AN EVALUATION OF FISH PASSAGE AT ROCK VORTEX WEIRS

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ABSTRACT

In the Upper Columbia River basin, many streams are diverted for irrigation. Some diversion dams are considered to block passage of endangered salmonids to spawning and rearing habitat. In addition, water diversions affect natural cycles of discharge, substrate composition, sediment transport, and channel morphology. On Beaver Creek, a tributary to the Methow River, in north-central Washington, the U.S. Bureau of Reclamation replaced irrigation diversion dams with a series of rock vortex weirs, with the goal of passing salmonids and maintaining irrigation diversion. To evaluate the effectiveness of the project for fish passage at rock vortex weirs, a monitoring program was implemented. At the subwatershed scale, temperature, discharge, and fish movement were monitored. At the site scale, discharge, temperature, channel topography, and substrate were monitored. A linear decoupled approach was applied to develop a four-mode hydraulic model that described 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, allowing a comparison of field hydraulic conditions to observed fish migration. Hydraulic drops during fish migration periods were estimated from 0.11 to 0.27 m, compared to the fish passage guideline of 0.24 m, maximum. The ratio of pool depth to hydraulic drop ranged from 1.6 to 6.1, compared to guideline value of 1.5, minimum. Energy dissipation factors in the weir pools varied from 66 to 450 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 0.65 m/s, compared to a guideline of 0.37 m/s, maximum. Using these data, effectiveness of rock vortex weirs on fish passage was quantified by applying a grading scale from A to F to the percent of time over the migration season that hydraulic parameters met existing fish passage guidelines for culverts, as set by the National Marine Fisheries Service and the Washington Department of Fish and Wildlife. The rock vortex weirs demonstrated favorable performance in the first two years following their installation. Methods for application of the four-mode model and hydraulic parameter rating curves are suggested for design of rock vortex weirs, with a focus on upstream fish passage.

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DEDICATION

To my wife Sharon, who has provided loving support through the years of field data collection, graduate coursework, model analysis, and development of the final report. Also, I would like to dedicate this thesis to our son, Samuel, born November 13, 2006, during the final stages of writing this thesis.

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LIST OF ABBREVIATIONS

ADV:	Acoustic doppler velocimeter
BOR:	U.S. Bureau of Reclamation
COE:	U.S. Army Corps of Engineers
DEM:	Digital elevation model
DTM:	Digital terrain model
DVWK:	Deutscher Verband für Wasserwirtschaft und Kulturbau
EDF:	Energy dissipation factor
NMFS:	National Marine Fisheries Service
PIT tag:	Passive integrated transponder tag
TIN:	Triangular irregular network
TYP:	Typical
UI-CER:	University of Idaho, Center for Ecohydraulics Research
USGS-CRRL:	United States Geological Survey, Columbia River Research Laboratory
WDFW:	Washington Department of Fish and Wildlife
WDOT:	Washington Department of Transportation

1. INTRODUCTION

Throughout the Upper Columbia River basin, small irrigation diversions provide surface water to farms and ranches. Some of these diversion barriers can block passage of fish into their spawning and rearing habitat. The affected species include native stocks of summer steelhead (*Oncorhynchus mykiss*) and spring Chinook (*O. tshawytscha*), which are listed as endangered under the Endangered Species Act (ESA) (NMFS BiOp 2000, COE UPA 2004).

In addition to small irrigation diversions, hydroelectric development on the Columbia River has been a major factor for the decline of these species. In 1939, a fish hatchery program was implemented in the Methow River basin to offset loss of access and mitigate impacts from Grand Coulee Dam, but salmon and steelhead have not been able to reach self-sustaining levels. Multiple state and federal agencies have focused their attention on the basin and have implemented actions to improve and increase habitat for summer steelhead, spring Chinook, and bull trout (NMFS BiOp 2000, COE UPA 2004).

This thesis evaluates pilot projects of rock vortex weir installations in the Methow River basin, which were designed to provide upstream migration of adult and juvenile fish, opening access to spawning and rearing habitat, while providing water diversion. Rock vortex weirs are designed to simulate natural stream conditions and provide upstream fish passage. Performance of the weirs was evaluated to provide recommendations for design improvements to future structures and monitoring of existing structures.

1.1 Background

In the document from the National Marine Fisheries Services (NMFS) titled “2000 Federal Columbia River Power System, Biological Opinion” (NMFS BiOp 2000, COE UPA 2004), 199 actions were detailed for implementation by the Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (COE), and U.S. Bureau of Reclamation (BOR) for the continued survival of eight stocks of salmon and steelhead in the Upper Columbia basin.

According to Hillman and Giorgi (2002), diversion dams in the Columbia River system should meet a standard where "upstream and downstream passage is possible at all flows and no fish end in irrigation systems". Existing agency guidelines are focused on fish passage at culverts, requiring fish passage during the migration season between exceedance flows of 5- and 95-percent (NMFS 2000, WDFW 2003). In this thesis, these agency guidelines are used for comparison to field observations and modeled hydraulic parameters.

Based on the findings in COE UPA (2004), actions were taken by the BOR in the Methow River basin to improve survival of fish in the spawning and rearing stages. In the Methow River basin (Figure 1.1), which meets the Columbia River 843 km (524 miles) from the Columbia River estuary, several important streams feeding the main stem of the Methow River are impounded by approximately 1-meter high barriers (Figure 1.2) that facilitate water diversion for local farmers and ranchers. Three subwatersheds, as defined by the drainages for Gold, Libby, and Beaver creeks, were identified by the BOR as potential restoration sites (Figure 1.1). The three subwatersheds meet the Methow River at river km 35.1 (mile 21.8), 42.5 (26.4), and 56.6 (35.2), respectively. Natural and artificial barriers exist in all three of these systems. Artificial barriers, primarily diversion dams and culverts, have severely restricted access of regionally-important anandromous (primarily steelhead and Chinook) and fluvial (primarily bull trout, rainbow trout, and cutthroat trout) fish species (Andonaegui 2000). Stream survey reports by the USDA Forest Service (USFS) describe barriers on their managed lands within Gold Creek (USFS 1997), Beaver Creek (USFS 1992), and Libby Creek (USFS 1999). Descriptions of barriers and species present within the three study watersheds are provided in Table 1.1 (USFS 1992, 1997, and 1999 and Andonaegui 2000).

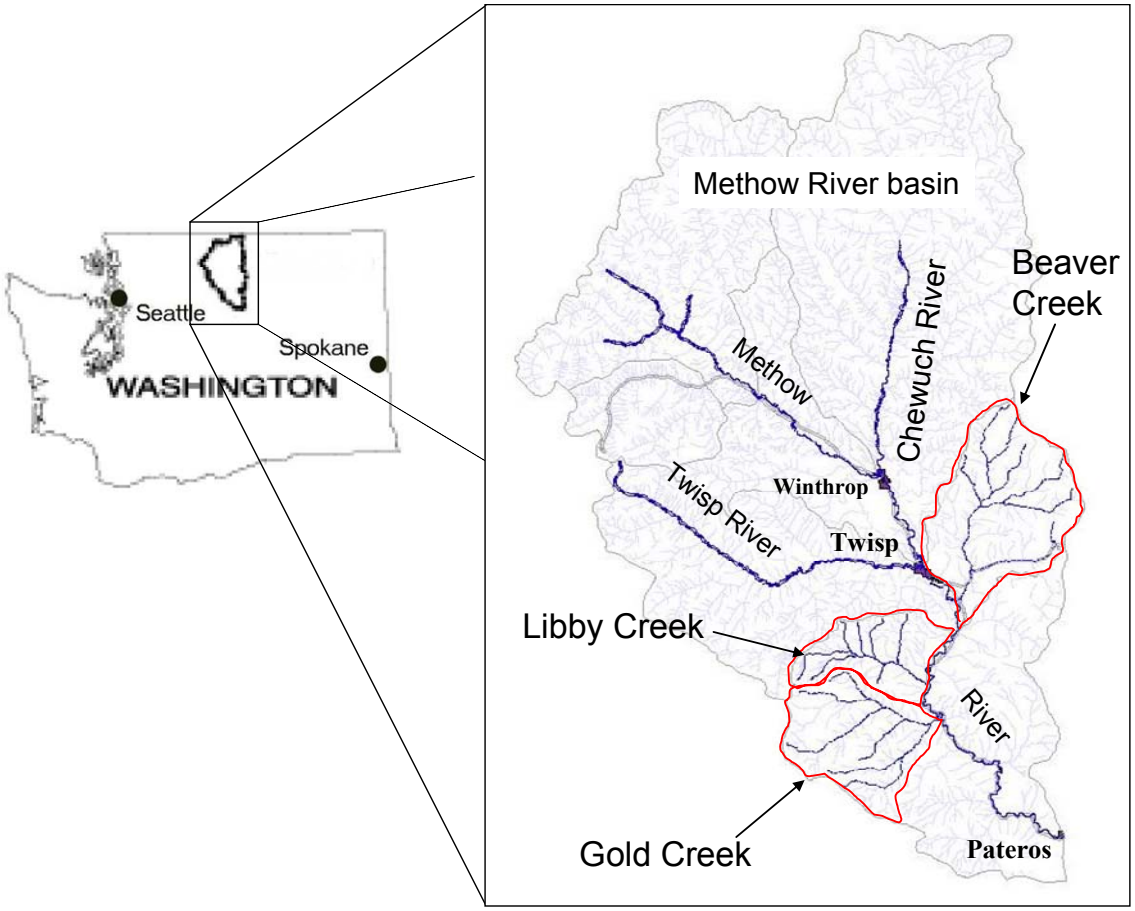


Figure 1.1. Methow River Basin near Twisp, Washington and study sites in Gold, Libby, and Beaver creek subbasins.

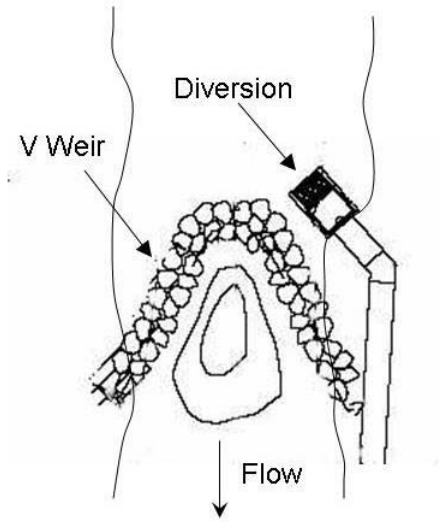
Figure 1.2. Typical diversion dam and fish barrier in the Methow River basin.

Table 1.1. Number of fish barriers, types, and locations by study watershed

Drainage basin	Number of fish barriers * circa 2000	Fish species present for rearing or spawning **
Gold Creek	3 full barriers	summer steelhead, spring Chinook, fluvial bull trout, westslope cutthroat trout, redband rainbow trout
Libby Creek	6 full or partial barriers	summer steelhead, bull trout, westslope cutthroat trout, redband rainbow trout
Beaver Creek	78 full or partial barriers	summer steelhead, bull trout, brook trout, rainbow trout, spring Chinook

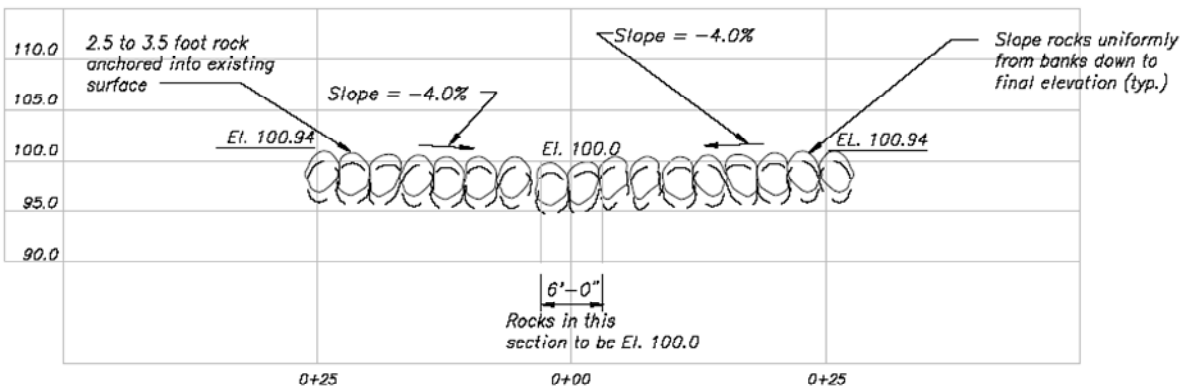
* Fish passage barriers are typically culverts and diversion dams spanning the channel. Since 2000 some of the culvert fish barriers have been replaced with bottomless arches to allow fish passage (Cross, personal communication, 2005). Data from Andonaegui (2000) and USFS (1992, 1997, and 1999).
** See glossary for scientific names of fish species

The BOR replaced four diversion dams in lower Beaver Creek to provide upstream fish passage. Each diversion structure was replaced by a series of rock vortex weirs and new or retrofitted head gates. Gold and Libby creeks serve as controls to compare fish response to actions taken in Beaver Creek. A rock vortex weir is a transverse installation of large boulders that are designed to emulate natural step pools. Typical plan, cross section, and profile views of a single rock vortex weir are shown in Figure 1.3.

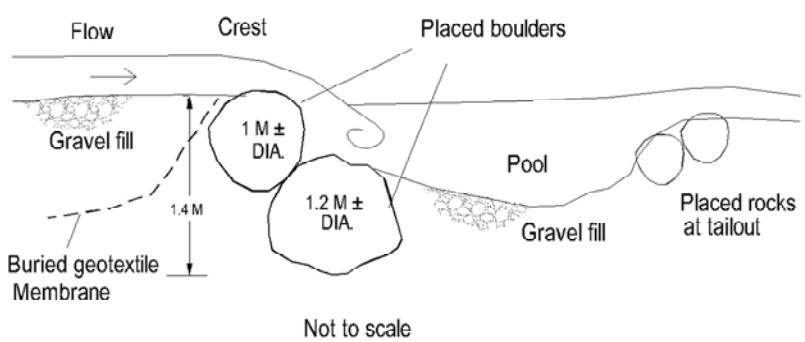


Typical Plan
(BOR, Thurlow Transfer Ditch)

Single rock vortex weir at Thurlow Transfer Ditch



Crest Profile (BOR, Thurlow Transfer Ditch)



Crest Cross Section (adapted from BOR)

Figure 1.3. Single rock vortex weir.

The projects implemented in Beaver Creek are the result of collaboration between the BOR, Okanogan Conservation District (OCD), and voluntary efforts by Beaver Creek landowners. The projects were implemented by the BOR and the OCD, which secured a grant from the State of Washington's Salmon Recovery Funding Board (SRFB).

Detailed descriptions of the design and construction, including photographs, of the rock vortex weirs on Beaver Creek are summarized in BOR (2004 a, b, and c). Brief descriptions of the four project sites, Lower Stokes, Thurlow, Upper Stokes, and Fort-Thurlow, are presented in Chapter 3. The Fort-Thurlow project was constructed after data collection was initiated for this thesis study, so limited monitoring efforts were performed at the Fort-Thurlow site. The locations of the replacement projects are shown in Figure 1.4.

In Beaver Creek, one 2-meter tall and three 1-meter tall diversion dams (located at the Fort-Thurlow, Lower Stokes, Thurlow, and Upper Stokes project sites, respectively) were replaced with series of rock vortex weirs (Figure 1.4). Each diversion dam was replaced with a series of rock vortex weirs strategically placed with the goals of providing grade control and maintaining back water for diversion, in place of the original diversion dam (BOR 2004 a, b, and c).

The rock vortex weirs were designed and installed under supervision of BOR engineers, in accordance with National Marine Fisheries Service (NMFS) and Washington Department of Fish and Wildlife (WDFW) fish passage criteria, as summarized in Appendix A. Each weir was designed to create a backwater for water diversion while providing a hydraulic drop of no more than 0.24 m (0.8 feet) to allow upstream passage of fish (NMFS 2000, WDFW 2003). The projects were also designed to meet fish species recovery needs described by the Endangered Species Act (ESA), NMFS BiOp (2000), and COE UPA (2004).

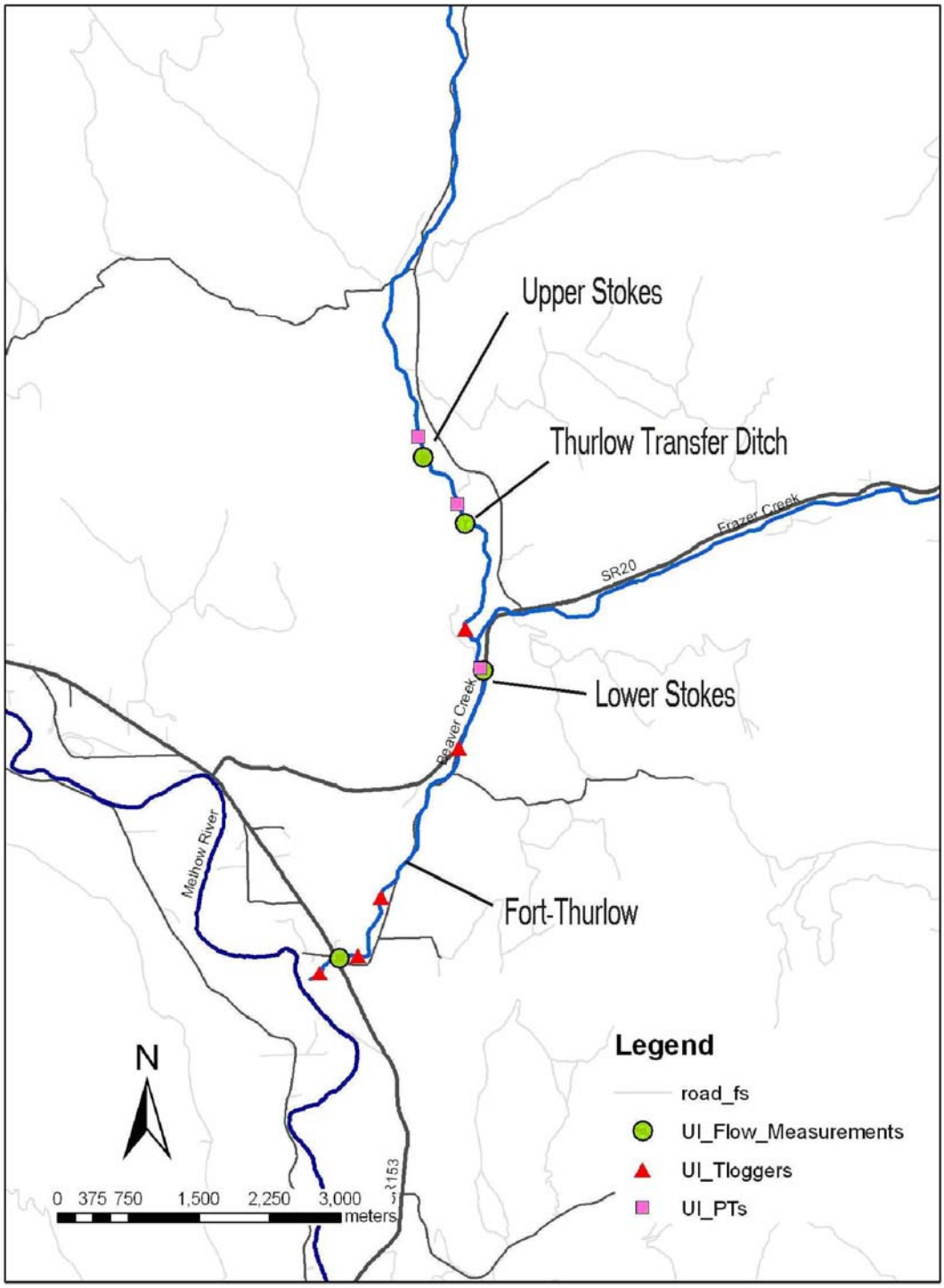


Figure 1.4. Fish barrier replacement project sites on Beaver Creek.

1.2 Project collaboration with USGS-CRRL

In conjunction with installation of the rock weirs on Beaver Creek, monitoring efforts were implemented by the University of Idaho, Center for Ecohydraulics Research (UI-CER), and U.S. Geological Survey's Columbia River Research Laboratory (USGS-CRRL) to determine the effect of rock vortex weirs on fish passage. Within the three study basins, the UI-CER measured discharge and temperature. Concurrently, the USGS-CRRL measured fish movement within the same study basins. Spatial scales for data collection varied from the watershed-scale for Beaver, Gold, and Libby creeks to the site-scale for the Beaver Creek project sites. Data collected at the site-scale by the UI-CER were developed into hydraulic models for each rock vortex weir to simulate hydraulic parameters for fish passage, as defined by NMFS (2000) and WDFW (2003). The hydraulic models were also developed to assist with future designs of rock vortex weirs for fish passage.

Fish movement data, developed by the USGS-CRRL and hydraulic model data at rock vortex weirs, developed by the UI-CER, were combined, facilitating a comparison of hydraulic conditions at the rock vortex weirs at the time of recorded upstream fish passage (Chapter 5). Inputs into the hydraulic models were continuous flow records, as developed by continuous records of water stage from pressure transducers and converted to discharge by rating curves (Chapter 3). Fish movement was tracked by the USGS-CRRL using PIT-tag readers placed above and below the rock vortex weirs (Chapter 4). In addition to temporal data, fish passage data from the USGS-CRRL described species, life stage, and estimated size of migrating fish.

1.3 Current knowledge on hydraulics and fish passage at rock vortex weirs

Research on fish passage and hydraulics has been focused on adult stages of fish and on engineered structures, such as spillways, culverts, and fabricated fishways (e.g., Denil, Steeppass, vertical slot, weir-pool). A review of available scientific and industry literature

revealed only limited data describing hydraulics or fish passage specific to "nature-like" fishways, such as rock vortex weirs.

The juvenile life stage of the target species are considered the limiting life stage factors for analysis in this thesis, since juveniles swim slower and cannot jump as high as adult fish. Life stage factors for migrating and spawning adult fish are also important for the success of salmonids and are presented below. The following is a synopsis of research describing upstream passage of juvenile and adult fish, and hydraulics at rock vortex weirs.

1.3.1 Fish swimming performance, and leaping performance

Swim speed and jumping abilities of fish have been well documented for traditional engineered fishways. Extensive findings on fish swimming and performance have been reported by Bell (1991) in the *Fisheries Handbook of Engineering Requirements and Biological Criteria*. This is a compilation of fish performance criteria for use in maintenance of existing facilities and design of new fishways. The criteria in Bell (1991) were based on examinations of published and unpublished works of various agencies and individuals. Data provided by Bell (1991) were developed to set workable limits and are not absolute thresholds. The handbook has 35 chapters, each dedicated to different topics important for fish survival, such as swim speeds, spawning criteria, water quality, temperature, toxic compounds and metals, hatchery design, fish diseases, migration and passage through hydraulic structures, predation, and fishway design.

