.

The hydrology of the Beaver Creek basin was derived from USGS records and continuous flow data collected by the CER at the pilot project sites on Beaver creek from pressure transducers and calibrated, log-based rating curves. Average daily flows from the USGS historical record from 1959 to 1978 and measured flow from 2004 to 2005 were combined for flow duration and Log Pearson Type III distribution flood frequency analysis (USGS 1981) (Table 1).

Table 1. Hydrology of Beaver Creek basin

	Flow Duration		Flow Frequency (years)						
units	Qlow (95%)	Qfp (5%)	1	2	5	10	25	50	100
m^3/s	0.1	3.5	0.7	4.2	6.9	8.7	10.7	12.2	13.5
cfs	3.5	124	25	149	245	306	380	430	478

The hydraulic modeling approach studied the Lower Stokes site as a calibration site, with the Thurlow and Upper Stokes as quasi-validation sites for the modeling methods. Velocities and spot discharges were measured by an acoustic doppler velocimeter (ADV) using protocols established by the USGS. Continuous discharge data from the pressure transducers in 2004 and 2005 were applied to hydraulic modeling. Water surface profiles were measured by visual observation of staff gages. Site topography was measured using total station ground survey equipment.

Field data were developed into four-mode, hydraulic models (Figure 1) for each rock vortex weir using a linear decoupled approach, calculating orifice flow (through cracks in the boulders), gap flow (between boulder gaps), weir flow (over the estimated weir crest), and rough boundary flow (over a drowned weir). A spreadsheet-based model was developed to simulate the first three flow modes over rock vortex weirs as water stage increases. As water surface increases each flow mode gains influence on the flow characteristic. The individual flow modes of the hydraulic model were calibrated by varying selected parameters and coefficients until the net calculated stage versus total discharge ($Q_{combined}$) curve matched field measurements (Table 2). Initiation of flow modes and transitions (h_{T1} and h_{T2}) between modes were determined from weir geometry, relative roughness relationships, and field observations (Ruttenberg 2007).

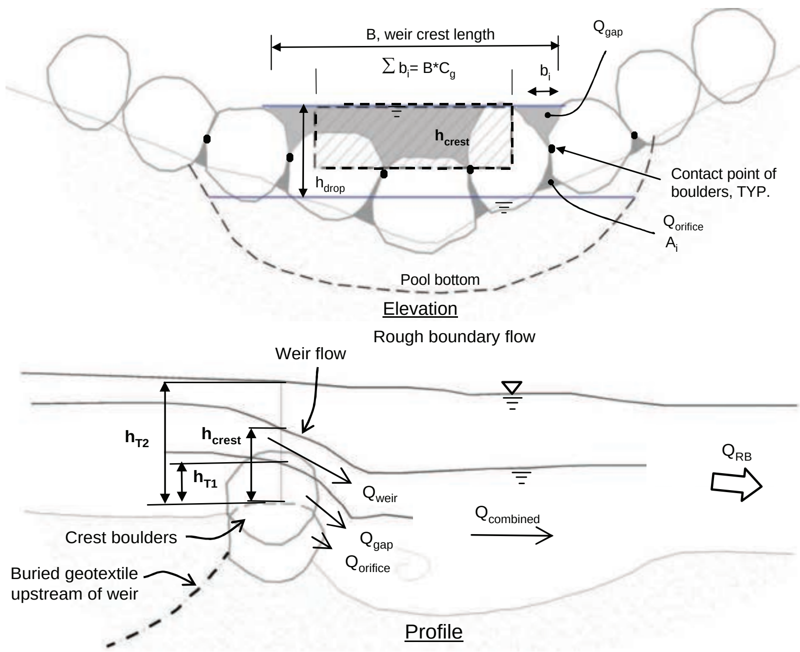

Figure 1. Elevation and profile of four-mode hydraulic model at rock vortex weirs.