In Bell (1991), fish swim speeds are described in three categories: cruising (maintained for hours), sustained (maintained for minutes), and darting (single effort, not sustainable). Cruising speed is maintained for movement, sustained speed is used for passing difficult areas, and darting speed for feeding, passing barriers, or escape. Darting speed can be maintained for 5–10 seconds. After exhaustive exercise, fish recovery time varies from rapid to 2 hours. The ratio of sustained speed to darting speed has been quantified from 0.5 to 0.7. The ratio of cruising speed to darting speed is estimated as 0.15 to 0.20. A summary of fish

swim speeds documented by various sources is reported in Table 1.2. The swim speeds reported in Table 1.2 may be reduced by 60 percent due to available oxygen or by 50 percent due to extreme warm or cold water temperatures (Bell 1991).

Table 1.2. Fish swimming speeds according to Bell (1991) and Ojanguen (2003)

Fish species and life stage	Cruising speed (m/s)	Sustained speed (m/s)	Darting speed (m/s)
Bell (1991)	*0.15-0.20 x darting*	*0.50-0.70 x darting*	
Adult Chinook	0.00 - 1.22	1.22 - 3.35	3.35 - 6.71
Adult steelhead	0.00 – 1.52	1.52 – 4.57	4.57 - 8.23
Coho, 5.1-cm	0.15 – 0.37	--	--
Coho, 8.9-cm	0.30 – 0.52	--	--
Coho, 12.1-cm	0.43 – 0.64	--	--
Brook trout, 10.2-cm	--	0.00 – 0.61	--
Ojanguen (2003)			
Brown trout, 7.5-cm	--	1.5	--

Swimming performance is also reported by Katopodis (1992) where swim speeds are correlated to morphological forms of fish and propulsion. This guideline is based on over 500 references and is intended to recommend values for similar species. Dimensionless variables were developed to relate fish length, swim speed, and swim endurance for anguiliform fish (full body undulations, like an eel) and subcarangiform fish (large side-to-side posterior motions, e.g., salmonids). Given two variables, the third can be calculated. For example, if fish length and water velocity through a structure are given for a subcarangiform fish, available swim endurance can be calculated and compared to required swim lengths in the structure, using calibrated curves and regressions Velocity data from Katopodis (1992) can be used to design a fishway and analyze a fishway for viable fish passage.

Leaping performance of fish is described by Bell (1991) as a function of velocity at the surface. In particular, the jump height of a fish can be quantified as:

$$h = \frac{V^2}{2g} \tag{1.1}$$

Where:

h = Jump height, in m

V = Velocity of the fish as it leaves the water surface, in m/s

g = Acceleration of gravity, 9.81 m/s^2

The behavior and jumping abilities of salmon at waterfalls and natural obstructions were documented by Stuart (1962) who studied fish leaping abilities in a laboratory and in a field setting at the Pot of Gartness on the River Endrick in Scotland. The laboratory set up was a 15-meter long flume with a sloped fish ladder equipped with orifice openings and weir overflows (estimated as 0.3 meter drops). Stuart (1962) studied the height of jump and length of run necessary to facilitate the jump. The study fish were 150 one- and two-year old salmon parr and trout, ranging from 0.06 to 0.15 m. Water flow rates varied, and fish movements were studied in different flow regimes. Key findings from Stuart (1962) were:

- Plunging water has an attraction effect for fish migrating upstream. The force of impact appears to determine whether a fish will leap, according to its size class.
- A ratio of pool depth to outfall drop of 1.25 optimized leaping performance.
- Fish will swim through vertical sheets of water, as long as the velocities do not exceed their swimming speed.
- Fish often leapt from a standing position at the surface near an upwelling current or at a standing wave below the weir. Leaps were initiated near the surface by a large tail flexion, with the tail almost in the mouth of the fish. When the fish is airborne, the tail continues to vibrate to provide propulsion upon landing in the high water velocity of the weir crest.
- The fish were very accurate in placement and height of their leaps, inferring that the fish sense the strength and direction of the upwelling currents and orient themselves to the height and character of a channel obstruction.
- Fish were speculated to orient their leap based on experience and visual cues, including light and dark contrasts in the nappe of the weir and looking at the geometry of the weir.

- As discharge and velocity increase, the standing wave in the pool is forced farther from the weir, reducing successful leaps.
- Fish preferred to jump weirs, as opposed to swimming through orifices in the fish ladder (later studies indicate limitations of the orifice design Stuart used).

Recent studies by Symons (1978) and Pearson (2005b) focused on the leaping abilities of juvenile Coho. Pearson (2005a, 2005b) utilized a full-scale physical model of a culvert system with a slope of 1.1-percent and a diameter of 1.8 m, which was built at the WDFW Skookumchuck hatchery near Tenino, Washington. Data were collected in 2004 and 2005. Five outfall heights (0.00, 0.12, 0.20, 0.26, and 0.32 m) were set for a perched culvert and juvenile Coho were observed for effectiveness of swim-through or leaping behavior. The fish for the study were hatchery fish about 103 mm in length. Each trial included 100 fish and lasted for 3 hours during evening hours. Flow was characterized as streaming for the zero height and plunging for the other heights. Discharge was typically 0.03 m^3/s, with a typical pool depth of 0.30 m. Video cameras were used to record behavior of fish in the pool and in the culvert. Success rates for jumping from a pool to a perched culvert are reported in Table 1.3.

Table 1.3. Success rates of juvenile Coho jumping to perched culverts from Symons (1978) and Pearson (2005b).

Symons (1978)		Pearson (2005b)	
Height (m)	% passing upstream	Height (m)	% passing upstream
--	--	0.00	71
0.12	32	0.12	30
--	--	0.20	18
0.27	17	0.26	3
0.57	7	0.32	0

Symons (1978) reported leap heights as high as much as five times the body length of the fish (5L) over an experimental water fall. Also, according to Symons (1978), fish could

jump up to 0.57 m, given adequate plunge pool depths, reasonable water velocities, and low velocities in the headwater of the leap, as in a weir-pool arrangement. Pearson (2005b) also determined jump heights were as high 5L, but no juvenile fish passed the perched culvert at 0.32 m (3L). In addition, as observed by Stuart (1962), Pearson (2005b) remarked that most successful leaps were from the edge of the plunging flow where upwelling occurred, near a standing wave formed by the plunge.

Regarding plunge pool depth for leaping fish, Powers and Orsborn (1985) cited the findings of Aeserude (1984) and presented two recommendations: 1) the plunge pool should be deeper than the length of the fish and 2) the penetration of plunging water into the pool should be less than the pool depth. Lauritzen (2002) determined the ratio of 1.0 of hydraulic drop to pool depth was effective for leaping, with deeper pools reducing upwelling effects that assist fish with jumping.

Results from these studies have been applied to the design of traditional fish passage structures (Katopodis 1992). However, applications of studies to rock vortex weirs or boulder weirs are limited. Rock vortex weirs have more complex hydraulics than traditional fish passage structures where geometry, energy dissipation, and discharge can be precisely controlled and measured.

1.3.2 Hydraulics, design, and evaluation of fishways, culverts, and rock vortex weirs

Many laboratory-based studies have been conducted specifically for engineered fishway design. For example, Katopodis (1992) and Odeh (2000) provide design recommendations and methods for traditional or fabricated fishways, including vertical slot, Denil, weir-pool, and culvert fishways. Geometric design and methods for hydraulic calculations are provided as a handbook for fishway designers (Katopodis 1992). Icthyomechanics are also provided in Katopodis (1992) to specify thresholds for fish passage and develop design constraints. Similarly, Katopodis (1997) studied Denil fishways in a laboratory setting to determine

channel roughness coefficients (Manning's n values varied from 0.03 to 0.12, depending on relative depth) and to optimize fishway design using dimensionless discharge and relative depth ratios.

More recently, Katopodis (2005) provided guidelines for fish passage to relate fish migration to hydrographs, attract fish to fishway entrances, analyze hydraulics and passage abilities, design fish screens, develop "nature-like" structures, and simulate hydrodynamic flow and sediment processes. Fish swimming speeds and swimming morphologies are revisited in Katopodis (2005), as well as motivation for migration. Katopodis (2005) indicates more studies are needed to analyze the hydraulics of pools below weirs and that "nature-like" fishways—including rock vortex weirs—have recent renewed interest.

Some studies and design guidelines have been developed for "nature-like" structures, focusing on bank and bed stabilization, rather than providing fish passage. Rosgen (2001) suggests conceptual designs for cross-vanes, W-weirs, and J-hook vane structures. The conceptual designs by Rosgen (1996) and Rosgen (2001) were used to develop designs for the rock vortex weirs at the Beaver Creek project sites. The Rosgen conceptual designs are focused on stabilizing bed elevation, reducing bank shear stress, and maintaining sediment transport, as well as a stable dimension pattern (Rosgen 2001). Additional benefits associated with cross-vanes, or rock vortex weirs, are improved fish passage, retention for irrigation diversion, improved fish habitat, and improved channel capacity (Rosgen 2001). A standard cross-vane has a center weir of large boulders that constitutes the middle 1/3 of the bankfull channel. Wing walls of large boulders extend upward and downstream at a slope of 2 to 7 percent, from the center weir until bankfull width and elevation are met. The result is a structure that redirects flow to the center of the channel (Figure 1.3). The pool dimensions are not specified, but Rosgen (2001) indicates that the pool depth will self-adjust.

In Thomas et al. (2000), a design procedure is provided for step pool structures. These structures are similar to rock vortex weirs, but they can accommodate steeper stream slopes. Data were developed in Thomas et al. (2000) from studies of eight steep, coarse-grained

mountain streams in Colorado. Regression equations were developed for pool length, scour depth, maximum pool width, and pool contraction for tailwater control. Thomas et al. (2000) also provides basic data for fish passage of trout (pool depth > 0.12 m, pool velocity < 1.22 m/s). Design of the step pools, as suggested by Thomas et al. (2000), consists of large boulders formed in a V-shape, with larger boulders to anchor the ends of the weirs. Field data collected on boulder size at natural step pools concurred with the formula used by the Army Corps of Engineers (COE 1991, Equation (5.4), Chapter 5), which lead Thomas et al. (2000) to recommend COE (1991) for sizing crest boulders.

A more robust design approach for flow-constrictor step pools was developed by Hegberg et al. (2001a, 2001b). In Hegberg et al. (2001a), a process was developed to evaluate target species characteristics, determine site base-flow hydrology, and calculate the hydraulics around the structures. Hegberg et al. (2001a and 2001b) include analysis of fish performance and swimming capabilities developed by Katopodis (1992). In Hegberg et al. (2001a), hydrologic design criteria specify use of Log-Pearson Type III flood duration analysis for design flows of 10, 50, and 90 percent exceedance. In Hegberg et al. (2001b), design procedures for rock weirs were suggested using a hydraulic modeling approach. A spreadsheet computation was described to model multiple rock weirs set at different elevations. The multi-level arrangement was suggested to emulate a natural structure and provide fish passage at low flows. Each weir in the multi-level structure effectively has the same tailwater elevation, so a method was proposed using the standard Poleni weir equation (Chow 1959) and the Villemonte submerged weir equation (Hegberg et al. 2001b) to determine a numerical solution for discharge in each individual weir. For higher flows, an approach was suggested to determine Manning's n for hydrodynamic modeling, based on Musseter (1989).

In addition, Hegberg et al. (2001b) described the energy dissipation factor (EDF), as used by WDFW (2003), to evaluate compliance of culverts for fish passage. The EDF is a way to quantify turbulence in the weir pool, which can disorient migrating fish. Calculation of EDF is based on discharge, hydraulic drop, and weir pool volume. A maximum EDF of 200 W/m^3 (watts per cubic meter) was suggested by Hegberg et al. (2001b). Also, Hegberg et al.

(2001b) suggested that the pool volume calculation, a factor in the EDF, should be limited to a zone within 3.0 m downstream of the crest, to limit turbulence measurement to the region near the plunging flow. EDF factors varied from 65 to 575 W /m^3 in natural analogs studied in Hegberg et al. (2001b).

Additional guidelines for design of culvert replacements and retrofits were prepared by NMFS (2000) and WDFW (2003). A summary of the fish passage guidelines in NMFS (2000) and WDFW (2003) is provided in Appendix A.

In NMFS (2000), guidelines are proposed along with additional design considerations for fish passage at culverts. The criteria in NMFS (2000) are described as general guidelines, with the caveat that site constraints may dictate modification of design elements. Three design methods are suggested by NMFS (2000): active channel design, stream simulation design, and hydraulic design. Active channel design specifies a deep round or oval culvert, backfilled with native bed material. This design method is suitable for channels with slopes less than 3-percent. Stream simulation design is intended to mimic natural conditions up to 6-percent slope with a bottomless arch or similar structure, with sufficient depth to allow natural channel adjustment. The hydraulic design method specifies a design process that determines structure geometry based on swimming abilities of target species. High and low passage design flows for the hydraulic design method in NMFS (2000) are suggested as 10-percent and 95-percent exceedance flows (juvenile fish), respectively. Maximum recommended velocities are 0.61 to 1.83 m/s, depending on the culvert length, with higher velocities allowable in shorter culverts. For juvenile fish, NMFS (2000) indicates that the 10-percent exceedance flow typically covers the flows when juveniles move upstream. The maximum hydraulic drops for juvenile and adult fish are suggested as 0.15 and 0.30 m, respectively. Hydraulic drop could be as high as 0.3 m according to Lang et al. (2004). In addition, NMFS (2000) suggests a ratio of 1.5 for pool depth to hydraulic drop.

The WDFW (2003) design guideline was prepared for property owners and engineers who are designing permanent road-crossing culverts to facilitate upstream migration of fish. Consecutive steps required for a culvert replacement or retrofit are given in WDFW (2003).

The WDFW (2003) guideline includes fish performance criteria, which comply with the Washington State publication WAC 220-110-070. In WDFW (2003), high and low design flows are established as 10-percent and 95-percent exceedance flows. Maximum allowable stream velocities for life stages and species of trout and salmonids are provided. The EDF factor is also discussed in WDFW (2003), and a limit of 200 W/m^3 in the plunge pools is suggested for culverts. According to personal communications with WDFW, EDF could be go as high as 400 W/m^3, but a maximum value of 250 W/m^3 is recommended for rock vortex weirs (Klavas, personal communications, 2006). Maximum hydraulic drop is suggested as 0.24 to 0.30 m and minimum water depth is suggested as 0.22 to 0.30 m (WDFW 2003).

In addition to guidelines like NMFS (2000) and WDFW (2003), the software Fish Xing (Love et al. 1999) was developed to evaluate fish passage at culverts. The hydraulic characteristics of a culvert crossing are computed using Fish Xing to assess the performance of the culvert for upstream fish passage. Within Fish Xing, fish performance data are inventoried from academic and industry sources and they are provided for user reference. These data are comparable to the above fish performance data for NMFS (2000) and WDFW (2003). Analysis in Fish Xing is dependent on the user's choice of limiting values for fish swim speed, hydraulic drop, and water depth. Analysis of flow over boulder weirs or rock vortex weirs is not performed by Fish Xing.

1.3.3 Fish passage at rock vortex weirs

There has been limited research focused on passage efficiency studies for "nature-like" structures or rock vortex weirs. Bain and Stevenson (1999) provide some data to assess fish barriers and maximum jumping heights, similar to analysis suggested by Bell (1991) and Equation (1.1).

Aarestrup and Lucas (2003) studied passage of sea trout, an anandromous form of brown trout, through "nature-like" structures (comparable to rock vortex weirs) in a field setting. In the study, 32 fish, with lengths from 0.30 to 0.67 m, were tagged with passive integrated

transponders (PIT-tags) and their movements were tracked by three antennas strategically placed to monitor upstream passage through a fish bypass. Out of 32 fish, 23 exhibited upstream searching behavior. During short periods of high flow (0.45 m^3/s), 8 of 18 fish (44%) were detected in the bypass channel. Migration was documented to occur when water temperature was between 2.0 and 6.7 ºC. A majority of fish approached the bypass during dark hours from 18:00 to 06:00. Detection efficiencies of the antennas were quantified by electrofishing surveys and applied to fish movement data. Of the trout attracted to the bypass, about half successfully ascended it. Aarestrup and Lucas (2003) suggested low overall efficiency of the bypass was determined to be a concern for long term survival of fish populations. Water velocity in the bypass was between 1.40 and 1.95 m/s. Aarestrup and Lucas (2003) suggested that the fish exhibited a behavioral barrier, that is, if fish encountered an obstruction in the channel, they would swim back downstream and look for an alternate route upstream.

1.4 Data gaps and thesis problem definition

Use of rock vortex weirs is relatively new and unstudied for fish passage effectiveness. Unlike engineered and fabricated fish passage structures, rock vortex weirs have complex hydraulics that introduce uncertainties in accounting for geometry, energy dissipation, and discharge relationships. Less data, especially from field studies, are available to evaluate fish passage at rock vortex weirs.

According to Kahler and Quinn (1998) and Pearson (2005a, 2005b), little is known about juvenile fish passing barriers, and more data are needed. To fill the data gap for fish passage at road culverts, the Washington Department of Transportation (WDOT) is planning to continue their studies at the WDFW culvert test bed facility. Future studies are expected to explore passage of fish over weirs and baffles in a culvert and movement up a fish ladder associated with a culvert, and possibly, performance of fish passage at rock vortex weirs in open channels (Pearson 2005a).

Currently, research on rock vortex weirs and other instream structures is underway with the Sedimentation and River Hydraulics Group of the BOR in Denver, Colorado to develop structure design guidelines (BOR 2007 and Holmquist-Johnson, personal communications, 2007). The research project is focused on improving the understanding of physical mechanisms to better meet project objectives and reduce maintenance requirements. Research products from the project will include design and performance parameters for a wide array of structures including spanning features (weirs, roughened channels, boulder clusters, rock ramps, check dams, etc.); deflector features (spur fields, barbs, dikes, bendway weirs, groins, hard points, etc.); and longitudinal features (stone toe, revetments, soil cement, bio-engineering). The research includes field studies of about 80 sites, physical modeling of scour patterns at structures, 3-dimensional numerical modeling of rock vortex weir hydraulics, and 1-dimensional modeling for simplified design tools. The end product from the study will consist of design guidelines and tools for achieving specific hydraulic and ecologic performance objectives in a sustainable manner.

This thesis is designed to fill data gaps in hydraulic modeling and evaluation of fish passage at rock vortex weirs. The project sites for this thesis were located in Beaver Creek, in the Methow River watershed. Effectiveness monitoring measures were used to determine whether the replacement of small diversion dams with rock vortex weirs allows fish passage and to quantify the values and benefits that inform future implementation of rock vortex weirs elsewhere in the Columbia River Basin. A primary focus of this study was the performance of the rock vortex weirs in maintaining a maximum hydraulic drop of 0.24 m (0.8 feet), as specified by NMFS (2000) and WDFW (2003) guidelines (McLaughlin, personal communications, 2006). Additional evaluation was done for three other hydraulic parameters, namely, the ratio of pool depth to hydraulic drop, energy dissipation factor, and average velocity at the rock vortex weirs (NMFS 2000 and WDFW 2003). Records of fish movement, provided by the USGS-CRRL, are integrated into the thesis for evaluating weir performance and design relative to fish passage guidelines at culverts (NMFS 2000 and WDFW 2003).

1.5 Thesis goals

The goals of this thesis study are to:

1. Describe watershed-scale characteristics of stream geomorphology, temperature, and discharge for the three study areas in the Methow River basin.
2. Develop techniques to model hydraulic parameters around rock vortex weirs important to upstream fish passage, as identified by existing NMFS (2000) and WDFW (2003) culvert design guidelines.
3. Characterize how hydraulic parameters change with flow over the rock vortex weirs.
4. Model continuous records of hydraulic parameters during fish passage at rock vortex weirs in a field setting.
5. Evaluate performance of rock weirs over a range of flows in meeting existing regulatory fish passage guidelines developed for culverts.
6. Comment on application of existing culvert design guidelines to rock vortex weirs.
7. Translate findings from hydraulic modeling to provide design recommendations for fish passage at rock vortex weirs.

1.6 Thesis study approach

The approach to data collection, model development, and performance evaluation of upstream fish passage is presented in Figure 1.5. Two data sets were collected. Physical data were collected by the UI-CER, and biological data on fish movement were collected by the USGS-CRRL.

Physical data for the study sites were collected by field visits and site instrumentation. Continuous discharge was measured using pressure transducers, data loggers, and stream rating curves. Discharges were measured during field visits using flow measurement devices and protocols established by the USGS (Nolan et al. 2001). Temperature records were measured by temperature sensors and data loggers. Water surface profiles were measured by

staff gages. Site topography was measured using total station ground survey equipment. Historic average daily stream flows were procured from the USGS.

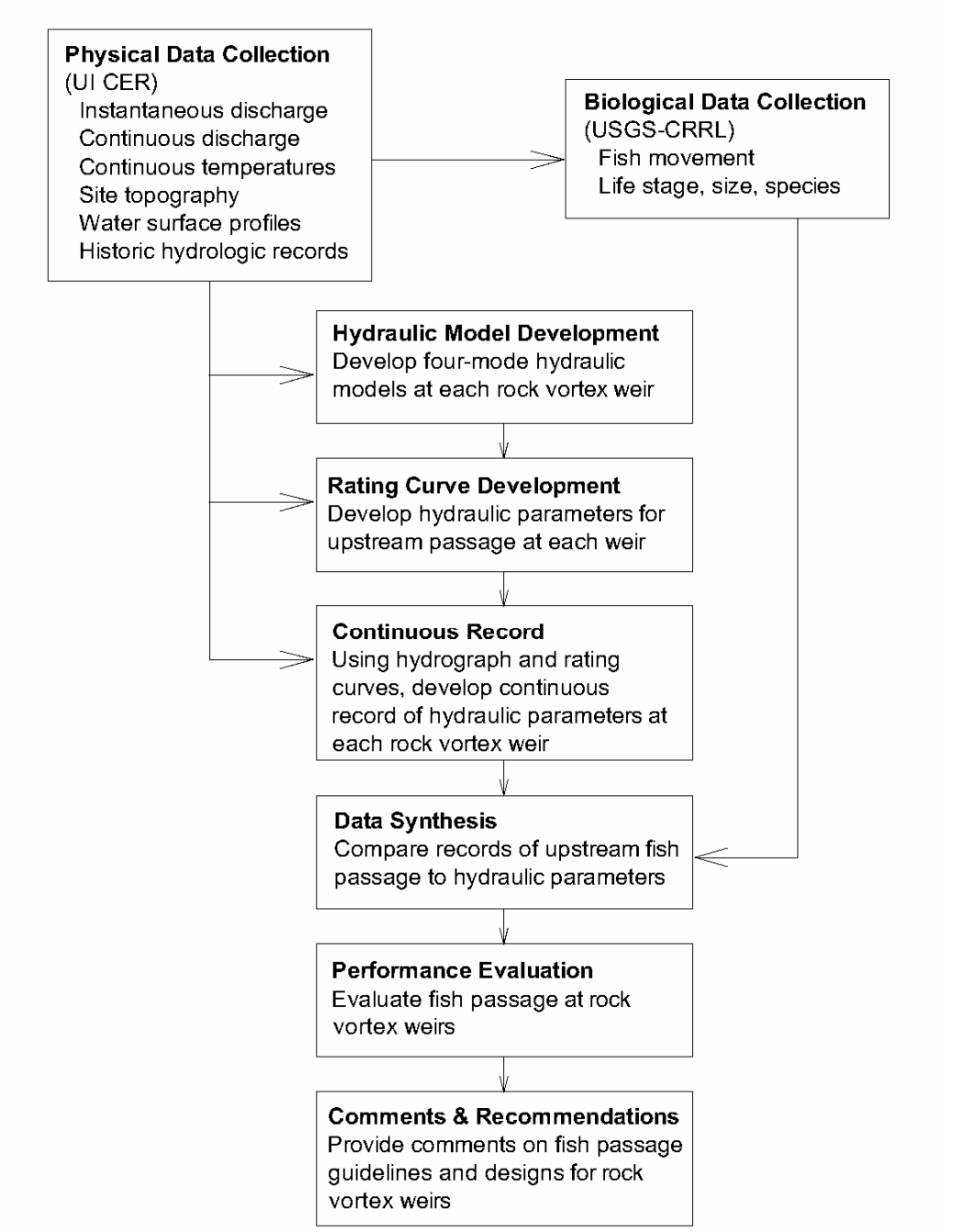


Figure 1.5. Approach to evaluation of upstream fish passage at rock vortex weirs.

Based on the physical data collected by the UI-CER, four-mode hydraulic models were developed for each rock vortex weir. The four-mode hydraulic models and additional data were then applied to develop rating curves for hydraulic parameters important to upstream fish passage, according to guidelines established by NMFS (2000) and WDFW (2003). For example, at a given weir, a rating curve of velocity versus discharge was developed using the four-mode hydraulic model at the weir and measured discharge. Additional rating curves for hydraulic parameters of hydraulic drop, energy dissipation, and drop-to-pool-depth ratio were based on observed staff gage and measured data. Using these rating curves and continuous records of discharge, as developed from hydrologic measurements, continuous records of hydraulic parameters for upstream fish passage were generated for each weir.

Once a chronological estimate of fish passage parameters was developed, biological data on fish movement, as collected by the USGS-CRRL was incorporated on the same time scale. The comparison of the two data sets examined key hydraulic performance criteria in the context of recorded fish passage. The comparison allowed a discussion of performance of the rock vortex weirs, as well as recommendations for fish passage guidelines and design improvements for rock vortex weirs.

The thesis is organized into five chapters. This chapter introduces the project background, discusses previous research, and defines project goals. Chapter 2 presents the watershed-scale and hydrologic analysis of the three subbasins (Gold, Libby, and Beaver creeks). Chapter 3 describes the development of the hydraulic model and calculation of hydraulic parameters for upstream fish passage over the rock vortex weirs. Chapter 4 summarizes efforts by the USGS-CRRL to track fish passage. Chapter 5 synthesizes the hydraulic model with fish movement data (provided by the USGS-CRRL), examines the implications of the study findings, discusses limitations, and proposes an approach to rock vortex weir design to further enhance fish passage.

2. WATERSHED CHARACTERIZATION AND HYDROLOGIC ANALYSIS

This chapter discusses the watershed-scale characterization and hydrologic analysis for Gold, Libby, and Beaver creeks, tributaries to the Methow River. To characterize the three study watersheds, topographic information was analyzed in a geographic information system (GIS) to determine geomorphic characteristics of Gold, Libby, and Beaver creek watersheds. Using GIS data, distinct geomorphic reaches were defined based on slope, valley confinement, and tributary junctions for each of the three study watersheds. In addition, continuous and spot measurements of flow and temperature were taken at the watershed and site levels to assess physical characteristics of the Gold, Libby, and Beaver creek watersheds. Using flow measurements collected for this thesis and historical flow records from the United States Geological Survey (USGS), a hydrologic analysis was performed to determine stream discharges in Beaver Creek. Using flood duration analysis, flood frequency analysis, and the internet-based software StreamStats from the USGS, discharges values were determined for the 5-percent and 95-percent exceedance flows and the 1-, 2-, 5-, 10-, 50-, 100-, and 200-year flood frequency flows.

2.1 Description of the Methow River Basin

The mouth of the Methow River is located approximately 843 km (524 miles) from the Columbia River estuary, upstream of Wells Dam and downstream of the Okanogan River. The Methow River basin lies south of the Canadian border in north-central Washington, bounded by the Cascade Mountains to the west and the Okanogan River watershed to the east. The Methow River has a drainage area of about 4,662 square km (1,800 square miles) with two major tributaries, the Twisp River and the Chewuch River. A map of the Methow River basin and the three study subbasins is shown in Figure 1.1 (Ely 2001).

The topography of the Methow basin ranges from elevation 240 m (790 feet) at the confluence with the Columbia River at Pateros to 2,730 m (8,960 feet) in the high peaks (Ely 2001). The Methow River valley is typically about 1.6 km (one mile) wide, and is bordered

by high granite ridges rounded by glaciation in the Pleistocene Epoch. These ridges typically reach elevations of approximately 2,130 m (7,000 feet). The middle reach of the Methow River follows a sinuous alignment that alternates across the valley floor.

According to Ely (2001), the valley geology of the basin is deep alluvial and glacial deposits up to several hundred feet thick. This creates a condition of ground water and surface water exchange that may water and dewater the upper Methow River reaches during dry summers. Above the valley floor there is exposed granite with a thin layer of alluvium (Ely 2001, Ely 2003). Rounded ridges and steep U-shaped canyons carved by glacial activity dominate much of the watershed.

The climate in the basin is diverse in temperature and precipitation (Ely 2001). During the year, temperatures range from -29 to +38 °C (-20 to 100 °F), with the coldest temperatures in the mountains, usually in January. Warmer temperatures are typically in July on the valley floor and closer to the mouth of the river. Average annual precipitation for the basin is 0.81 m (32 inches) and ranges from 0.25 to more than 2.03 m (10 to more than 80 inches), with lower precipitation on the valley floor, on the eastern side, and near the mouth. The east side of the basin receives considerably less precipitation and typically has an earlier pattern of snowmelt. The west side and the upper watershed of the Methow River basin receive more snow, and they retain snow packs to generate year-round runoff (Ely 2001).

Land use in the Methow basin is heavily dominated by grazing, forestry, and agriculture (alfalfa and orchards). Also, there is strong recreational use throughout the year that includes hunting, skiing, rafting, fishing, hiking, and mountain biking (USFS 1992, 1997, 1999). Historically, vegetation communities were strongly influenced by fire. Currently, about 75-percent of the watershed is forested, with the remainder of the land covered by grasslands, shrubs, irrigated crops, and bare rock (Ely 2001).

2.2 Description of Gold, Libby, and Beaver creek watersheds

Three subbasins within the Methow basin are included in this thesis study. Descriptions of fish and barriers and species present in each basin are provided in Table 1.1. Summaries of the characteristics for the subbasins are shown in Table 2.1. There are man-made and natural fish barriers in the each basin. Culverts and diversion dams documented as fish passage barriers have been targeted for replacement by the USFS and BOR and some culverts considered to be fish barriers have been replaced by the time of this thesis report (Cross, personal communication, 2005).

The Gold Creek basin, located on the west side of the Methow River, is the southern-most basin in this thesis. Gold Creek a major tributary to the Methow River and is a source of cold water, which is critical to maintaining low temperatures for salmonids in the Methow River. A diversion dam, considered to be a fish barrier, is on private land near the mouth of Gold Creek. There is interest in replacing this dam to improve upstream fish passage of native stocks. In the upper watershed of Gold Creek, there is a permanent snow field, which provides year-round flow (USFS 1997).

A second study area was the Libby Creek watershed, located just north of the Gold Creek basin and west of the Methow River. This basin inputs less flow to the Methow River than Gold Creek, but it has hydrology and topography similar to the Gold Creek basin. Libby Creek is also considered a major tributary to the Methow River. There is significant beaver activity throughout the basin, especially in the lower reaches near creek km 7.2 (mile 4.5). In the Libby Creek basin, there are issues with a shortage of large woody debris, sedimentation, and pool habitat in the lower reaches. Libby Creek is also an important source of cooler water (USFS 1999).

Table 2.1. Characteristics and descriptions of Gold, Libby, and Beaver creek basins (USFS 1992, 1997, 1999)

Watershed Feature	Gold Creek	Libby Creek	Beaver Creek
Methow River station km (miles) from mouth	35.1 (21.8)	42.5 (26.4)	91.1 (56.6)
Watershed area in square km (square miles)	230.5 (89.0)	104.4 (40.3)	290.1 (112.0)
Land use	- Heavily managed for grazing and forestry - Irrigated crops - Year-round recreation	- Heavily managed for grazing and forestry - Irrigated crops - Year-round recreation	- Heavily managed for grazing and forestry - Irrigated crops - Year-round recreation
Aquatic habitat quality notes	- Heavily impacted - Significant beaver activity - Man-made fish passage barriers present	- Heavily impacted - Significant beaver activity - Man-made fish passage barriers present - Shortage of large woody debris - Concerns with sedimentation and pool habitat in lower reaches	- Heavily impacted - Significant beaver activity - Man-made fish passage barriers present - Winter range for deer - Concerns with sedimentation and embedment of cobbles and gravels

The third basin studied in this thesis, Beaver Creek, is located further upstream and east of the Methow River. The Beaver Creek watershed is typically drier and has an earlier snowmelt compared to the Gold and Libby creek basins, but it has a largest drainage area of the three study watersheds. Run-off in the late spring is typically rainfall-driven. Historically, there has been significant beaver activity throughout the basin, thus the name "Beaver Creek". The upper watershed has been owned by Okanogan National Forest since 1907, with the lower watershed held in private ownership. Intensive timber harvest began in the 1960s and has continued until at least 1992, as reported by USFS (1992). The forest is designated as a deer winter range, thereby subject to winter road closures. Collectively, land use and recreational use have impacted aquatic habitat in much of the Beaver Creek basin (USFS 1992). Major recreational uses include hunting, snow-mobiling, nordic skiing,

hiking, and mountain biking. There are concerns with sedimentation that embed cobbles and gravels in the Beaver Creek basin, as such features tend to inhibit salmonid spawning.

The BOR selected the Beaver Creek basin to implement four pilot projects to replace four separate diversion barriers with series of rock vortex weirs. To facilitate comparisons in all three basins, hydrology, temperature, and fish distribution were monitored.

2.3 Existing hydrologic information in the Methow River basin

The USGS and BOR maintain flow measurement stations in the Methow River basin. Locations of eight streamflow measurement sites on the Methow River basin are shown in Figure 2.1. The periods of record for the gages at these sites are show in Table 2.2. Most of the USGS flow data represent the main stem of the Methow River, with some discontinuous measurement periods in the Beaver Creek watershed. For USGS streamflow gages located along the Methow River there is a long period of record, especially at the mouth near Pateros, which has a record of average daily streamflow from 1903 to present, with a gap from 1920 to 1959 (Figure 2.2).

Measured discharges from the USGS in Beaver Creek are less extensive, with some data gaps and short records (Table 2.2 and Figure 2.3). For example, the USGS gage for Beaver Creek near the mouth, near Twisp (Station 12449710) had data for only one year, from October 2000 to September 2001 (Figure 2.3 and Table 2.2). Also, there is a long gap in the Beaver Creek record from 1978 until 2000 (Figure 2.3). Additional flow measurements have been performed by the BOR in Gold, Libby, and Beaver creeks, but the data were unavailable for this thesis study.

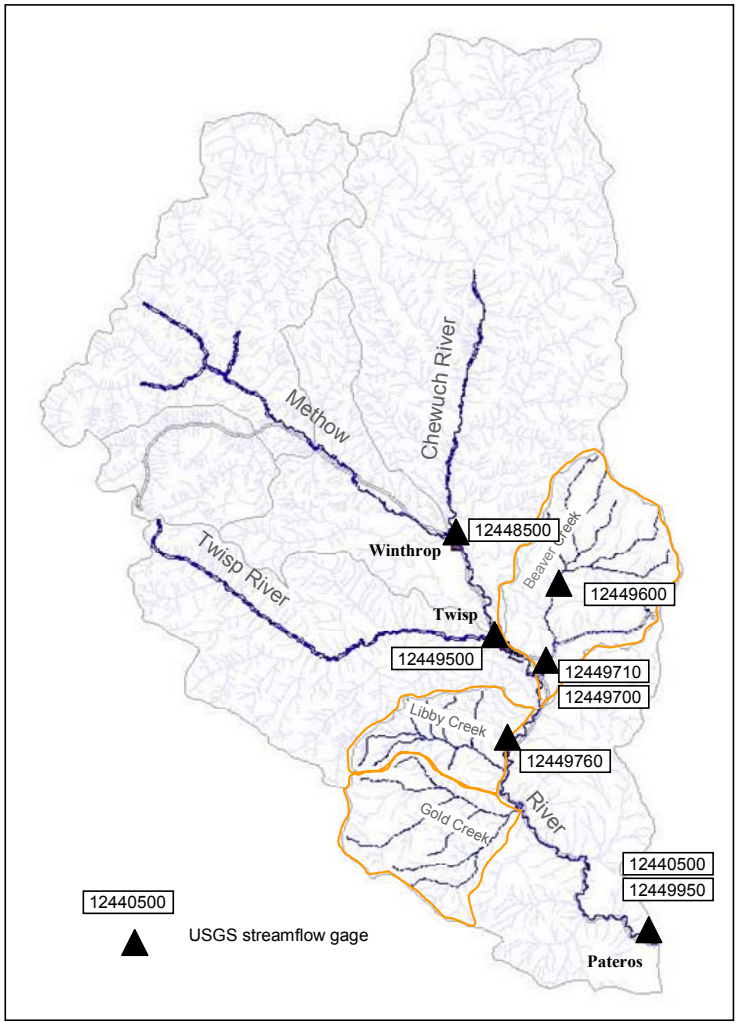


Figure 2.1. Location of USGS streamflow measurement stations.

Table 2.2. USGS flow gages in the Methow River Basin.

Site number	Site name	Period of record
12448500	Methow River at Winthrop, WA	Jan 1912 – Oct 1912 Aug. 1971 – June 1972 Nov. 1989 – present
12449500	Methow River at Twisp, WA	June 1919 – Sept. 1929 Oct 1933 – Sep 1962 Apr. 1991 - present
12449700	Beaver Creek near Twisp, WA	May 1956 – Sep 1961
12449600	Beaver Creek below South Fork near Twisp, WA	Apr 1960 – Oct 1978
12449710	Beaver Creek near mouth near Twisp, WA	Oct 2000 – Sep 2001
12449760	Methow River at Carlton, WA	Oct 2001 – Sep 2003
12449950	Methow River near Pateros, WA	Apr 1959 – present
12440500	Methow River at Pateros, WA	Jun 1903 – Sep 1915 Oct 1916 –Sep 1920

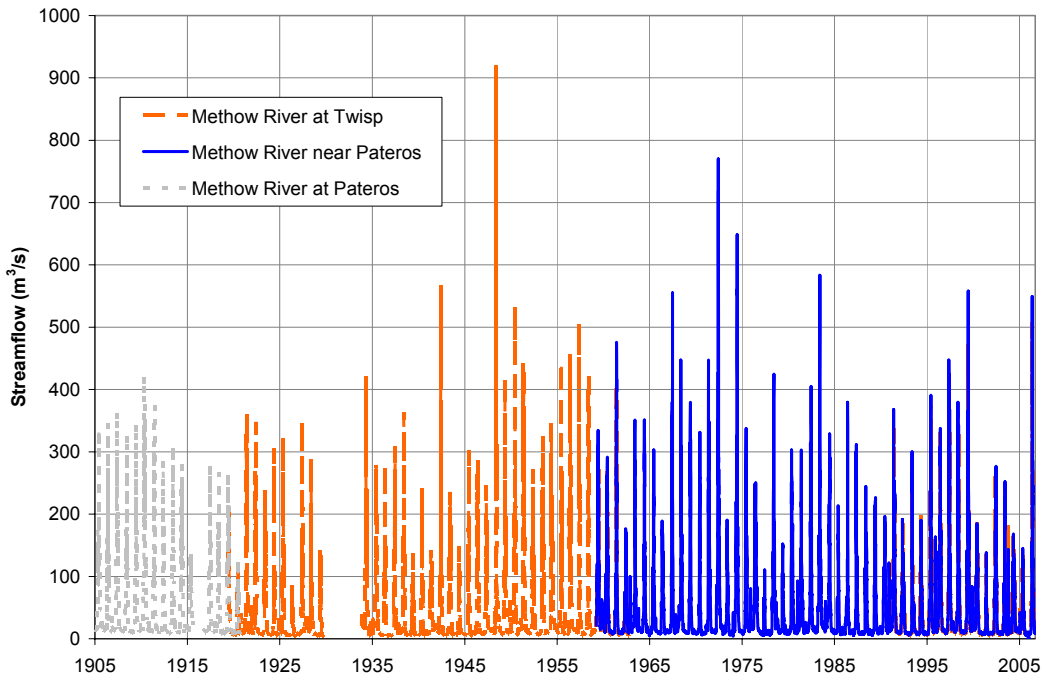


Figure 2.2. USGS streamflow measurements for the Methow River.

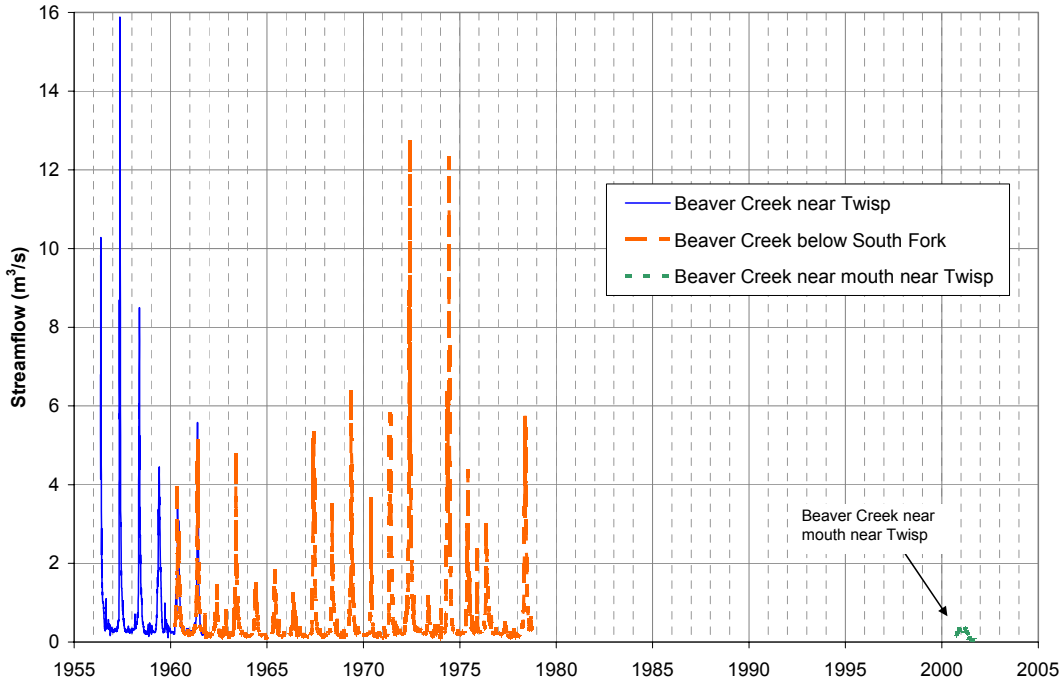


Figure 2.3. USGS streamflow measurements for Beaver Creek.

2.4 Data collection performed in the Methow River basin

Data were collected at the watershed- and site-scale for completion of this study. Watershed-scale monitoring consisted of establishing geomorphic reaches, measuring discharges, installing temperature sensors, performing hydrologic analyses, and installing stage measurement recorders (pressure transducers) for continuous discharge estimates from rating curve development. Watershed-scale monitoring provided information for potential removal of fish barriers in other sub watersheds. Site-scale data collection was focused on hydraulic model development to evaluate fish passage at rock vortex weirs in Beaver Creek (Chapter 3).

Locations of discharge and temperature measurements sites are shown in Figure 2.4 to 2.6. To describe changes over time, discharge measurements at approximately three to eight locations in each watershed were repeated approximately four times per year at the same locations.

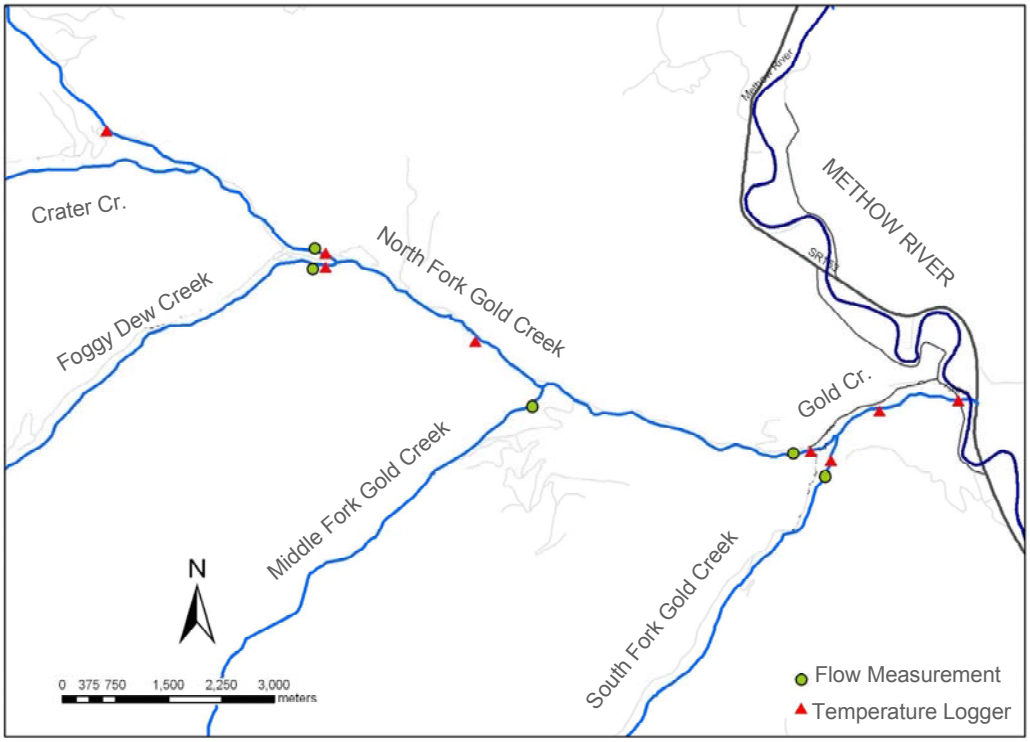


Figure 2.4. Streamflow measurement locations and recording instruments for Gold Creek.