Formulae for each flow mode were drawn from traditional theories and general formulations (Table 2). The orifice flow equation was standard formulation from Chow (1959). Gap flow was derived from balancing specific energy upstream with specific energy and critical flow in the gaps between the boulders of the weir crest, plus friction losses (DVWK 2002, Ruttenberg 2007). Weir flow used the general form of the Poleni equation (Chow 1959) and projected weir length, initiating at the threshold height h_{T1}. By adding each flow mode to calculated total combined flow, $Q_{combined}$, a stage discharge curve was constructed to represent each flow mode and total flow. The transition from gap flow to weir flow (h_{T1}) was estimated using weir length versus depth (Ruttenberg 2007). Transition to rough boundary flow (h_{T2}) was estimated based on relative roughness relations from Chow (1959), where rough boundary flow begins when the ratio of water depth to weir boulder roughness, is about 3.0–5.0 (Chow 1959).

Table 2. Formulations for flow modes of hydraulic model

Flow mode	Formulation	Calibration terms
Orifice	$Q_{orifice} = \sqrt{2g \cdot h_{drop}} \cdot A_{eff} \cdot K$	K, A_{eff}
Gap (before weir flow)	$Q_{gap} = \left(\frac{2}{3} \cdot \frac{h_0 + \frac{v_0^2}{2g}}{\left(1 + \frac{\xi}{3}\right)} \right)^{\frac{3}{2}} \cdot \sqrt{g} \cdot B \cdot C_g$	ξ, C_g
Gap (during weir flow)	$Q_{gap} = V_{weir} \cdot A_{gap*}$	None, driven by weir flow
Weir	$Q_{weir} = \frac{2}{3} \cdot \mu \cdot C_w \cdot B \cdot \sqrt{2g} \cdot h_{weir}^{1.5}$	μ
Rough Boundary	One dimensional modeling, replaces orifice, gap, and weir flow modes	

Where:
A_{eff} = total assumed effective flow area in rock orifices, in m^2
K = friction loss coefficient for orifice flow, fixed at 0.6 to reflect higher losses
h_0 = Head just upstream of the boulder crest, based on field observation of staff gages, in m
v_0 = Velocity upstream of the boulders crest, based on discharge, in m/s
Cg = Contraction and roughness coefficient, dimensionless
ξ = Sharp-edged inlet loss coefficient, assumed to be 0.5, dimensionless
B = Total profile length of rock vortex weir crest, from weir geometry, in m
V_{weir} = average cross section velocity according to weir flow, in m/s
A_{gap*} = total flow area below transition to weir flow per h_{T1}, in m^2
μ = Weir coefficient, function of geometry, varies from 0.6 to 0.8
C_w = Contraction coefficient for projected weir crest length, function of weir geometry
h_{weir} = Depth at weir crest for weir flow = depth above transition from gap to weir flow (h_{T1}), in m

Results

Calibration and validation coefficients for the models are shown in Table 3. Sample results from a developed four-mode hydraulic model are shown on Figure 2.

Table 3. Calibration and validation data for hydraulic models of rock vortex weirs.

Beaver Creek pilot project sites	Calibration site			Validation sites	
	Lower Stokes			Thurlow	Upper Stokes
	Weir 1	Weir 2	Weir 3	Weir 1	Weir 1
Weir crest width (m)	1.5	1.5	1.5	1.5	1.8
Average plan angle of wing wall (degrees)	32	28	30	22	40
Wing wall profile slope (percent)	9	10	9	7	11
C_g, contraction factor for gaps	0.10	0.17	0.45	0.07	0.15
μ, weir coefficient	0.80	0.70	0.80	0.50	0.57
C_w, contraction coefficient	ranges from 0.42 to 1.00, varies by geometry				
Transitions for four-mode hydraulic model, estimated					
Gap to Weir, discharge, (m^3/s)	0.15	0.15	0.20	0.09	0.07
Gap to Weir, depth, (m)	0.37	0.34	0.34	0.21	0.18
Weir to Rough boundary, depth, (m)	0.6	0.6	0.4	0.6	0.6