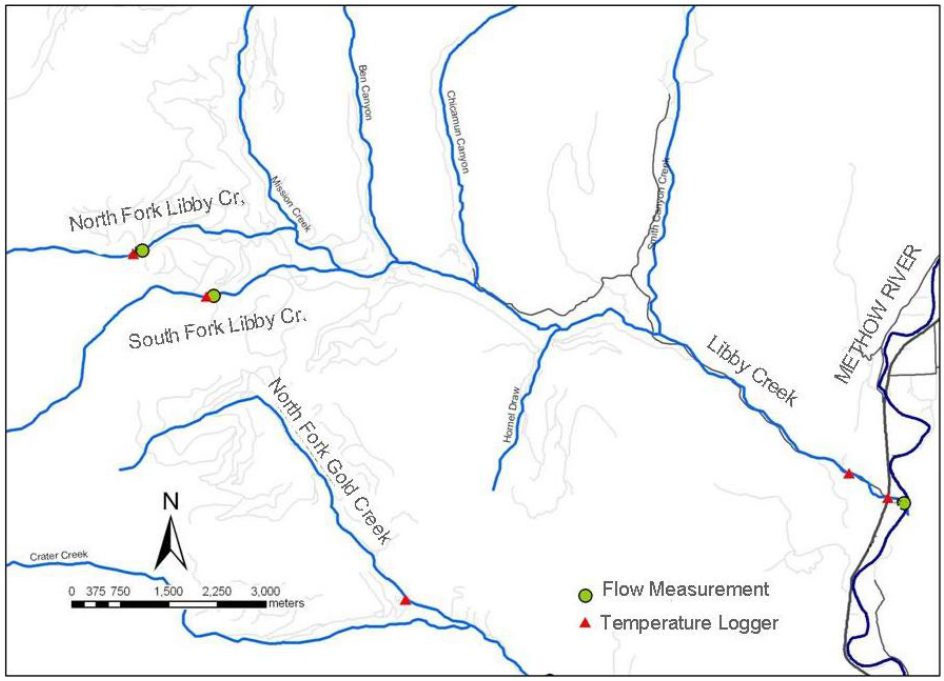


Figure 2.5. Streamflow measurement locations and recording instruments for Libby Creek.

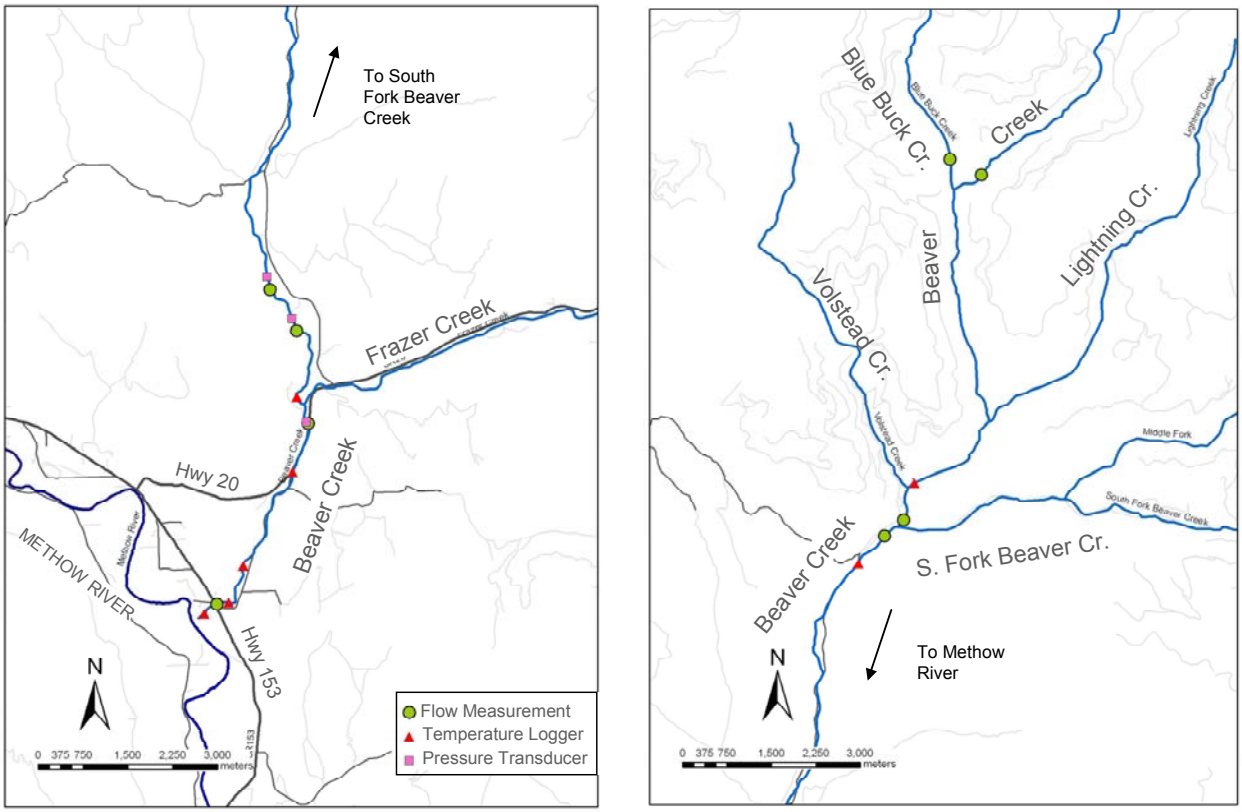


Figure 2.6. Streamflow measurement locations and recording instruments for Beaver Creek.

2.5 Geomorphic analysis for reach breaks

To characterize unique geomorphic reaches, reach-scale characteristics of slope and valley confinement were calculated for the three watersheds (Beaver, Gold, and Libby creeks). Channel slope was determined in GIS using ESRI ArcGIS software version 9.1 (ESRI, Redmond, California), USGS data base stream alignments, USGS 10-meter digital elevation models (DEM), and USGS 7-1/2 minute quads. Using the 3D analyst module within ESRI ArcGIS, elevations along the stream alignments from the DEM were sampled and reported to a spreadsheet file with station and elevation. Elevations of tributary channels were also sampled along the stream alignments. Stations of the tributary channels were offset to align the mouth of the tributary to stationing on the main stem of creek. These data were then plotted and channel slopes were calculated. Valley confinement was determined by measuring valley width on USGS 7-1/2 minute quadrangles. Data from the analysis were provided to the USGS-CRRL to assist in the selection of index reaches.

Plots of the stream profiles used to determine reach breaks are shown in Figure 2.7, Figure 2.8, and Figure 2.9 for the Gold, Libby, and Beaver creeks, respectively. Slopes of the creeks varied from relatively flat (i.e., approximately 1 percent) in the lower reaches to greater than 10 percent in the headwaters. Valley confinement was more prominent in the upper watershed. Gold Creek appears to have the greatest proportion of steeper streams, followed by Libby Creek then Beaver Creek.

Beaver Creek and Gold Creek have approximately the same watershed area (290 versus 231 square km), but Beaver Creek has more stream length with flatter slopes. This was confirmed by field observations of large cobbles dominating the stream bed in Gold Creek, compared to the Beaver Creek stream bed, which typically has more gravel substrate that is important for spawning.

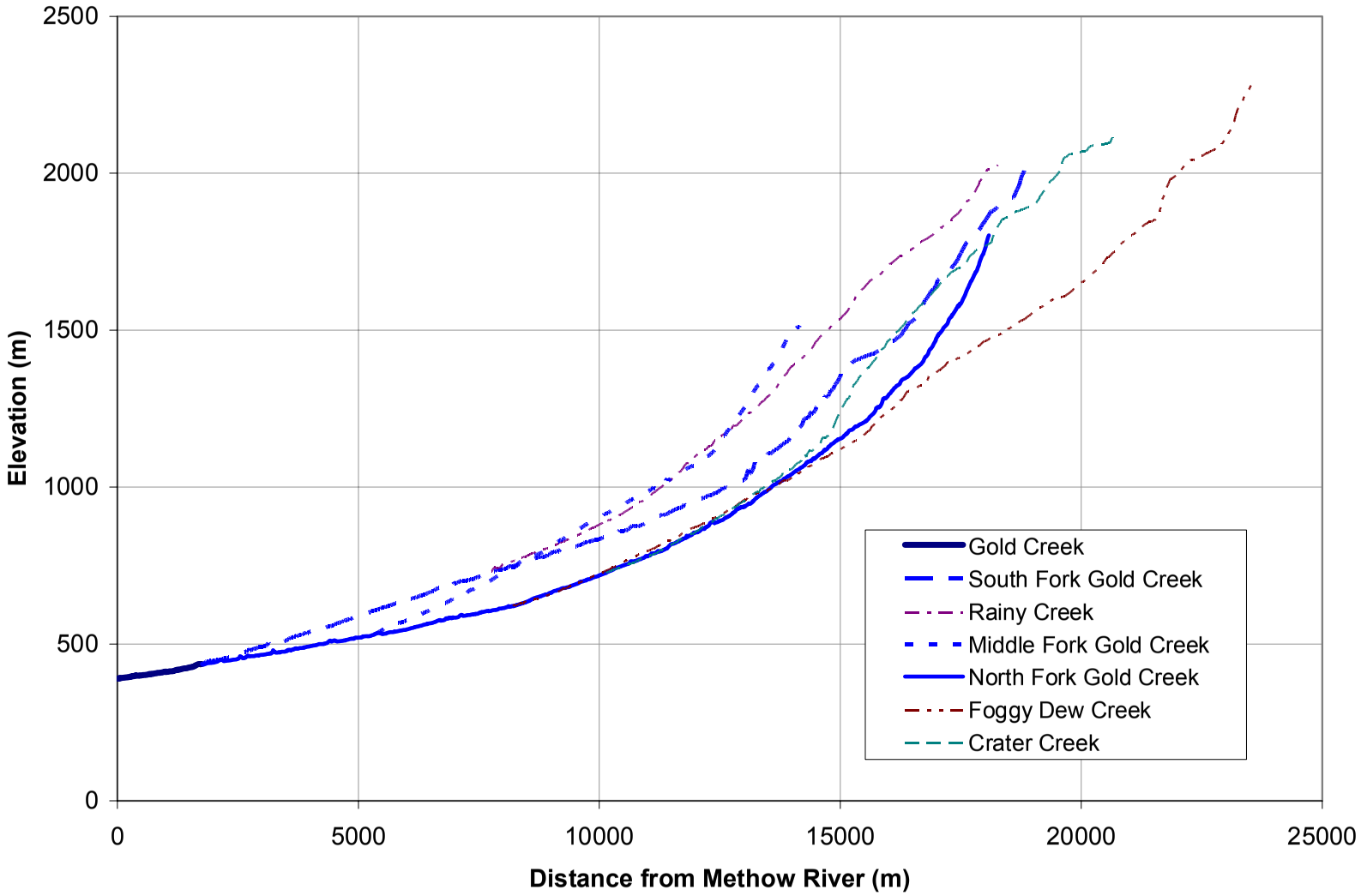


Figure 2.7. Stream profiles for Gold Creek and its tributaries.

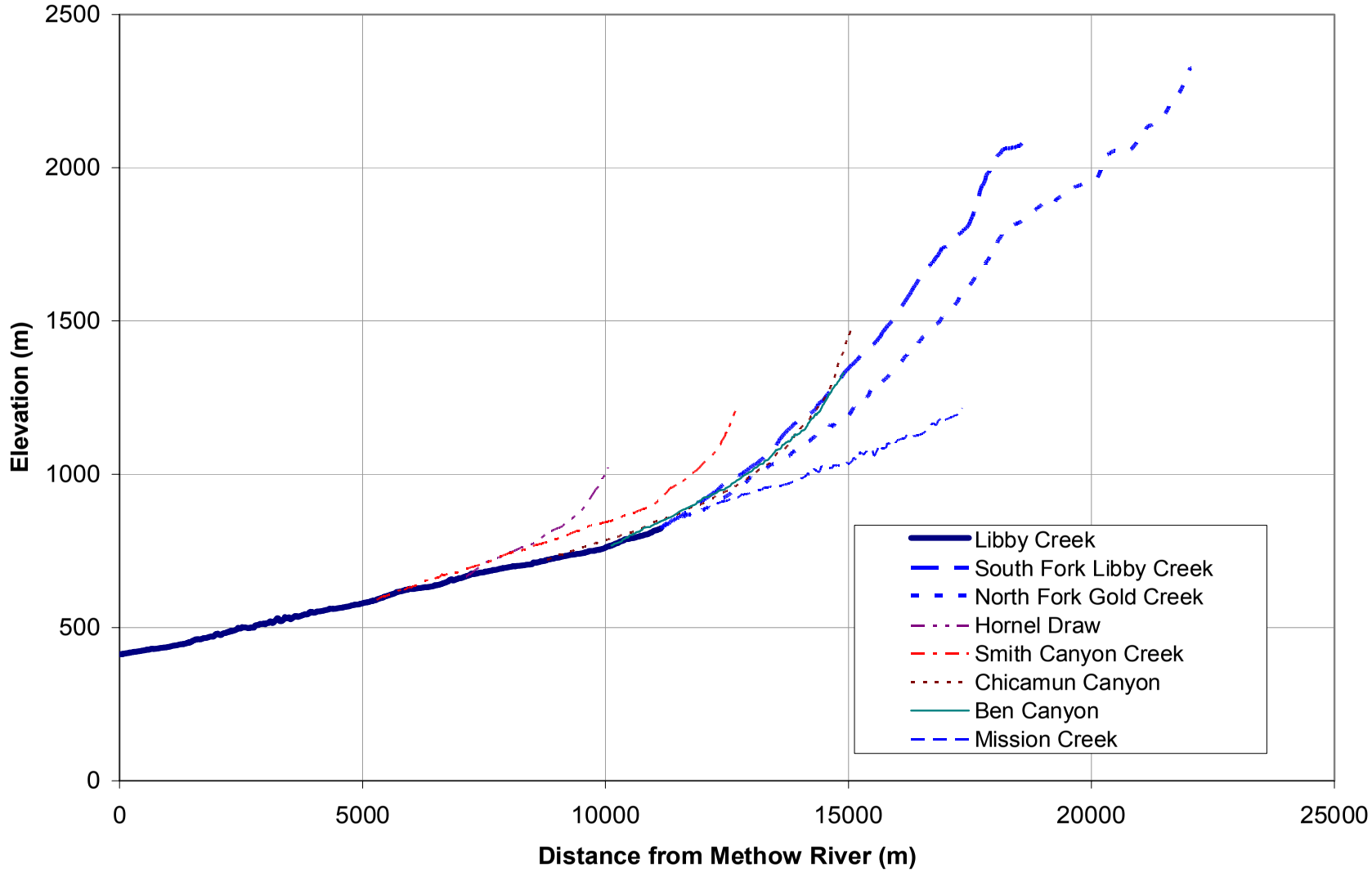


Figure 2.8. Stream profiles for Libby Creek and its tributaries.

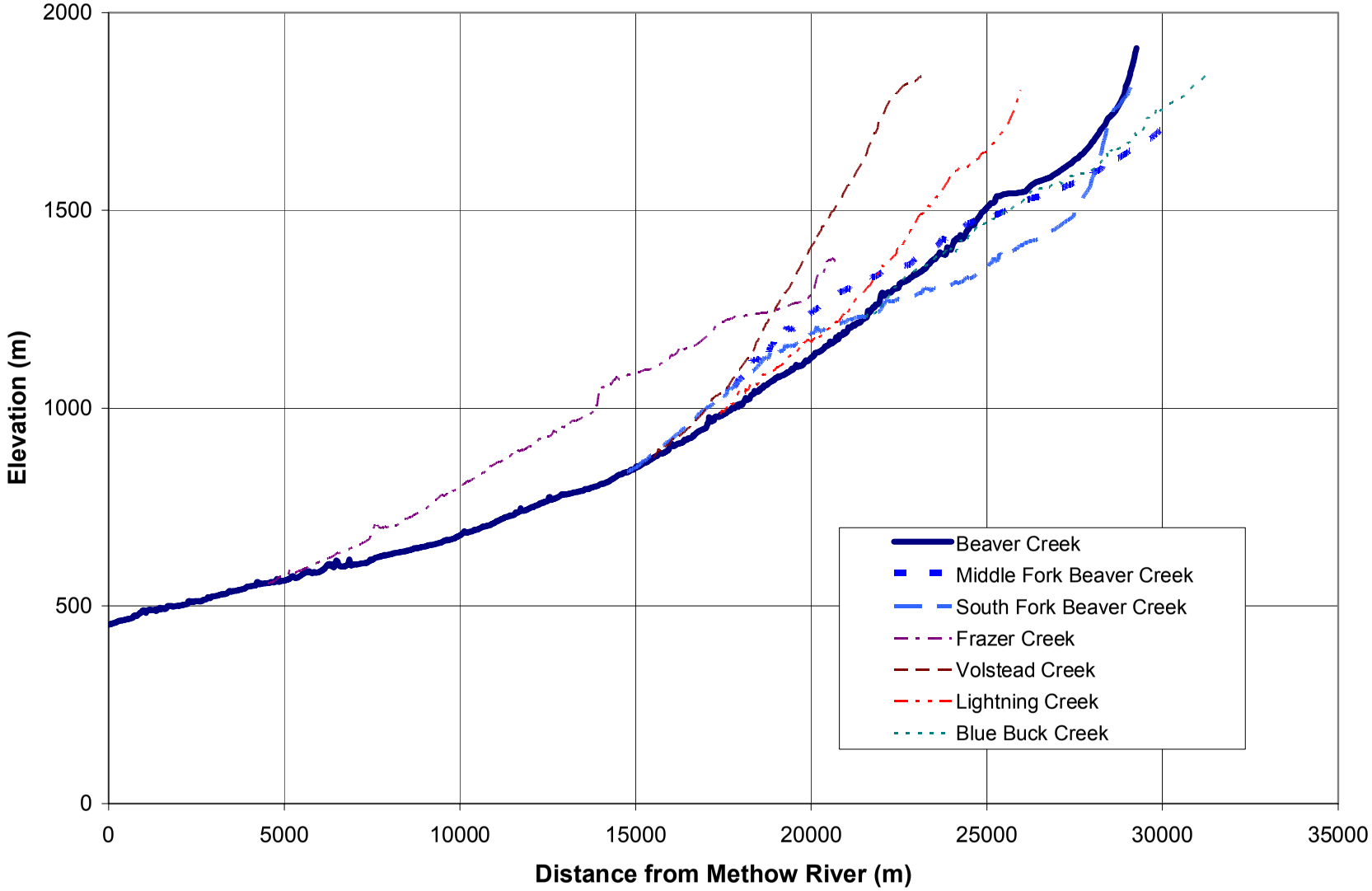


Figure 2.9. Stream profiles for Beaver Creek and its tributaries.

2.6 Discharge measurements

Water discharges were measured on eight site visits conducted between June 2004 and April 2006 to describe how flow changes throughout the three watersheds over time and to develop rating curves for pressure transducers at the project sites. The objective was to measure a range of flows, including highs in the spring, the declining limbs in July, and lows in the summer and fall. A total of 175 discharge measurements were taken, including 90 on Beaver Creek, 40 on Libby Creek, and 45 on Gold Creek. Flow measurement locations are shown in Figure 2.4 to 2.6.

All discharge measurements were conducted using a FlowTracker Handheld Acoustic Doppler Velocimeter (ADV, Sontek Corporation, San Diego, California) device with an electronic recorder and a traditional top-setting wading rod assembly. Discharge measurements were performed following standard protocol (Nolan et al. 2001). Stream sections were chosen to be relatively free of large wood, stream bed irregularities, eddies, and focused currents. Shallow water (0.05 m or less) was also avoided to facilitate proper functioning of the ADV. When a suitable location was selected, a tape was stretched across the stream perpendicular to the creek centerline, starting at the left bank and ending on the right bank, looking downstream. The flow was then calculated by measuring a minimum of 20 velocity samples across the wetted width using a wading rod with the ADV mounted at 0.6 of total depth, considered to represent average velocity over depth. Velocity sample locations were initially set at equal intervals along the tape, but were adjusted during the measurement to capture high velocity cores. Also, prior to the velocity measurement, care was taken to place the foot of the wading rod at the stream bed. The tops of isolated large cobbles were avoided. In silt-bedded irrigation ditches, measurements were performed carefully to avoid sinking the instrument into the soft bed.

The ADV instrument recorded station and depth, measured velocity, and automatically calculated discharge upon completing all velocity samples in the transect. Discharge and average stream velocity were recorded in field books and the ADV measurement file was saved and checked later against field notes for accuracy. In addition, during the discharge

measurement, air and water temperatures were measured, digital photos were taken (facing upstream, downstream, and towards the right and left banks), and a global positioning system (GPS) waypoint was sampled at the flow measurement site.

Based on site visits from 2004 to 2006, flow measurements within the three study subwatersheds ranged as follows: 0.01 to 0.91, 0.09 to 1.20, and 0.22 to 6.65 m^3/s in the Beaver, Libby, and Gold creek basins, respectively (Table 2.3, Figure 2.10 to 2.12). These flows represent field conditions at the time of measurement and do not reflect the full range of flows in the watersheds.

Table 2.3. Measured discharges in Beaver, Libby, and Gold creeks from 2004 to 2006.

Site	Min. flow (m^3/s)	Date	Max. flow (m^3/s)	Date
Beaver Creek				
Beaver Creek at Hwy 153 (mouth)	0.01	7/9/2004	0.72	5/16/2005
Beaver Creek at Lower Stokes	0.06	7/14/2005	0.74	5/16/2005
Beaver Cr. at Thurlow	0.10	7/27/2005	0.63	4/14/2006
Beaver Cr. at Upper Stokes	0.10	7/27/2005	0.65	5/18/2005
Beaver Cr. above SF	0.08	10/15/2004	0.57	5/16/2005
Beaver Cr. below SF	0.16	10/24/2005	0.91	5/16/2005
Beaver Cr. above Blue Buck	0.03	7/27/2005	0.15	5/16/2005
Blue Buck Cr. above Beaver Cr.	0.02	10/24/2005	0.27	5/16/2005
Volstead Creek	0.00	7/25/2004	0.02	5/16/2005
Libby Creek				
Libby Creek at mouth	0.09	10/23/2005	1.20	5/17/2005
NF Libby Creek	0.02	10/16/2004	0.43	5/17/2005
SF Libby Creek	0.01	10/16/2004	0.53	5/17/2005
Gold Creek				
Estimated flow at mouth *	0.22	10/22/2005	6.65	5/19/2005
NF Gold Cr. upstream of SF/NF	0.15	10/22/2005	5.40	5/19/2005
SF Gold upstream of SF/NF	0.07	10/22/2005	1.25	5/19/2005
MF Gold Creek	0.01	7/24/2004	0.34	4/16/2006
NF Gold Cr. upstream Foggy Dew	0.07	10/22/2005	3.14	5/17/2005
Foggy Dew Cr. upstream of NF	0.10	10/17/2004	3.22	5/17/2005

* Flow at mouth of Gold Creek estimated from sum of measured flow of NF and SF Gold Creek at confluence.

Instantaneous measurements indicated discharge increases in the downstream direction. In addition, during fall measurements (October 2004 and October 2005), the variation in flows at different locations in the watershed is less compared to the range of flows in the spring, presumably a result of base flow conditions. Gold Creek has the highest flows and Libby and Beaver creeks follow in terms of discharge level (Figure 2.10 to 2.12). The Gold Creek basin is smaller than the Beaver Creek basin (230 versus 290 square km), but has higher flows due to permanent snow fields and higher precipitation than Beaver Creek, since it is located on the west side of the Methow River basin (Ely 2001).

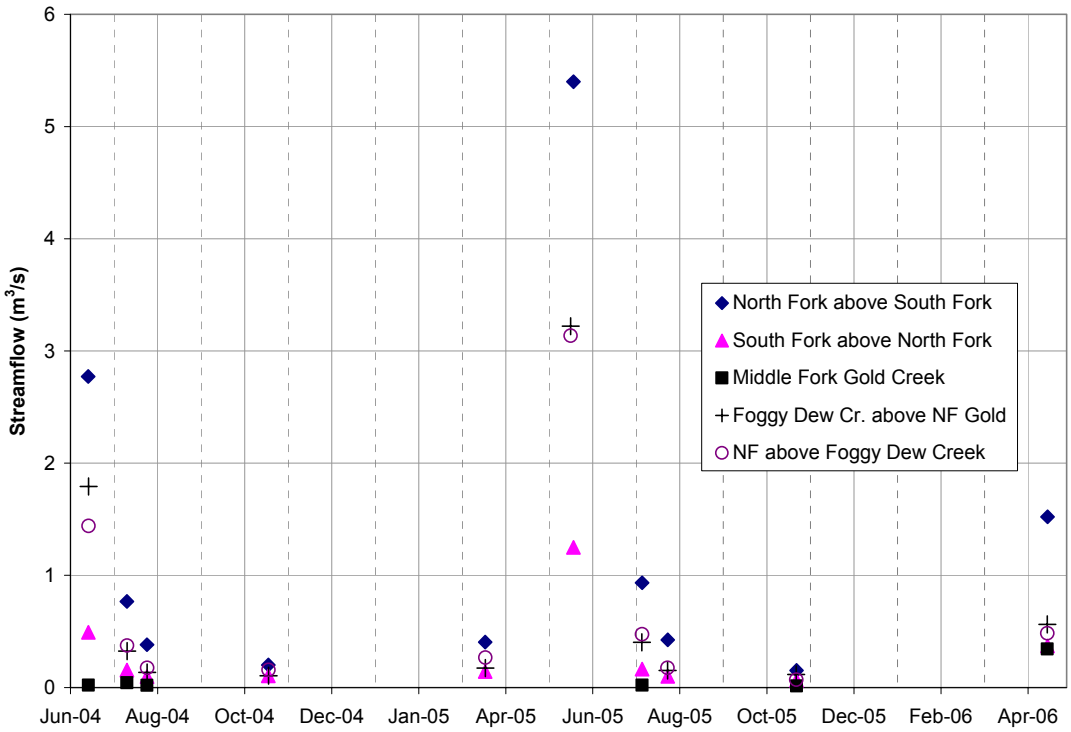


Figure 2.10. Flow measurements in the Gold Creek basin.

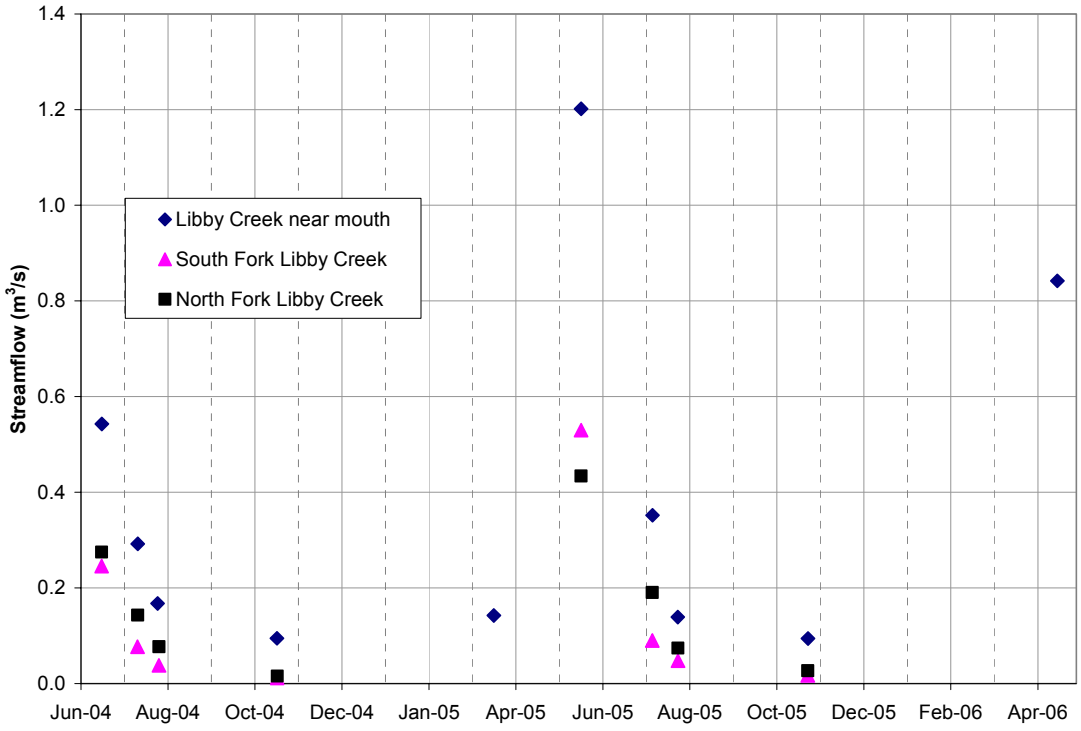


Figure 2.11. Flow measurements in the Libby Creek basin.

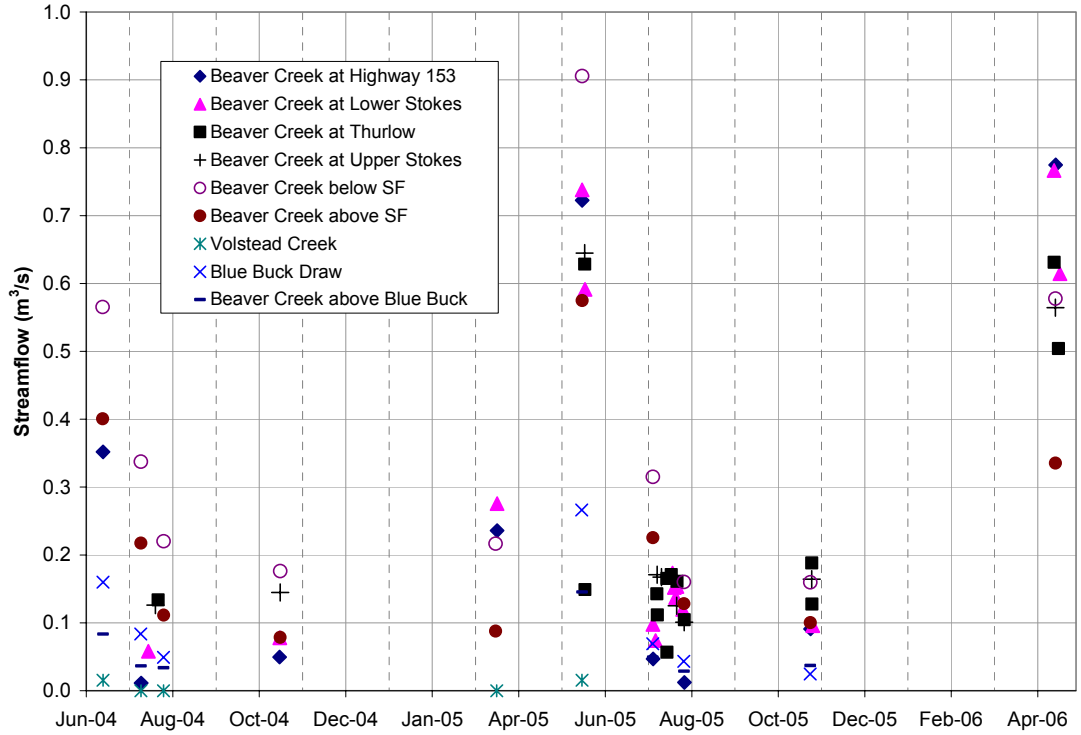


Figure 2.12. Flow measurements in the Beaver Creek basin.

2.7 Temperature monitoring

Twenty temperature loggers were installed in the three study watersheds between July 2004 and May 2005. In the Beaver, Libby, and Gold creek watersheds, eight, four, and eight temperature loggers were installed, respectively. Locations were selected based on irrigation diversion sites, stream junctions, and input from the USGS-CRRL team to support their fish movement analysis. The locations of the deployments in the three study watersheds are shown in Figure 2.4 to 2.6. Coordinates were sampled at the temperature logger sites using a GPS to facilitate GIS analysis and field recovery. Digital photos of the locations were taken to assist with retrieval and to document the condition of the sites.

Each temperature logger was a Hobo Water Temp Pro (Onset Corporation, Bourne, Massachusetts) with an infrared communications window. Sites for the temperature loggers were chosen according to strategic locations in the watersheds to sample temperature changes at tributary junctions, as well as to characterize temperature in index reaches established by the USGS-CRRL for fish movement monitoring. Temperature loggers were placed in pools or deep water to maintain year-round submersion. Each temperature logger was about the size of a cigar (150-mm long by 20-mm diameter) and was secured in a PVC pipe, which was anchored to the stream bank by a stainless steel wire rope. The PVC pipe was labeled in permanent ink with the serial number of the logger and contact information for the University of Idaho, in case of displacement. The temperature loggers were typically placed in the stream bed by stacking cobbles and boulders on top to secure them in high flows.

Each logger was programmed to record temperature at 15-minute intervals in the summer and 30-minute intervals in the winter. Each spring, summer, and fall, data recorded on the temperature loggers were transferred to a laptop via an infrared communicator. Prior to the winter season, the temperature loggers were checked, secured, and re-launched at 30-minute

intervals to prepare for adverse conditions. Data were collected periodically to check the status of the instruments and maintain data records in case of malfunction or loss.

Temperatures in Beaver, Libby, and Gold creeks ranged from (ºC): 0.0 to 25.6, 0.0 to 19.5, and 0.0 to 21.3, respectively (Figures 2.13 to 2.15 and Table 2.4). Full records of temperature variation for selected temperature loggers are shown in Figure 2.13 to 2.15. The temperature data shown in the plots are from loggers in the upper watershed and near the mouths of the creeks. As expected, the data show a warming trend in water temperature in the downstream direction. In the summer, the average daily temperature warms by approximately 5 ºC in the summer and nearly zero in the winter, as water moves downstream in Gold, Libby, and Beaver creeks, towards the Methow River. In addition, the daily change in temperature at a given sampling site oscillates from about 8 ºC to 0 ºC in the winter. Libby Creek had the coolest water temperatures at the mouth in the summer, followed by Gold Creek and Beaver creeks (Figures 2.13 to 2.15).

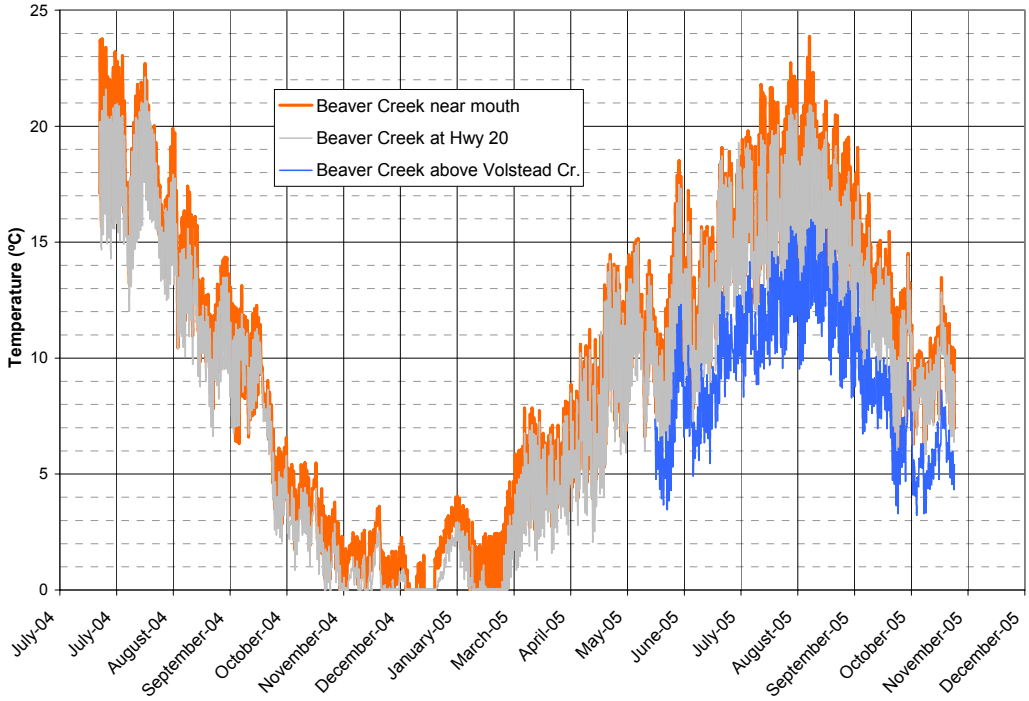


Figure 2.13. Temperatures in Beaver Creek.

Table 2.4. Stream temperatures in the Beaver, Libby, and Gold Creek basins.

	Period of record			
Location	**from**	**to**	**Min. (ºC)**	**Max. (ºC)**
Beaver Creek at mouth	7/22/2004	10/24/2005	0.0	23.9
Beaver Creek above MVID return flow	7/22/2004	10/24/2005	0.0	25.6
Beaver Creek below Fort-Thurlow	7/22/2004	4/15/2006	0.0	21.7
Beaver Creek at Highway 20 bridge	7/22/2004	4/14/2006	0.0	22.1
Beaver Creek at Lower Stokes	7/23/2004	1/8/2006	0.0	20.1
Beaver Creek above Fraser Creek	5/18/2005	10/24/2005	5.2	22.6
Beaver Creek below South Fork	5/16/2005	10/24/2005	3.2	16.0
Beaver Creek above Volstead Creek	7/5/2005	4/15/2006	0.0	14.7
Libby Creek at Highway 153 bridge	7/19/2004	10/22/2005	0.0	19.5
Libby Creek above barrier	7/19/2004	10/22/2005	0.0	19.5
North Fork of Libby Creek	10/16/2004	10/23/2005	0.0	14.9
South Fork of Libby Creek	7/19/2004	10/22/2005	0.0	15.0
Gold Creek below barrier	7/23/2004	10/22/2005	0.0	21.2
Gold Creek above barrier	10/17/2004	10/22/2005	0.0	20.3
NF Gold Creek above SF confluence	10/17/2004	10/22/2005	0.0	18.5
NF Gold Creek above MF confluence	7/20/2004	10/22/2005	0.0	21.3
SF Gold Creek above NF confluence	7/6/2005	10/22/2005	4.9	16.6
NF Gold Creek above Foggy Dew	7/20/2004	10/22/2005	0.0	17.8
Foggy Dew Creek upstream of NF Gold	7/20/2004	10/22/2005	0.0	17.7
NF Gold Creek above Crater Creek	5/17/2005	10/22/2005	4.1	12.1

Notes:

1. Data computed from temperature logger records measured at 15 to 30 minute intervals from 2004 to 2006.
2. Some records are discontinuous due to instrument malfunctions.

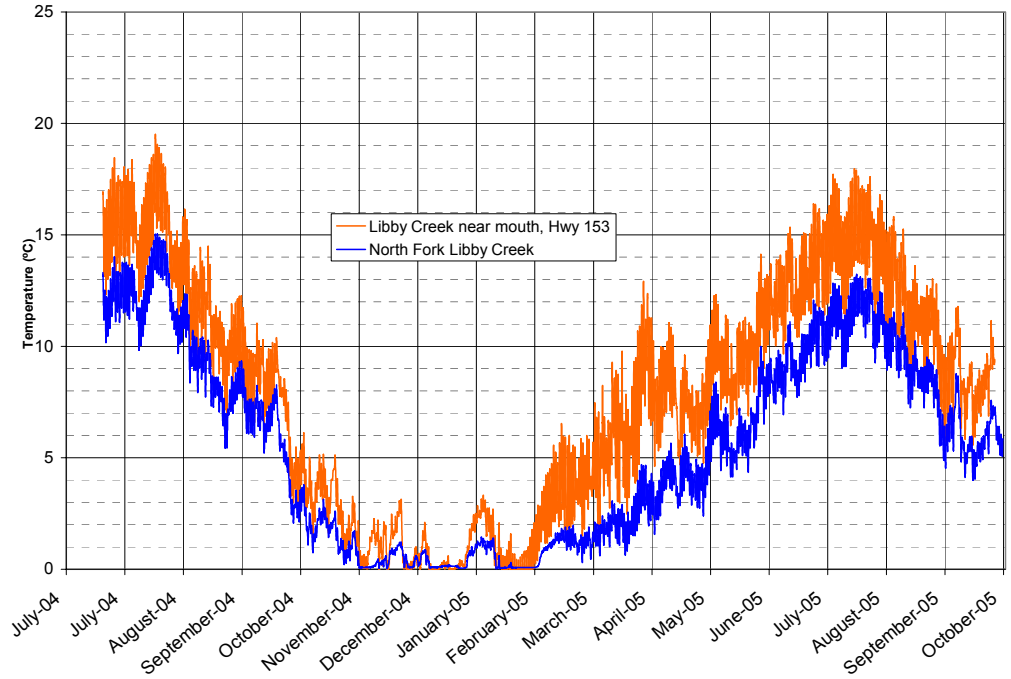


Figure 2.14. Temperatures in Libby Creek.

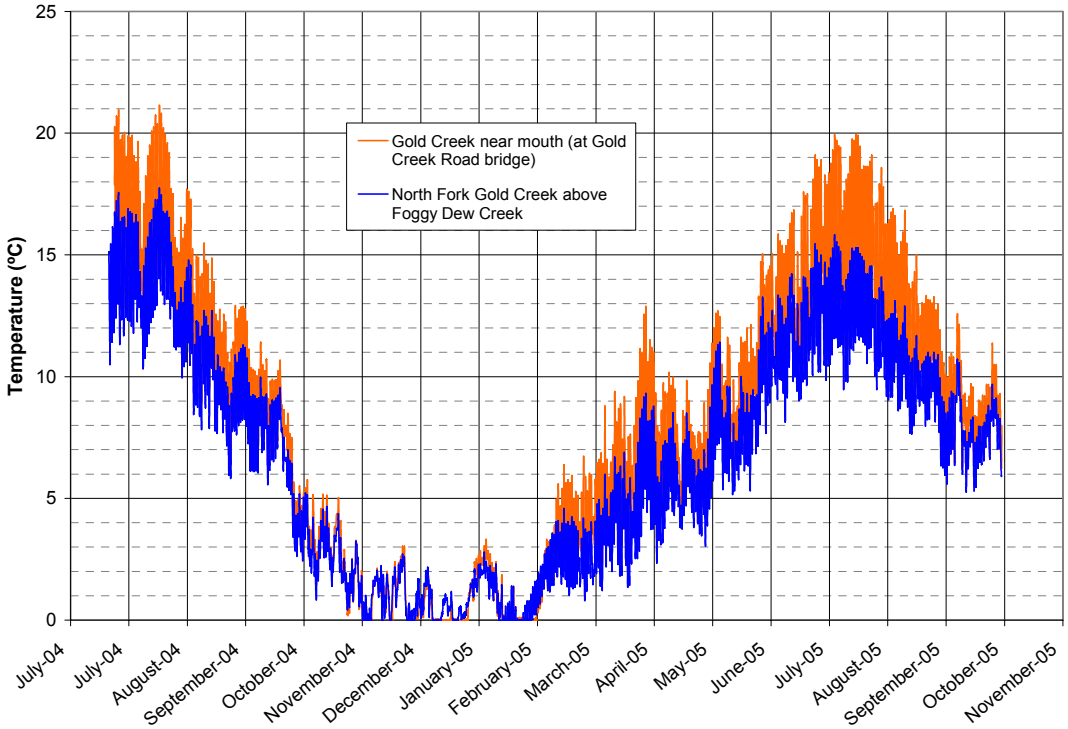


Figure 2.15. Temperatures in Gold Creek.

2.8 Streamflow monitoring with pressure transducers

To develop a continuous record of discharge in Beaver Creek at the Lower Stokes, Thurlow, and the Upper Stokes project sites, a pressure transducer was installed at each site upstream of the installed rock vortex weirs. The pressure transducers measured continuous records of water depth, which were converted to continuous records of discharge by rating curves for each site. Locations for the pressure transducers were selected to be sufficiently upstream of the rock vortex weirs and in stream segments of deeper water, relatively clear of debris that could displace the instruments or create poor conditions for a rating curve development. The pressure transducers recorded water depth at 15 to 30 minute intervals, depending on the season. Data were downloaded during field visits via direct connection to the instrument from a laptop computer.

The type of pressure transducer sensors varied between sites. At Upper Stokes and Thurlow, Aquarods (Stevens Water Monitoring Systems, Inc, Beaverton, Oregon) were installed at each site. These instruments are vertical rods secured within perforated PVC that change capacitance as water depth changes. The PVC casing acts as a stilling well to stabilize water levels. The pressure transducer at Lower Stokes was a Minitroll (In Situ Corporation, Fort Collins, Colorado) titanium plate pressure sensor, bolted in place inside a perforated PVC pipe. For all pressure transducer installations, steel posts were driven vertically a minimum of 0.5 m (1.5 feet) into the gravel / cobble substrate of the bed, and the PVC casings holding the pressure transducers were secured to the posts with a minimum of eight high strength plastic zip ties. Staff gages were strapped on the outside of the PVC to facilitate visual water depth measurements and rating curve calibration points. The whole assembly was secured to shore by high strength 3/16” stainless steel wire rope.