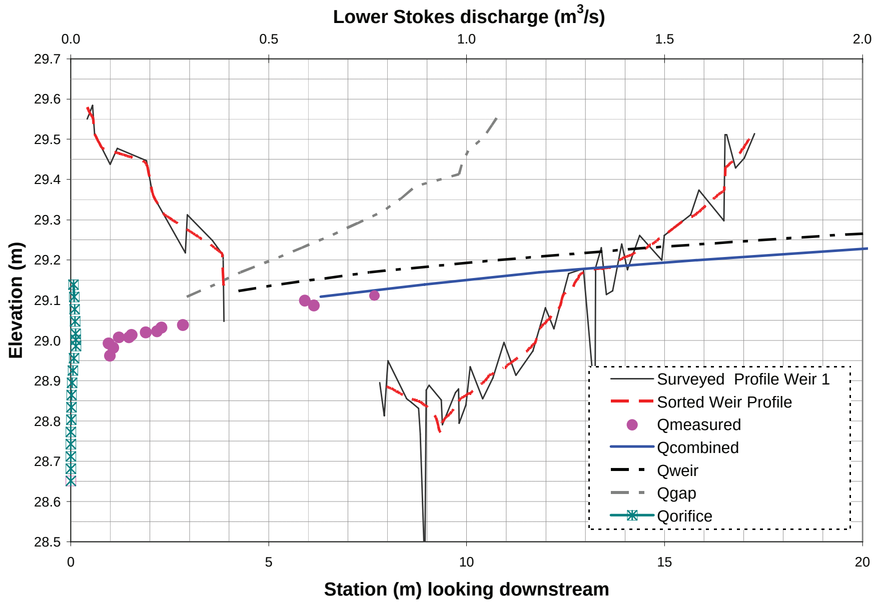

Figure 2. Hydraulic model at Lower Stokes, weir 1. Cross section compared to stage-discharge relations for the hydraulic model. Axes for cross section station and discharge on bottom and top, respectively. Individual flow modes ($Q_{orifice}$, Q_{gap} , and Q_{weir}) and total modeled flow ($Q_{combined}$) compared to measured stage versus discharge. Relative flow contributions of flow modes versus stage shown.

Time series for hydraulic parameters at using rating curves

The four-mode hydraulic models and additional observed data were applied to develop rating curves for hydraulic parameters versus discharge. At each weir, four rating curves were developed: hydraulic drop, ratio of pool depth to hydraulic drop, EDF, and average velocity over the weir (Ruttenberg 2007). Using these rating curves and continuous records of discharge from field recorders, continuous records of critical hydraulic parameters for upstream fish passage were generated for each weir. Fish movement data, as collected by the USGS-CRRL, were compared to time series for these key hydraulic parameters. An example of an estimated time series of hydraulic drop is shown in Figure 3. The hydrograph is also shown in Figure 3 to demonstrate when flow was within the calibrated range *and* within the low and high fish regulation flows (Qlow and Qfp). Additional data are available in Ruttenberg (2007). Summary statistics on hydraulic parameters are shown in Table 4.

Model results show the orifice flow mode had minimal contribution to $Q_{combined}$ of about 0.014 m^3/s, likely due to geotextile sealing the weir crest. The weir coefficient, μ, varied from 0.5 to 0.8 and the gap contraction factor, C_g, varied from 0.07 to 0.45. Transition from gap to weir flow, h_{T1}, occurred from 0.18 to 0.37 m above the weir crest low point, within the trapezoidal shape of the rock vortex weir. Hydraulic parameters for upstream fish passage, based on model output and field observations, indicated values beyond thresholds set by guidelines for culverts. Records of upstream fish movement from the USGS-CRRL confirm fish passage when guidelines were exceeded.