To develop a rating curve for each pressure transducer, rating points were developed by correlating instantaneous flow measurements at the pressure transducer to observed staff gage readings. A range of rating points was measured from spring peak flows to winter base

flows. Rating points at the three project sites on Beaver Creek were measured from July 2004 to April 2006, to develop rating curves for the pressure transducers at Lower Stokes, Thurlow, and Upper Stokes. Each rating curve was typically generated by fitting a line to plots of log-stage versus log-flow (Q) for rating points, resulting in a slope coefficient (A) and an intercept constant (B) with the following equation:

$$\log(Q) = A \cdot \log(Z) + B \tag{2.1}$$

Where:

Q = Discharge, in m^3/s

log(Q) = Logarithm base 10 of discharge, Q

A = Fixed slope coefficient for line fitted to measured points of log(stage)-log(Q)

Z = Water stage, in m

B = Fixed value for y intercept of line fitted to measured points of log(stage)-log(Q)

By solving the above equation for Q, a discharge for any stage in the continuous depth record could be calculated as follows:

$$Q = 10^{(A \cdot \log(Z) + B)} \tag{2.2}$$

The flow record is considered uncalibrated when data are beyond the range of the rating points. Discharge was calculated beyond the calibrated range using the same linear fit of log-stage versus log-Q. These calculated discharges outside the calibrated range are considered estimates and should be verified with additional rating point measurements that extend the calibrated range.

Rating curves for the pressure transducers at Lower Stokes, Thurlow, and Upper Stokes are shown in Figure 2.16, Figure 2.17, and Figure 2.18, respectively. Calculated streamflows, based on rating curves for the Lower Stokes, Thurlow, and Upper Stokes project sites are shown in Figure 2.19, Figure 2.20, and Figure 2.21, respectively.

The rating curves for the pressure transducers were typically developed using a linear fit to rating points, calculated as log(Q) versus log(Stage). For the pressure transducer at Lower Stokes, an additional rating point at 8.5 m^3/s (300 cfs) on May 17, 2005 was added, based on

communications with the BOR (McLaughlin, personal communications, 2006). This high flow was combined with a measured water stage in Beaver Creek at Lower Stokes of 2.2 m, recorded by the Lower Stokes pressure transducer. Based on this additional point, the rating curve was fitted to a second order polynomial, which provided a better estimate of 7.46 m^3/s at a stage of 2.2 m, compared to an estimate of 14.16 m^3/s from a log-log fit.

Within the calibrated range of the pressure transducers, between 0.1 and 0.7 m^3/s, a trend of increasing in discharge in the downstream direction was observed, likely due to additional flow inputs augmenting the flow in the downstream direction (Figure 2.19 to 2.21). Peak flows on May 10, 2005 at Lower Stokes and Thurlow, extrapolated from recorded stage data and the site specific rating curves, matched well for Lower Stokes and Thurlow (2.56 versus 2.44 m^3/s). However, the rating curve at Upper Stokes significantly overestimated peak discharge as 5.83 m^3/s, or roughly a 230 percent error. This is due to the lack of rating points for high flows at the Upper Stokes pressure transducer.

Daily oscillations of approximately 0.05 m^3/s (1.8 cfs) were observed in the estimated discharge at the pressure transducers. Larger daily oscillations of approximately 0.35 m^3/s (12.4 cfs) were observed at the pressure transducers during freezing temperatures in February, likely due to freeze cycles affecting the sensor. These measurements were corrected by using average daily values in February 2005, based on a running average at noon each day.

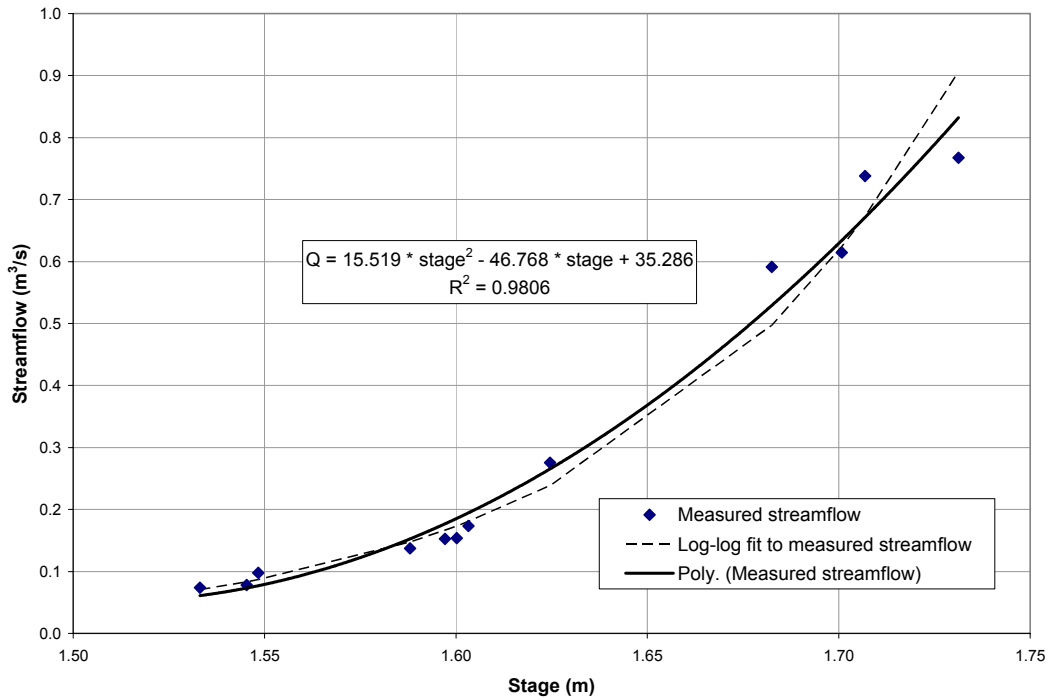


Figure 2.16. Rating curve for the Lower Stokes project site with a polynomial fit.

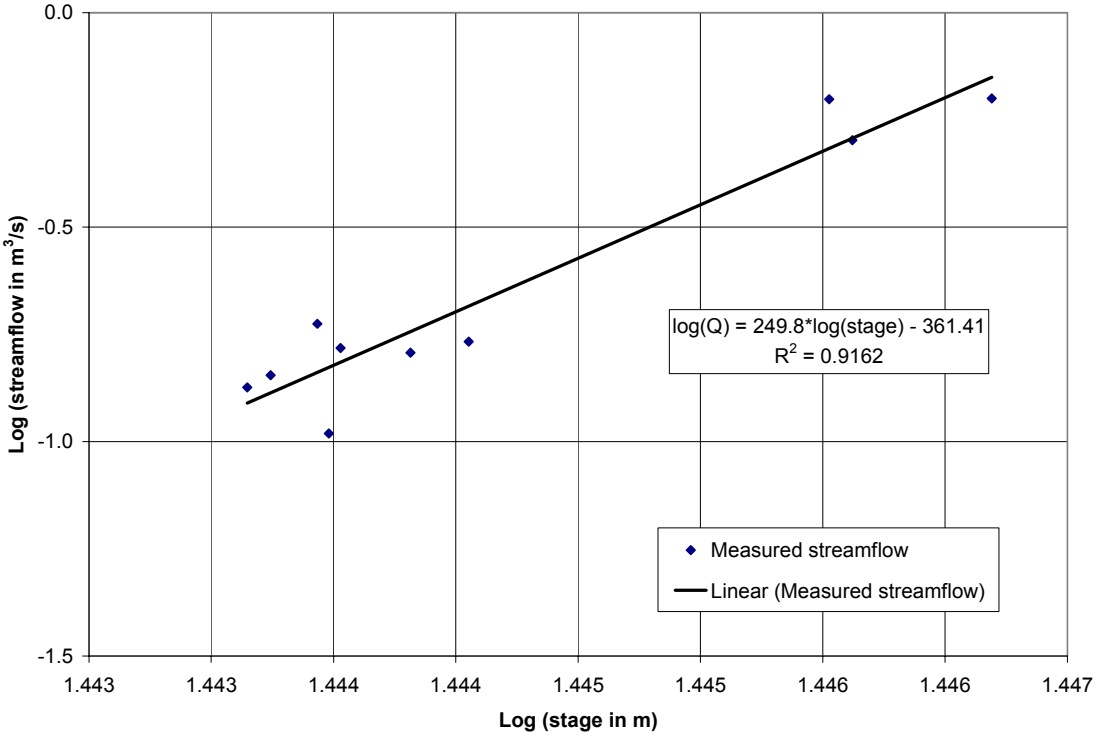


Figure 2.17. Rating curve for the Thurlow project site.

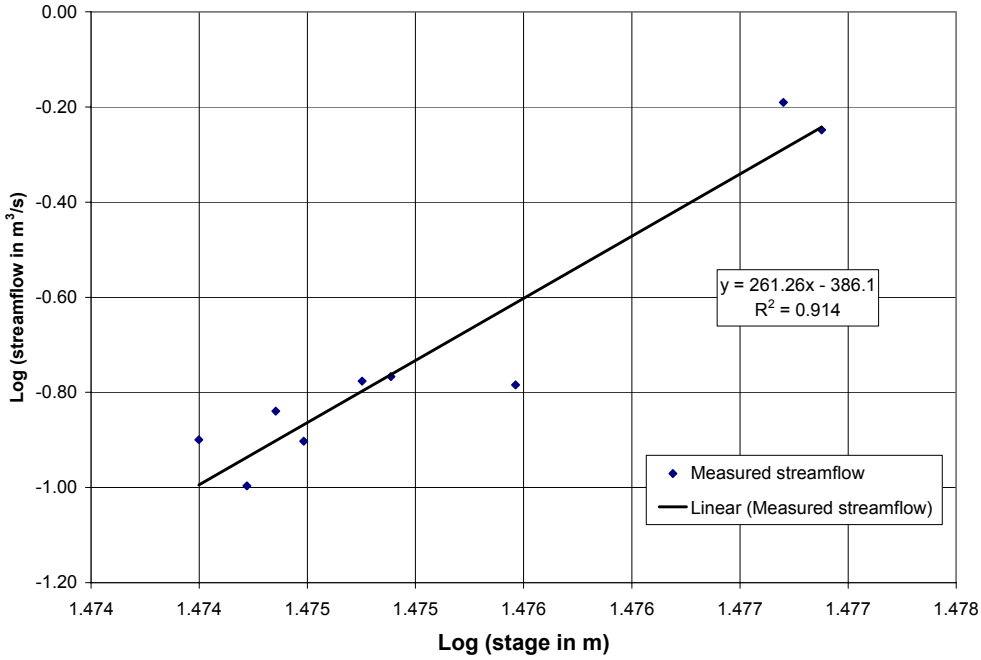


Figure 2.18. Rating curve for the Upper Stokes project site.

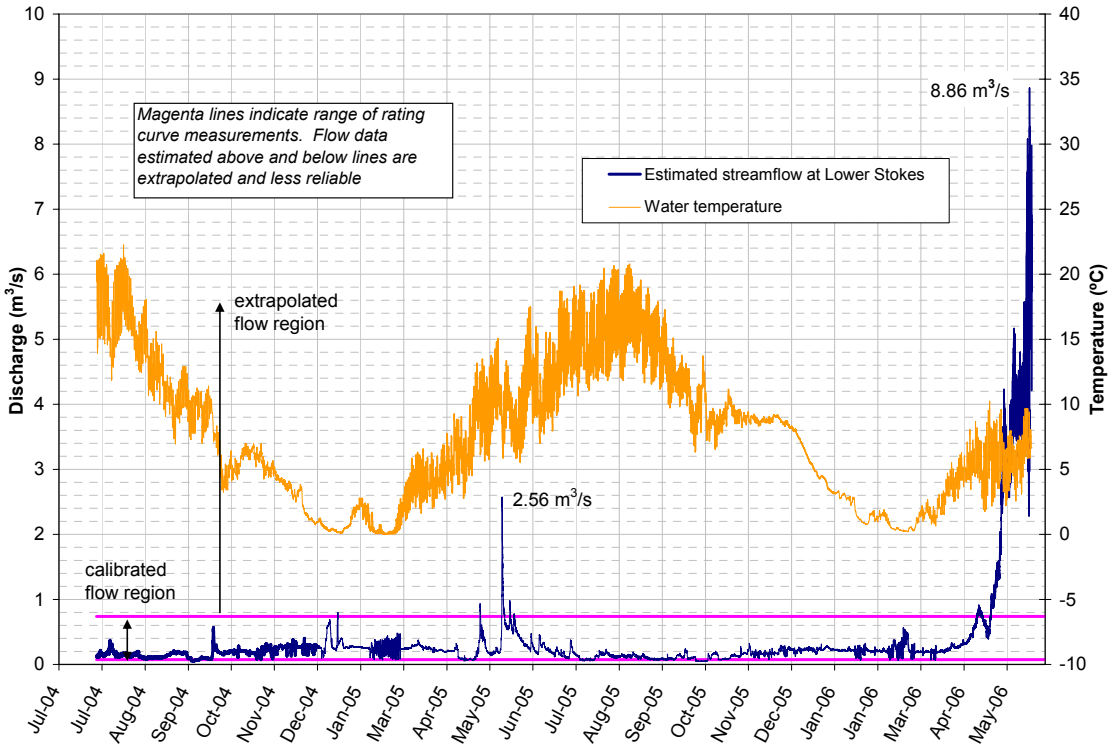


Figure 2.19. Estimated streamflow and temperature at Lower Stokes project site.

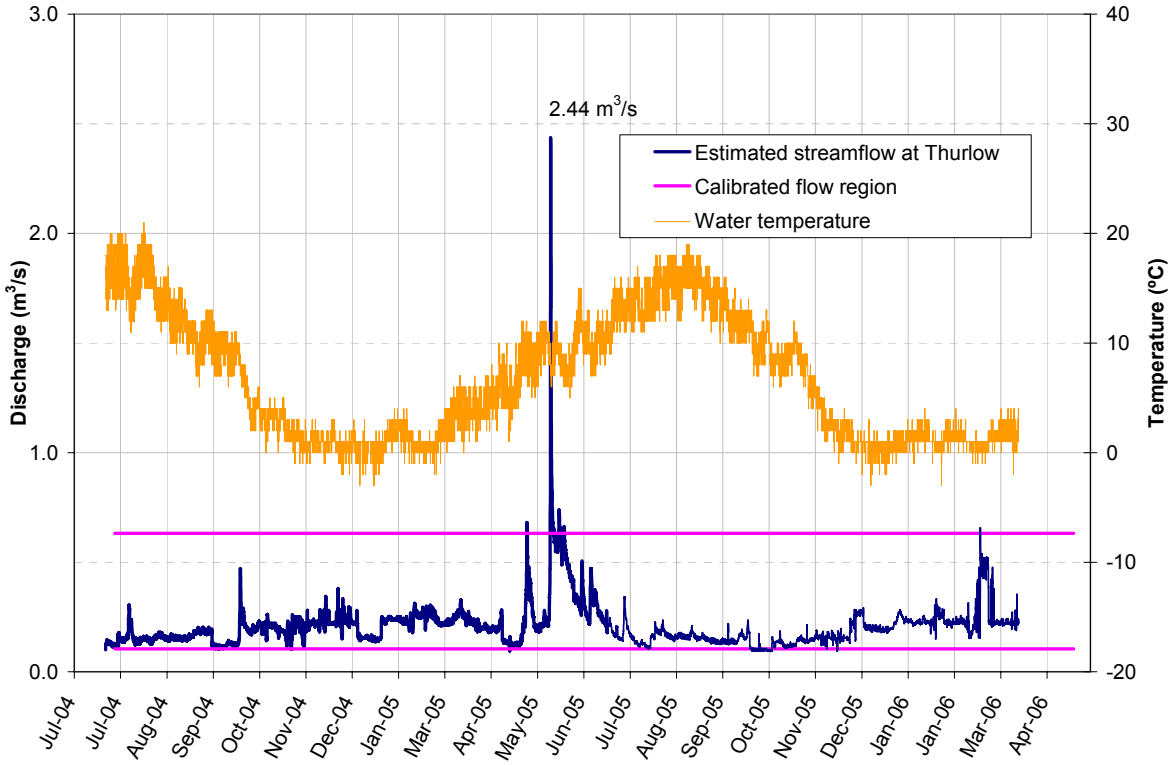


Figure 2.20. Estimated streamflow and temperature at Thurlow project site.

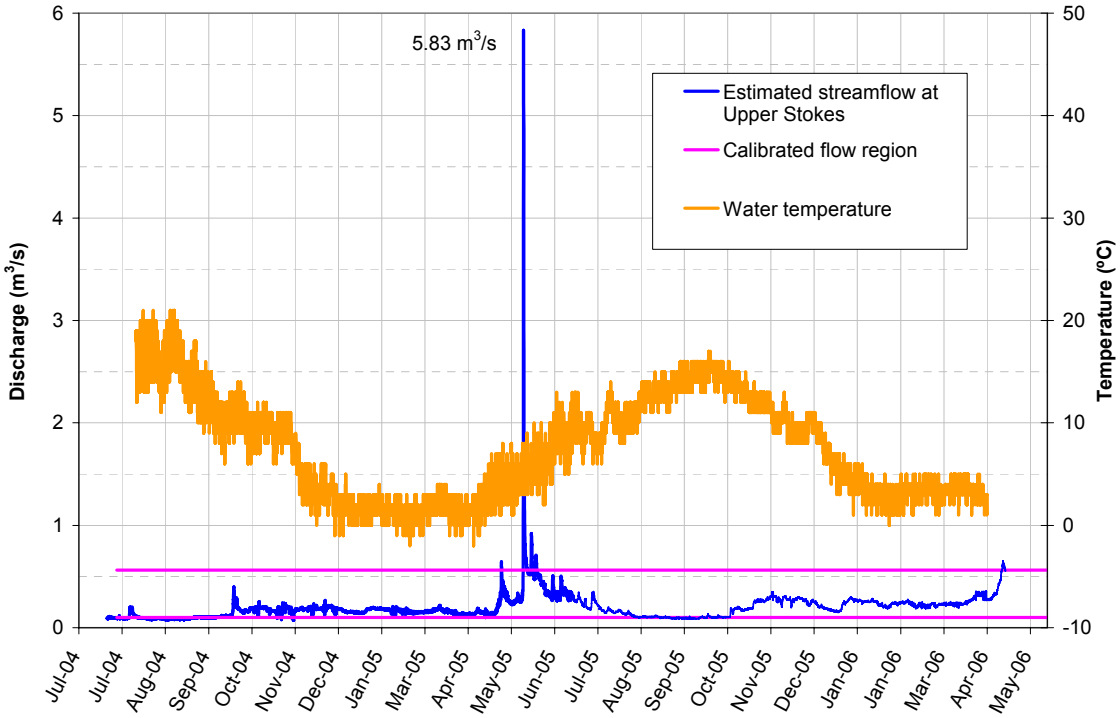


Figure 2.21. Estimated streamflow and temperature at Upper Stokes project site.

2.9 Hydrologic analysis

Hydrologic analysis was performed on the Gold, Libby, and Beaver creek basins. USGS measurement records and flow data collected for this study were used to develop estimates for flood frequencies and flood durations. Flood duration was calculated for 5-percent and 95-percent exceedance using standard procedures (OSU 2006). Flood frequencies for 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 200-year storms were determined two ways, the online server StreamStats (USGS StreamStats 2006) and Log Pearson Type III distribution flood frequency analysis (USGS 1981).

2.9.1 Flow duration analysis

Fish passage guidelines (NMFS 2000, WDFW 2003) were used to evaluate performance for upstream fish passage. Following these guidelines, a high flow at 5-percent exceedance (Q_{fp}) and low flow at 95-percent exceedance (Q_{low}) were calculated using Equation (2.3) to establish a flow window that captures 90% of all flows and identifies the flow range where fish passage is required. An exceedance flow is a discharge that identifies a threshold, and the indicated percentage is associated with historical average daily flows exceeding that value. For example, a five-percent exceedance flow of 3.5 m^3/s is exceeded during five percent of all historical average daily streamflows (in the migration period).

Percent exceedance was calculated by a flood duration analysis (Oregon State University 2005). The data used for the flow duration calculation were average daily flows in Beaver Creek (USGS flows and flows measured at the pressure transducers) during the primary upstream migration period between February 1 to July 7, each year, based on fish movement data collected by the USGS-CRRL in 2004 and 2005 for the target species and all life stages of summer steelhead and spring Chinook (Chapter 4).

The formula for percent exceedance is:

$$P = 100\left(\frac{M}{(n+1)}\right) \tag{2.3}$$

Where:

P = Probability a given flow will be equaled or exceeded (% of time), according to analysis of historical record

M = Ranked position of the streamflow

n = Total number of records for the period of record

The probability value P was calculated for every flow in the period of record (all years, migration season only). These data then were counted into bins, based on log cycles, i.e., the range of each bin was defined by a logarithmic scaling. Cumulative counts of flows were calculated for each bin, and the percent of flows exceeding the bin were calculated. Based on plots of the percent exceedance data, Q_{fp} and Q_{low} were determined by inspection.

2.9.2 Flow frequency analysis using USGS StreamStats

Discharges for multiple flow frequencies for the three study watersheds were determined using a USGS internet GIS server called StreamStats (USGS StreamStats 2006). The online software uses interactive displays and regional regression equations to determine discharges associated with 2-, 10-, 25-, 50-, 100-, and 500-year return intervals. Drainage area, mean annual precipitation, and streamflows for the above flood frequencies are calculated and reported onscreen with a “Streamflow Statistics Report”. The user inputs the point in the watershed where the streamflows are required, and the system graphically reports the watershed delineation and the associated streamflow statistics. The accuracy of the predictions is not reported.

2.9.3 Flow frequency analysis using Log Pearson Type III distribution

Flow frequency analysis using a Log Pearson Type III (LP3) distribution was completed for the Beaver Creek watershed where detailed studies were conducted for this thesis, as described by USGS (1981) and Oregon State University (2005). This method produces a more robust estimate of discharge for flood events, since recorded flow data are used, rather than regional regression equations. Streamflow data used in the analysis were USGS historical average daily streamflows for three gages in Beaver Creek and one gage at the mouth of the Methow River (at Pateros), as well as streamflows measured in Beaver Creek for this thesis study. Average daily flows were sampled based on water year to determine minimum, maximum, and average values. The maximum average daily flows for each water year were calculated, tabulated, and ranked from largest to smallest. These data formed the basis for the LP3 analysis.

The LP3 analysis utilizes a statistical curve fit to predict peak discharge values within and outside the calibrated range of discharges (Oregon State University 2005). Average daily streamflow data for the period of record (all years, during the migration season) were tabulated, and the variance (R^2), standard deviation (s), and skew coefficient (β) were calculated using Equations (2.4), (2.5), and (2.6). Based on the value of β and the desired flood frequency, Tr, values for k in the LP3 distribution were determined from tables. The general equation (2.7) for the LP3 distribution was then used to estimate peak discharges for each flood frequency by solving for Q_{tr} in Equation (2.8). The required formulas for LP3 analysis are:

Variance, R^2:

$$R^2 = \frac{\sum\left(\log(Q_{avg}) - \text{average}(\log(Q_{avg}))\right)^2}{(n-1)} \tag{2.4}$$

Standard deviation, s:

$$s = \sqrt{\text{Variance}} = R \tag{2.5}$$

Skew coefficient, β:

$$\beta = \frac{\sum \left(\log(Q_{avg}) - \text{average}(\log(Q_{avg}))\right)^3}{(n-1)(n-2)\cdot s^3} \tag{2.6}$$

Log Pearson Type III (LP3) general equation:

$$\log(Q_{Tr}) = \text{average}(\log(Q_{avg})) + k \cdot s \tag{2.7}$$

re-arranged to calculate Q_{Tr}:

$$Q_{Tr} = 10^{\left(\text{average}(\log(Q_{avg}) + k \cdot s\right)} \tag{2.8}$$

where:

Q_{avg} = Measured average daily discharge, in m^3/s

$\log(Q_{avg})$ = Logarithm base 10 of Q_{avg}

n = Number of data records

Q_{Tr} = Peak streamflow in m^3/s, associated with recurrence interval, Tr, in years

average($\log(Q_{avg})$) = Average value of logarithms of each measured flow, Q_{avg}, for period of record = $\Sigma \log(Q_{avg})/n$

k = Log Pearson Type III constant for general equation, based on recurrence interval Tr (1-, 2-, 5-, 10-, 25-, 50-, 100-, 200-year) and skew coefficient, β, from period of record for average daily flows (calculated per above)

2.9.4 Results of hydrologic analysis

Results from the flow duration, flow frequency, and StreamStats analysis are reported in Table 2.5, Figure 2.22, and Figure 2.23. Average annual precipitation was estimated in StreamStats. The flows Q_{low} and Q_{fp} were estimated as 0.1 and 3.5 m^3/s, as required for fish passage analysis (Table 2.5 and Chapter 5). Flows calculated by StreamStats for flood frequencies in Beaver Creek were high, relative to the more robust method of the LP3 analysis (Table 2.5). StreamStats may also overestimate peak flows for Libby and Gold creeks, since it utilizes general regional regression equations for the Methow River basin.

Table 2.5. Hydrology of Beaver, Libby, and Gold creek basins.

	Beaver Creek				Libby Creek		Gold Creek	
Basin area sq km (sq. mi.)	290.1 (112.0)				104.4 (40.3)		230.5 (89.0)	
Average annual precipitation cm (inches)	58.2 (22.9)				71.4 (28.1)		89.2 (35.1)	
Flow Duration	m^3/s	cfs						
Q_{low} (95% exceedance)	0.1	3.5			*not calculated*		*not calculated*	
Q_{fp} (5% exceedance)	3.5	123.6						
Flow Frequency								
recurrence interval	*StreamStats*		*LP3 analysis*		*StreamStats*		*StreamStats*	
years	m^3/s	cfs	m^3/s	cfs	m^3/s	cfs	m^3/s	Cfs
1			0.7	23				
2	9.2	326	4.2	149	5.3	188	15.6	550
5			6.9	245				
10	21.0	741	8.7	306	11.6	409	30.9	1090
25	27.6	973	10.7	380	15.0	528	38.8	1370
50	33.1	1170	12.2	430	17.8	628	45.3	1600
100	37.9	1340	13.5	478	20.7	732	52.1	1840
200			14.8	522				

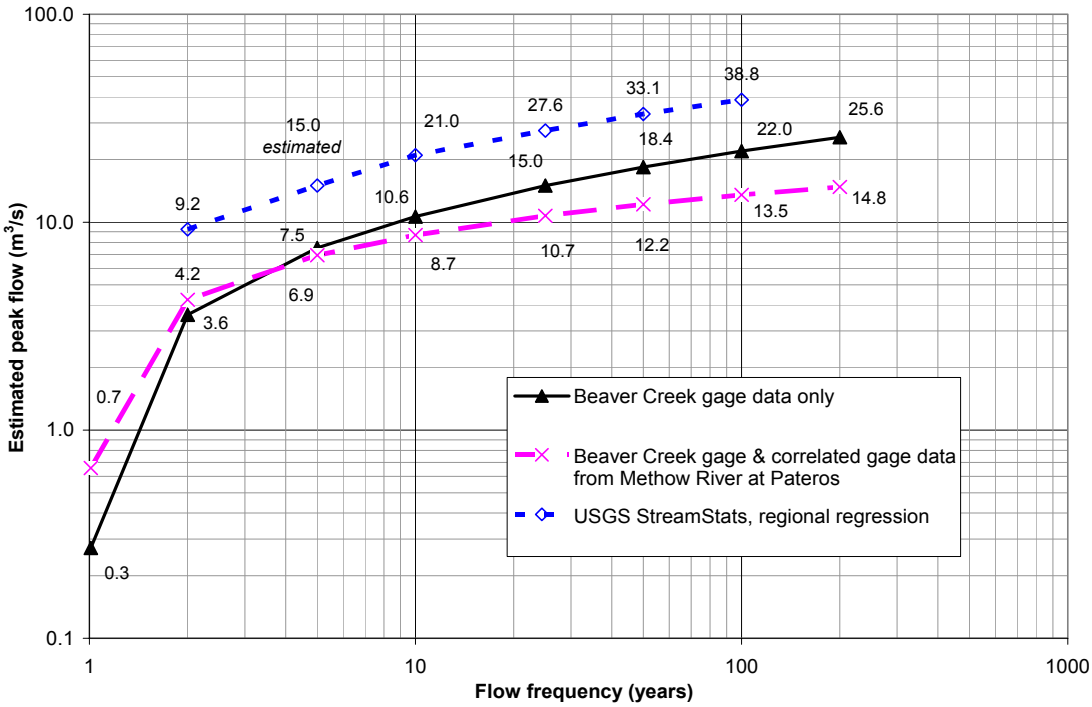


Figure 2.22. Comparison of flow frequency analysis to StreamStats for Beaver Creek.

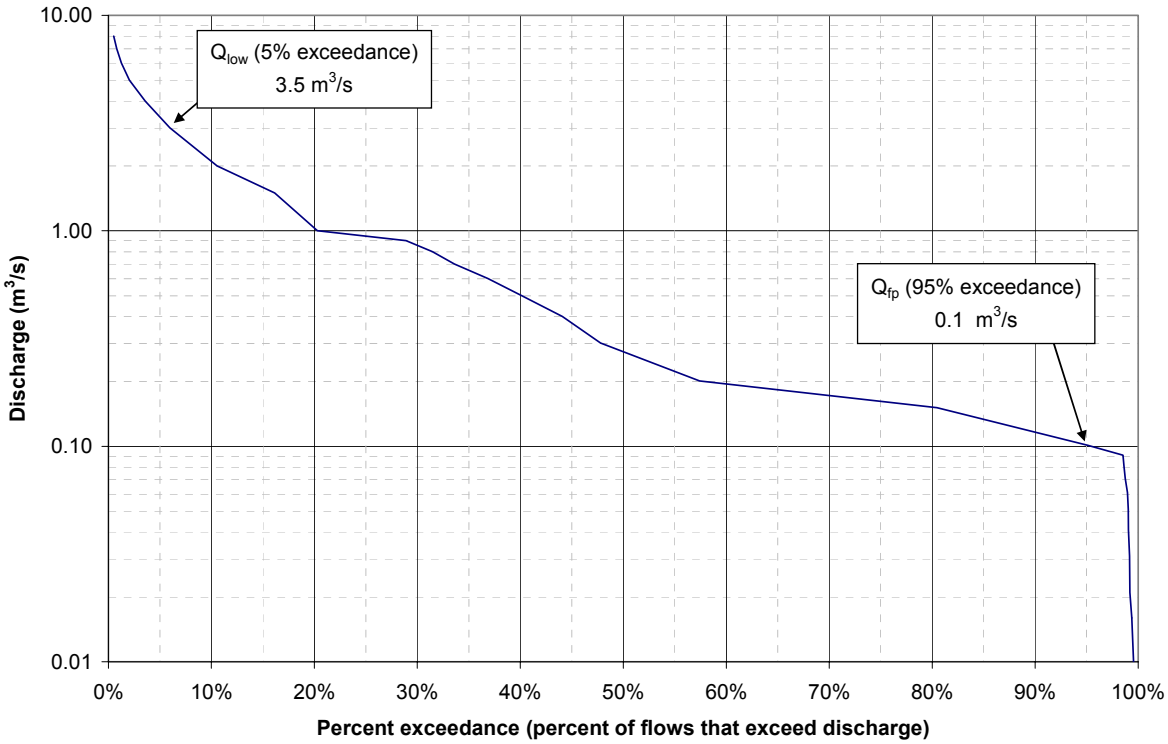


Figure 2.23. Flow duration analysis results for Beaver Creek.

2.10 Discussion

Results of the field monitoring were incorporated into hydraulic models at the rock vortex weirs and the synthesis of fish movement (Chapters 3, 4, and 5), with the goal of quantifying the effectiveness of rock vortex weirs on fish passage in a field setting. Moving from lab studies to field research decreases the ability to control factors influencing the project. The greatest challenge, and one with important implications to this study, was defining the hydrology at the watershed and site scales. External factors such as climatic patterns and local irrigation practice are two of the known challenges that influence this field study.

The period of record used to determine the flow values Q_{fp} and Q_{low} (5-percent and 95-percent exceedance) was 1959–1978. Data were available at the USGS gage in the Methow River at Pateros after 1978, but this gage represented runoff for the entire Methow River

watershed. Hydrology on the west and east sides of the watershed varied significantly, so the data at Pateros were not scaled to the Beaver Creek watershed to fill out the period of record to present day.

The period of record selected for hydrologic data is important since a regional climate regime shift has been documented starting 1977 (Mantua et al. 1997). The authors of Mantua et al. (1997) documented a reversal of polarity of oscillations in climatic factors in 1977, also labeled as "pacific decadal oscillation". This phenomenon is described as an interdecadal oscillation in pacific climate factors, such as sea surface temperature (main factor), sea level pressure, stream flow records in western North America and Alaska, salmon harvest, wintertime land surface temperatures, and 500 mb isobar height fields (air pressure). The change in these factors is associated with changes in climatic factors, most importantly, the decline of salmon fisheries in the Pacific Northwest. A narrow band of warmer air (approximately 0.5 °C warmer) that has been lingering over the west coast of Washington since about 1977 has been associated with reduced precipitation and snow accumulation in the Cascades (Mantua et al. 1997).

One implication of regional climate shift to this thesis study is that the calculated values of Q_{fp} and Q_{low} would be reduced if gage data in Beaver Creek were available after 1978. The trend indicated by pacific decadal oscillation was a sequence of warmer and drier years, which would likely drive the values of Q_{low} and Q_{fp} lower in an LP3 analysis for Beaver Creek. However, the actual changes in Q_{fp} and Q_{low} are difficult to determine.

More importantly, the magnitude of Q_{low}, at 0.1 m^3/s is about the same as daily flow fluctuations in Beaver Creek due irrigation water diversions, so a recalculation of Q_{low} based on climate change may not be as significant as sensitivity analysis on diversion activity, which significantly affects streamflow in Beaver Creek during low flows in irrigation season.

For comparison, in the context of climatic regime shift, the gap in the Beaver Creek period of record after 1977 was filled with scaled data from the USGS gage in the Methow River at

Pateros and the LP3 analysis was repeated. A scale factor of 0.15 was applied to discharge on the Methow River at Pateros to estimate discharge in Beaver Creek. A factor of 0.15 was determined by comparing average daily flows for the two gages during overlapping periods of record and calculating an average scalar. Estimated average daily flows from the gage on the Methow River at Pateros were added to the Beaver Creek data, and the flood frequency analysis was repeated. The result from filling the period of record on Beaver Creek was smaller discharges for flows for the flood frequencies, shown in Figure 2.22, as expected from regional climatic shift. However, the drop in the discharges could be associated with uncertainties from comparing runoff at the mouth of the Methow River basin to runoff in Beaver Creek basin, which have different hydrologic characteristics (Ely 2001). Given this uncertainty, discharges for flow frequencies are likely closer to those developed using only measured data from the Beaver Creek basin (Figure 2.22).

Discharge estimates from StreamStats appeared to overestimate discharge for the Methow River basin (Figure 2.22). The online server for StreamStats was released for the state of Washington in 2005 by the USGS and is considered a provisional software (USGS StreamStats 2006). More spatial resolution in the regression equations built into StreamStats and better precipitation data would likely provide better estimates of peak flood flows. Better estimates from for flood frequency discharges are generated from LP3 analysis, since they are based on measured data for the study area, but this approach is limited by the availability and quality of discharge data for the area of interest.

Water diversions in Beaver Creek had affected the hydrographs developed from the pressure transducer data recorded at the project sites (Figure 2.24). A review of water right records revealed a complex diversion history. A particular diversion may carry water for multiple users who own different priorities of water rights, all of which vary based on the type of water year, as identified by the regulatory agencies. Overall, the total water rights at each diversion location are approximately 0.42 m^3/s (1.5 cfs), which may vary on a daily or intra-day basis. Discharge data measured outside of irrigation season were more reliable for estimating flow over the rock vortex weirs at the project sites in Beaver Creek since irrigation diversions near the rock vortex weirs were closed during these periods. Where

possible, rating curves for the pressure transducers were developed based on flow measurements outside the diversion periods.

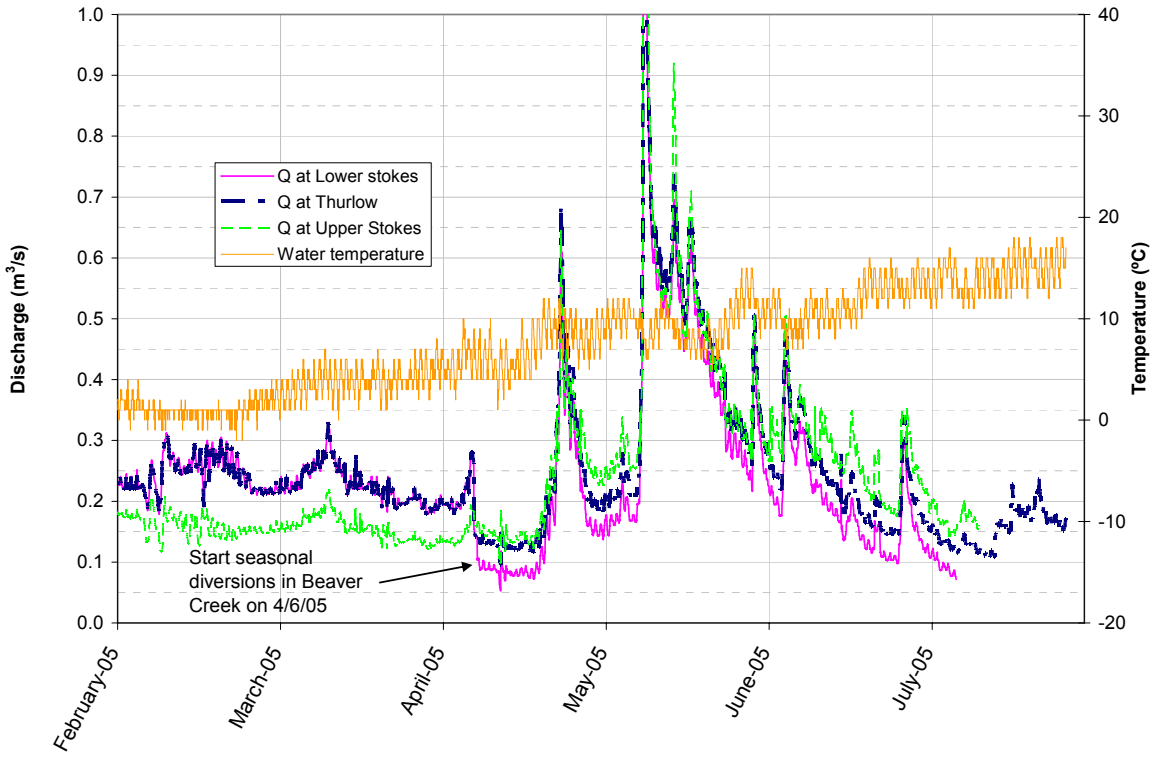


Figure 2.24. Discharge in Beaver Creek at Lower Stokes, Thurlow, and Upper Stokes, February 1 to August 1, 2005. The start of the irrigation season and opening of the head gates are apparent at Thurlow and Lower Stokes around April 6, 2005 when discharge in Beaver Creek drops by approximately 0.14 and 0.18 m^3/s, respectively.

Regarding flow data from the pressure transducers, only data within the calibrated range were used for fish passage analysis (Chapter 5). During most of the primary migration period at Lower Stokes, the measured flow was within the calibrated range and the lower bound of the calibrated range (0.07 m^3/s) is close to the calculated lower bound for fish passage Q_{low} (0.10 m^3/s). The upper bound of the calibrated range (0.74 m^3/s) is lower than the upper bound for Q_{fp} (3.5 m^3/s), but the hydrograph only exceeds 0.74 m^3/s for brief periods of high runoff (Figure 2.19 to 2.21).

The pressure transducers were carefully placed upstream of the rock vortex weirs to minimize backwater effects. At Upper Stokes, Thurlow, and Lower Stokes, the pressure

transducers at were located approximately 80, 14, and 10 m upstream from the rock vortex weirs, respectively. Installing the pressure transducers with a buffer distance does not eliminate the possibility of transient debris or other factors in Beaver Creek temporarily affecting water stage. The period of record for the pressure transducers was reviewed to eliminate possible irregularities in water stage and discharge estimates at each site. Estimated flows from each pressure transducer were assumed follow the similar temporal patterns. However, during irrigation season, diversions introduce differential flow patterns at the project sites (Figure 2.24).

Detailed data from the pressure transducers provided continuous measurements of stage, which facilitated continuous flow estimates at rock vortex weirs. These data were critical for hydraulic modeling (Chapter 3) and fish passage analysis (Chapter 5). In addition, temperature measurements provided useful information on migration cues (Chapter 4).

3. HYDRAULIC MODELING AT ROCK VORTEX WEIRS

The hydraulics of rock vortex weirs are complex due to large roughness elements and super to subcritical plunge effects, occurring in three dimensions. This type of structure has not been well analyzed, so this thesis attempts to describe the hydraulics of the rock vortex weirs using sets of equations and field observations to calibrate these equations.

Two types of models were developed to describe hydraulics at the rock vortex weirs. The first type was a spreadsheet-based model, which used utilized sets of equations to estimate the first three modes of a four-mode model, describing stage versus discharge relationships at rock vortex weirs. The second model type was a numerical hydrodynamic model, which estimated the fourth mode, rough boundary flow. Techniques were also developed to transition between gap flow, weir flow, and rough boundary flow, the four modes of flow estimated at the rock vortex weirs.

Using field measurements of water stage, topography, and output from the model of flow over the rock vortex weirs (for the first three modes), rating curves for hydraulic parameters important for fish passage (Appendix A) were developed, with discharge as the dependent variable. Using data from the rating curves and continuous flow records, time series of hydraulic parameters during critical times of migration for target species were developed.

To develop the hydraulic models, data were collected at three project sites (Lower Stokes, Thurlow, and Upper Stokes). These data include continuous discharge measurements at the project sites, staff gage observations at the rock vortex weirs for measurement of water surfaces, velocity profiles, spot velocity measurements, and substrate classification from Wolman Pebble Counts. Topographic surveys were performed to determine channel cross sections, water surface profiles, channel thalweg profiles, and topography at rock weirs.

3.1 Fish passage improvements in the Beaver Creek watershed and hydraulic modeling

Along Beaver Creek, there are four project sites where previously existing low barriers (constructed of logs and concrete) were removed and replaced with rock vortex weirs: Upper Stokes, Thurlow, Lower Stokes, and Fort-Thurlow. Removal and replacement of all of the barriers was required to provide access to spawning and rearing habitat. This chapter describes the development of hydraulic models at the Lower Stokes project site and validation of the application of the models at the Upper Stokes and Thurlow project sites. The locations of the project sites on Beaver Creek are shown in Figure 1-4.

At each of the project sites, data were collected and hydraulic models were developed to monitor performance of rock vortex weirs for upstream fish passage. Hydraulic models were developed to simulate key hydraulic parameters as a function of stream discharge. Four hydraulic parameters were used to evaluate effectiveness of fish passage at rock vortex weirs (Appendix A): hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation factor, and average velocity over the rock vortex weirs,

Average stream velocity over the rock vortex weirs was evaluated using hydraulic models to deconstruct discharge into four flow modes. Based on the flow modes activated, flow depth and area were correlated with discharge, which facilitated the calculation of average velocities over the weirs ($Q = V*A$). An average velocity rating point was calculated for each observation of stage and discharge. The rating points were then combined to develop a rating curve that was applied to the continuous flow record. The final result was a continuous record of average velocity at the rock vortex weirs (Chapter 5).

Rating curves were also developed for the three other hydraulic parameters (hydraulic drop, ratio of pool depth to hydraulic drop, and energy dissipation factor). The rating curves were developed from staff gage observations, flow records, and ground survey. Using the rating curves and the continuous record of discharge, continuous calculations of the three hydraulic

parameters were generated and compared to fish passage guidelines as described in Appendix A (Chapter 5).

3.2 Project site descriptions

Ground survey and analysis of USGS digital elevation models (DEMs) were used to calculate an average stream slope of about 1.5 to 2.0 percent within the reach of Beaver Creek that contains the project sites. Average bank full width of Beaver Creek is estimated at 10 m, and bank full depth is estimated to be about 1 m in the vicinity of the project sites, based on ground survey of cross sections and field observations.

Descriptions of each project site follow. Additional information on the designs of the rock vortex weirs are available in construction completion reports (BOR 2004 a, b, and c).

3.2.1 Lower Stokes Project Site

The Lower Stokes project site is located on Beaver Creek just downstream of Fraser Creek and 4.0 km (2.5 miles) upstream from the mouth at the Methow River. The original diversion dam at Lower Stokes was about 1 m (3 feet) high and constructed of stacked logs and plastic sheeting. The original dam structure was removed and replaced in fall 2003 with a sequence of three rock vortex weirs, designed based on Rosgen (2001) (McLaughlin, personal communications, 2006). Designs were prepared by the BOR and implemented by the Okanogan Conservation District with construction supervised by the BOR design team. A plan view and photo of the Lower Stokes project are shown in Figure 3.1 and Figure 3.2.