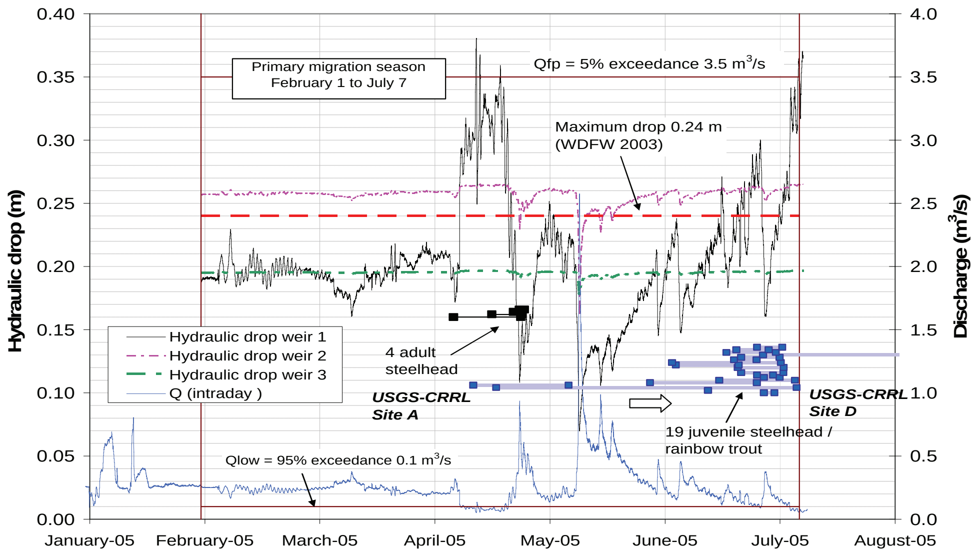

Figure 3. Comparison of fish movement from USGS-CRRL to calibrated hydraulic model of drop at rock vortex weirs at Lower Stokes during 2005 primary migration season. Horizontal bars for fish movement from left to right indicate detection time 3 km downstream (Site A or Site B) to detection time upstream, about 100 m upstream of the rock vortex weirs at Lower Stokes (Site D).

Table 4. Estimated maximum and minimum values for hydraulic parameters at Lower Stokes site during fish passage. Data shown for migration season from February 1 to July 7, within calibrated range of discharge measurement.

Hydraulic parameter		Weir 1	Weir 2	Weir 3
Hydraulic drop	max. (m)	0.28	0.27	0.20
(0.24 m max.)	min. (m)	0.17	0.16	0.18
Ratio of pool depth to hydraulic drop	max. (m/m)	20.4	6.7	6.9
(1.5 min.)	Min.(m/m)	1.6	2.6	2.7
Energy dissipation factor	max. (W/m3)	281	448	573
(250 W/m^3 max.)	min. (W/m3)	177	63	119
Average velocity	max. (m/s)	0.71	0.84	0.94
(0.37 m/s max.)	min. (m/s)	0.14	0.15	0.32

Conclusions

1. A calibrated, four-mode hydraulic model for flow over a rock vortex weir effectively simulated stage versus discharge for rock vortex weirs. These data could be used for stage-discharge relationships at other rock weirs, with field verification.
2. The combination of PIT-tag technology, continuous stage recorders, and models for hydraulic parameters at rock vortex weirs were effective tools to quantify, qualify, and evaluate upstream fish passage at rock vortex weirs.
3. During detected upstream fish movement, comparison of hydraulic parameters to fish passage guidelines for culverts indicated the hydraulic parameters slightly exceeded the guidelines. Further study is needed to better understand effectiveness of rock weirs for leaping versus swim-through behavior during upstream passage.
4. The rock vortex weirs demonstrated favorable performance, based on comparison of hydraulic parameters to fish passage guidelines for culverts and fish movement.

These data and field measurements demonstrate the hydraulic heterogeneity of rock weirs and their effectiveness for upstream passage of salmonids in a wider range of flow conditions than indicated by current literature and guidelines.

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Acknowledgements

Funding for this CER study was provided by the U.S. Bureau of Reclamation. Technical expertise and field support from the USGS-CRRL were essential to the CER modeling. Thanks are also extended to U.S. Forest Service, WDFW, and the Washington State Department of Ecology. Field equipment for the University of Idaho CER was provided by Congressional Award: Fund for the Improvement of Postsecondary Education Award Number P116Z010107, EPSCoR Research Infrastructure Improvement (RII) Grant Grand Challenge Initiative, 2005-2008.