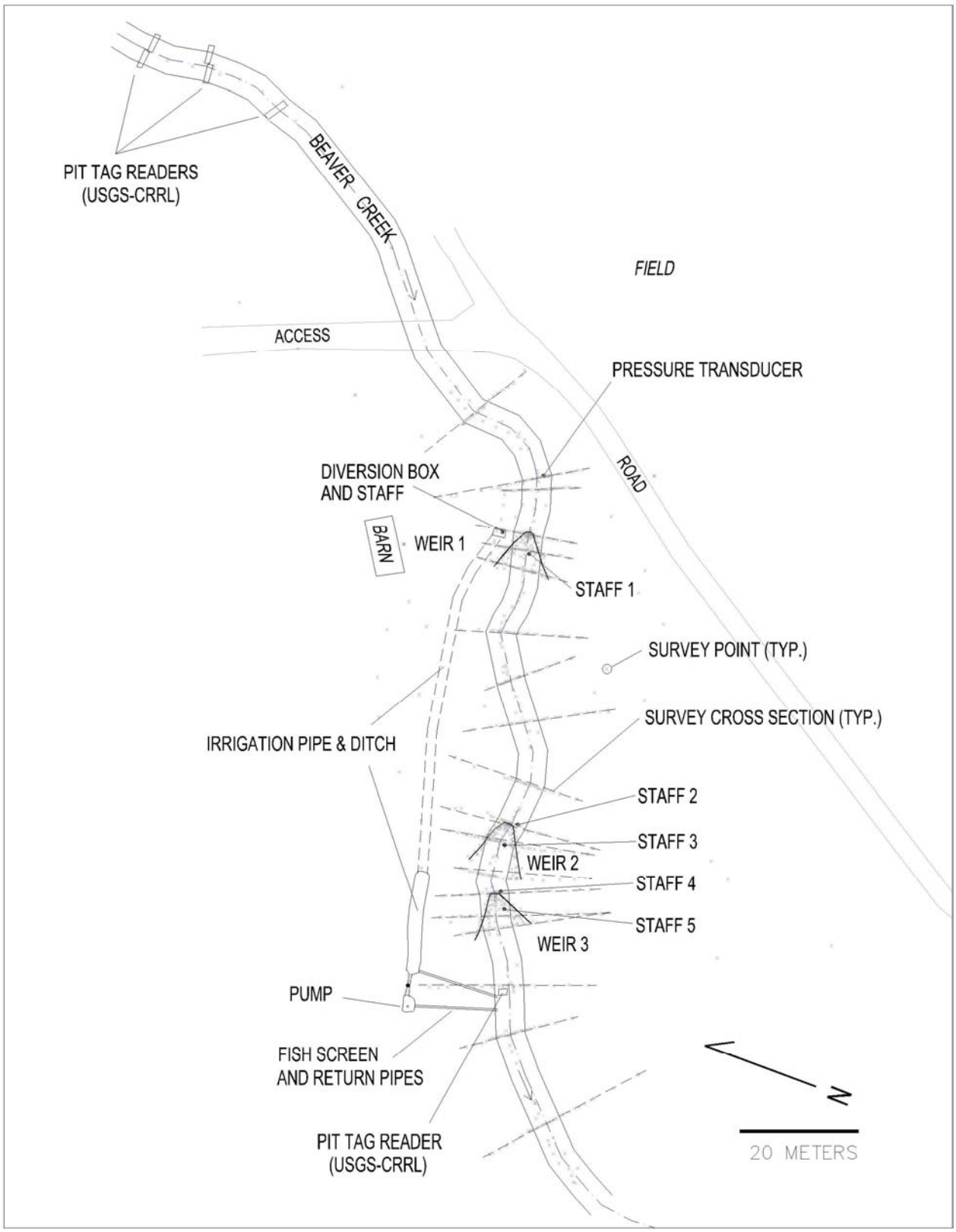


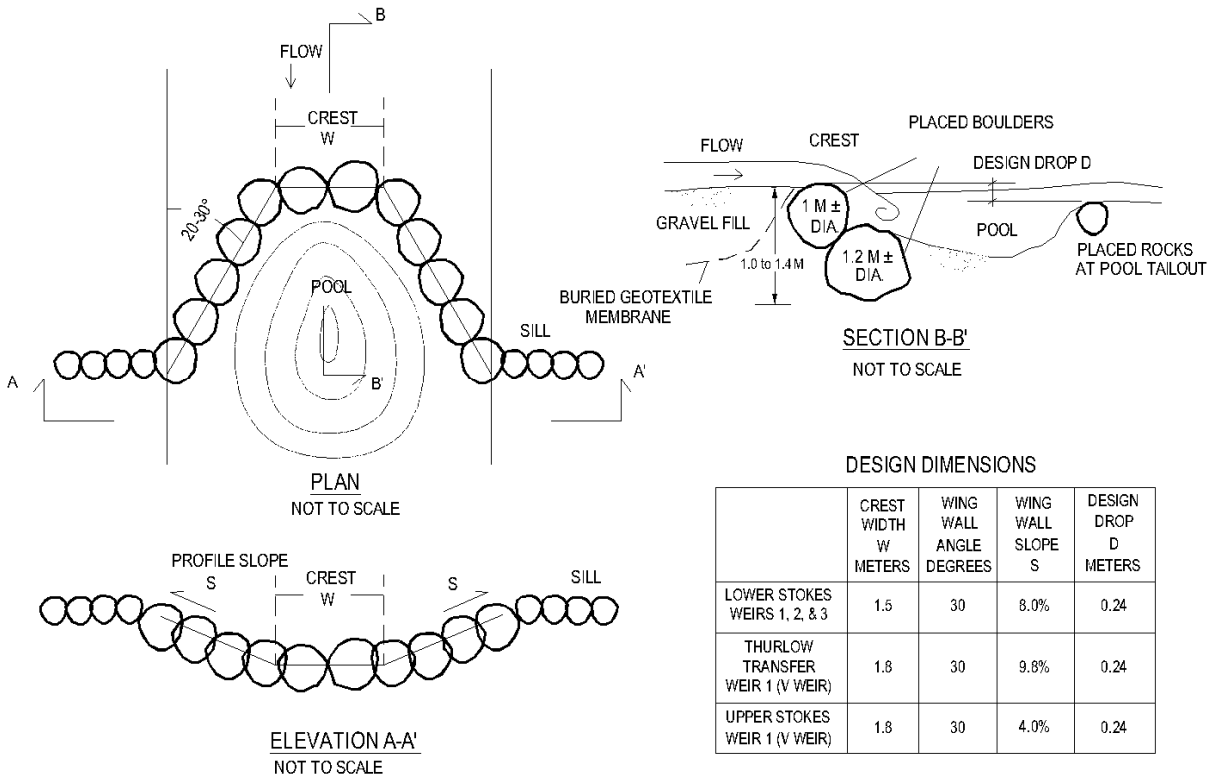
Figure 3.1. Lower Stokes project site.

Figure 3.2. Photo of Lower Stokes site.

The upstream weir at Lower Stokes was designed to form a small pool to facilitate irrigation diversion and the installation of a new diversion box, head gate, and pipe. The design hydraulic drop for each structure was 0.24 m (0.8 feet), to comply with Washington State standards (WDFW 2003). The project engineers estimated that the large stones used for the weir crest weighed between 270 and 1800 kg (600 to 4000 pounds). To reduce seepage through the rock weir, a layer of geocomposite fabric was installed in the stream bed on the upstream side of each rock vortex weir.

A typical plan and profile of the rock vortex weir is shown in Figure 3.3, and a photo of a typical rock vortex weir is shown in Figure 3.4. Weir geometry was designed to resemble a trapezoid with a bottom base width or crest width of approximately 1.5 m (5 feet) and side slopes on the wing walls from 4 to 10 percent (Rosgen 2001). Weir shape was designed to pass the estimated 100-year flow (McLaughlin, personal communications, 2006). As shown in Figure 3.3, the wing walls of the rock vortex weirs form approximately 30 degree angles

relative to the stream banks. The pools of the weirs were constructed to allow ratios of pool depth to hydraulic drop of 2:1, or 0.5 meter (1.6 foot) for a 0.24 meter (0.8 foot) drop. The ends of the scour pools (pool tailout) were determined by the BOR engineer in the field, located by connecting a line between the downstream ends of the wing walls. A row of approximately 0.25 meter (10-inch) diameter rocks was placed across the tailout of the pool to encourage backwater effects and deposition upstream.



DESIGN DIMENSIONS

	CREST WIDTH W METERS	WING WALL ANGLE DEGREES	WING WALL SLOPE S	DESIGN DROP D METERS
LOWER STOKES WEIRS 1, 2, & 3	1.5	30	8.0%	0.24
THURLOW TRANSFER WEIR 1 (V WEIR)	1.8	30	9.8%	0.24
UPPER STOKES WEIR 1 (V WEIR)	1.8	30	4.0%	0.24

Figure 3.3. Conceptual design for rock vortex weir (Rosgen 2001, BOR 2004 a, b, and c).

Figure 3.4. Photo of typical rock vortex weir.

3.2.2 Thurlow Project Site

The Thurlow project had the same goals, design criteria, and construction time frame as Lower Stokes project. The diversion was re-built using rock vortex weirs in 2003 and is located upstream of Lower Stokes and downstream of Upper Stokes, about 5.6 km (3.5 miles) from the mouth of Beaver Creek. Water from the diversion supplies five irrigators. A plan view of the Thurlow Transfer Ditch (Thurlow) project site is shown in Figure 3.5.

The original diversion dam was a 1.1 meter (3.5-foot) high log and plastic sheet structure. The barrier was replaced in November 2003 with two rock vortex weirs. The downstream rock vortex weir is a double weir or an “A type” weir according to Rosgen (1996), as shown in Figure 3.5. The upstream weir is a "V type” weir according to Rosgen (1996) (Figure 3.6).

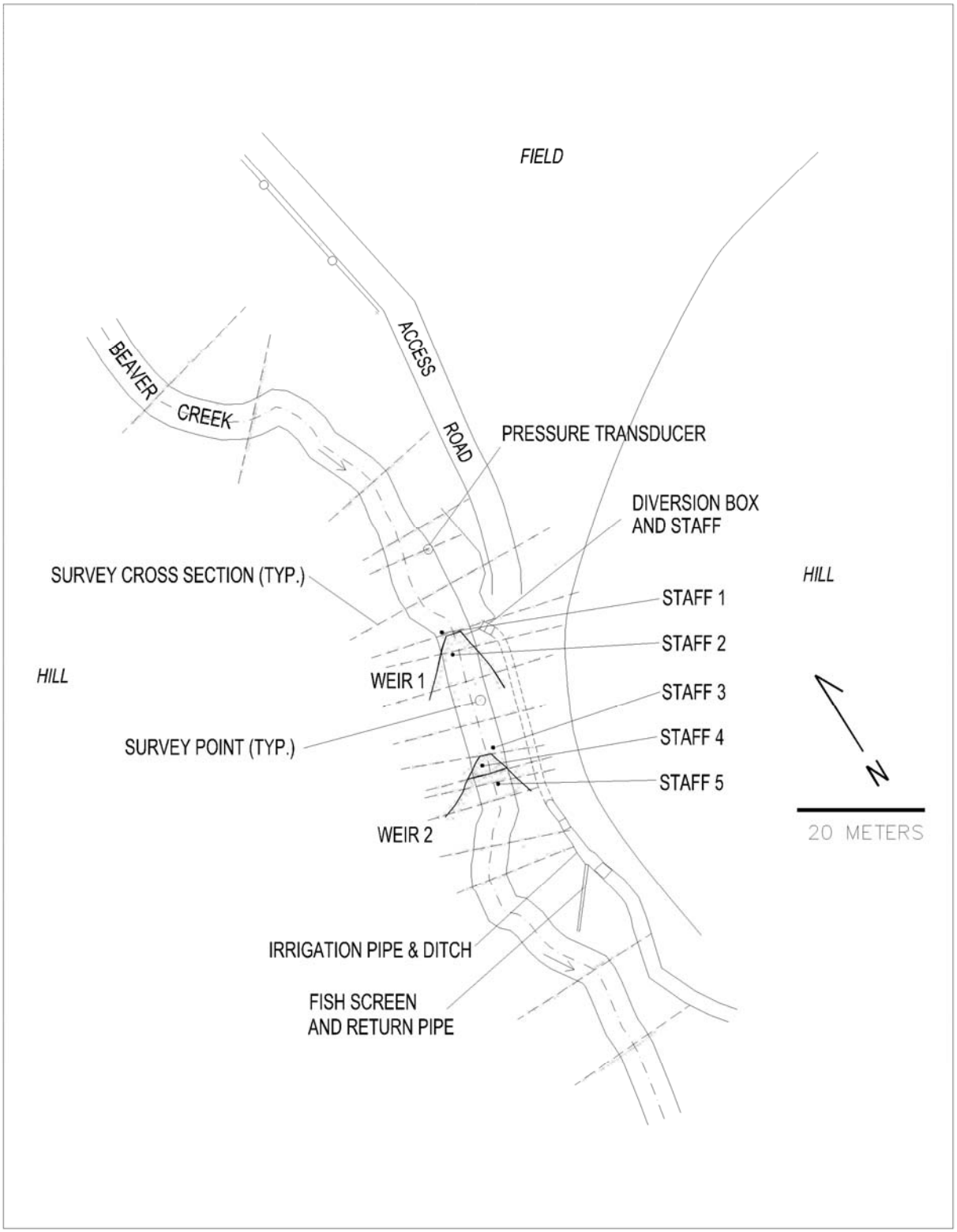


Figure 3.5. Thurlow project site.

Figure 3.6. Photo of Thurlow project site.

3.2.3 Upper Stokes Project Site

Upper Stokes is located on Beaver Creek about 7.2 km (4.5 miles) from the mouth. Construction of the rock vortex weirs was completed in September 2003. The original diversion dam was also about 1.1 m (3.5 feet) high, constructed of logs and plastic sheets. The original log barrier was replaced with two rock vortex weirs. The downstream weir is a double weir or an "A type" weir and the upstream weir is a 'V type' weir according to Rosgen (1996) (Figure 3.7 and Figure 3.8).

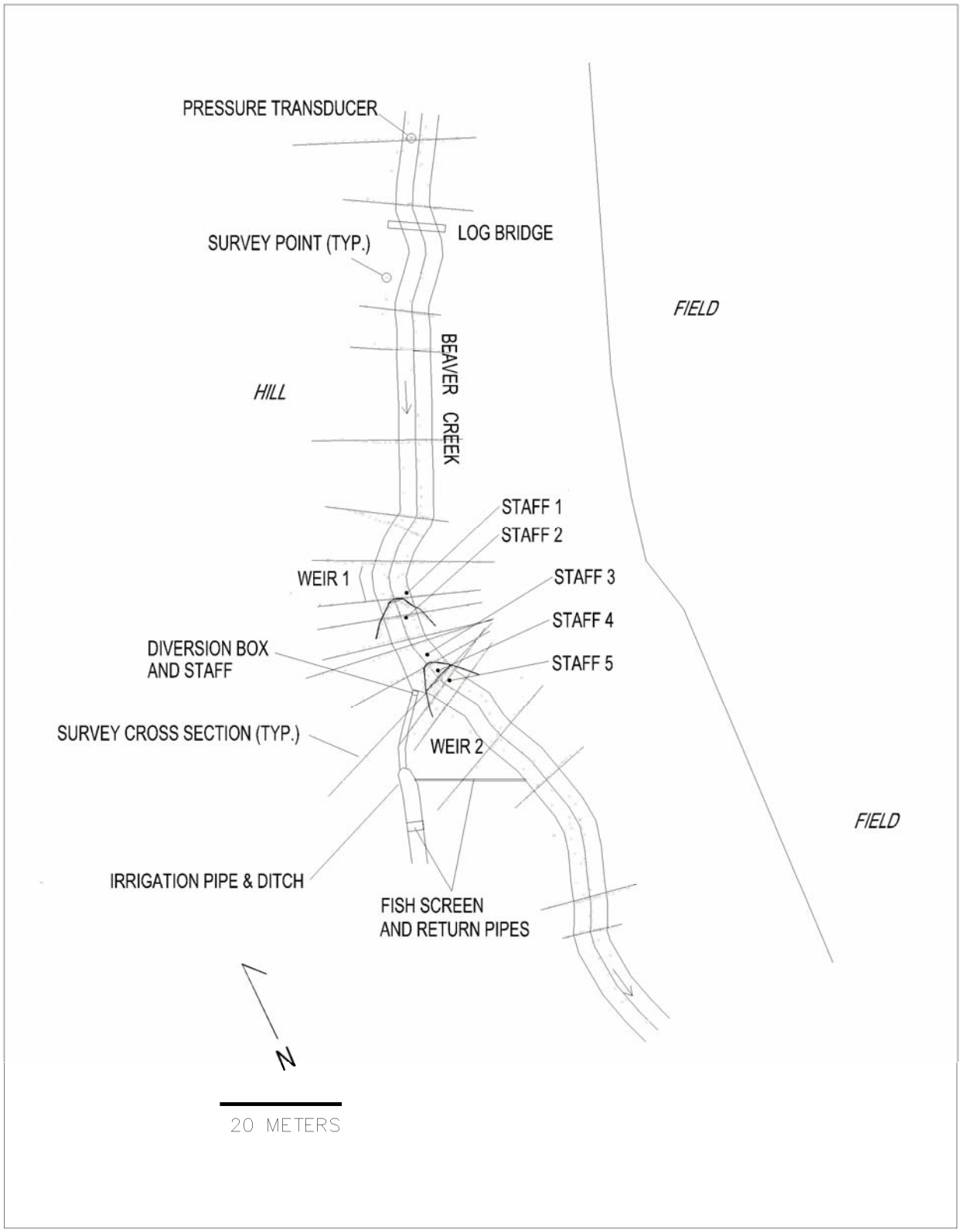


Figure 3.7. Upper Stokes project site.

Figure 3.8. Photo of Upper Stokes project site.

After construction of the weir at Upper Stokes, the downstream "A" weir was noted to produce a 0.30 m (1 foot) hydraulic drop, slightly higher than the 0.24 meter (0.8 foot) hydraulic drop recommended by WDFW (McLaughlin, personal communications, 2006). The BOR indicated the weir was recently modified using hand tools to bring it into compliance with the WDFW recommendation (McLaughlin, personal communications, 2006).

3.2.4 Fort-Thurlow Project Site

The Fort-Thurlow site was the fourth, and furthest downstream, diversion replaced on Beaver Creek. With the removal of Fort-Thurlow and the other three project sites, all fish passage barriers between the mouth and the upper watershed were considered removed (McLaughlin, personal communications, 2006). Fort-Thurlow is located at river km 2.4

(mile 1.5) from the mouth of Beaver Creek. Construction was completed on Fort-Thurlow in November 2004. This project replaced an aging 1.5 meter (5-foot) high concrete dam. The barrier was replaced with a sequence of three “A type “ weirs and one “V type” weir, to attain a maximum hydraulic drop of 0.8 feet at each step (Figure 3.9).

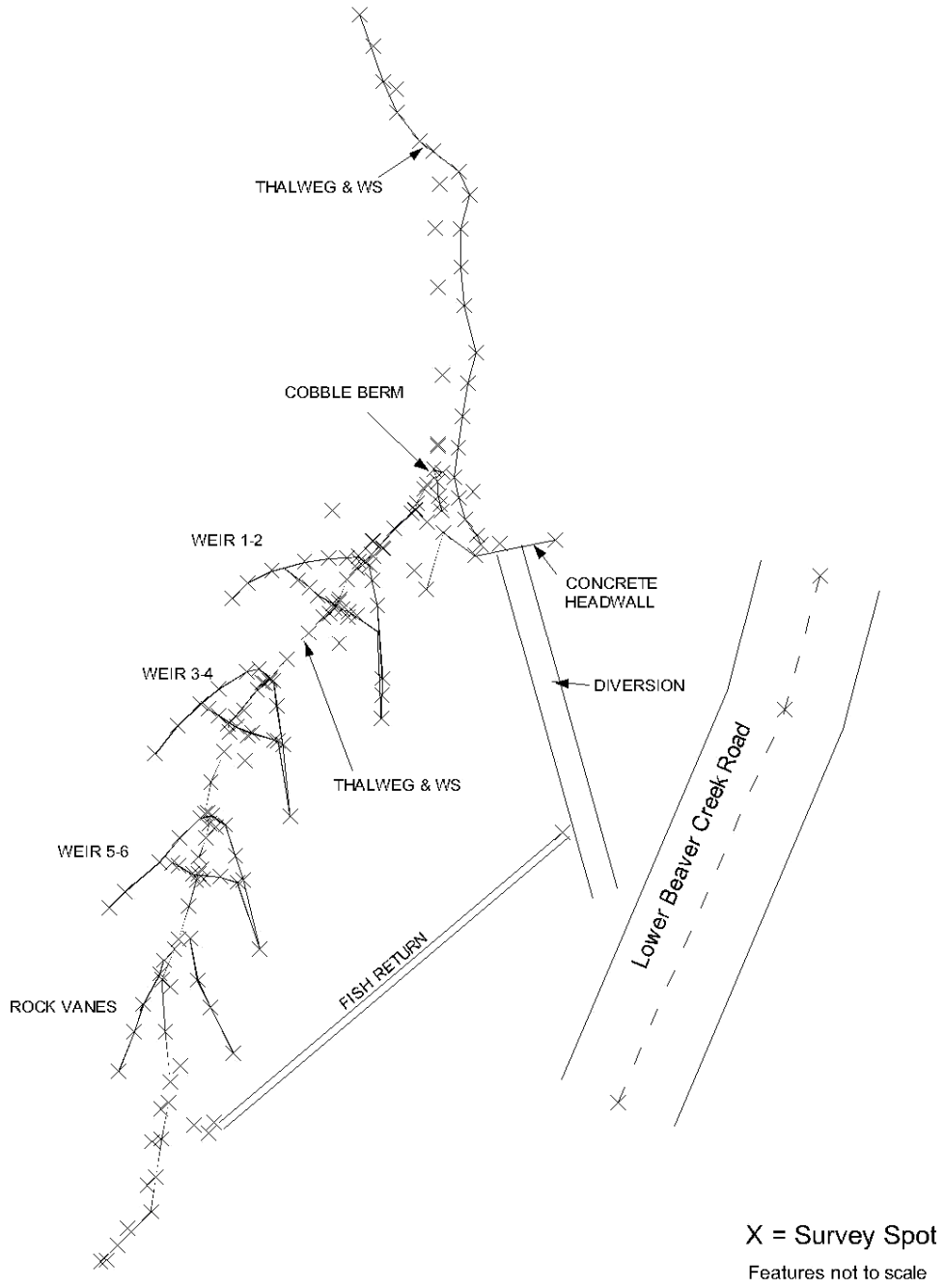


Figure 3.9. Layout of Fort-Thurlow project site.

3.3 Data Collection for hydraulic model development

Data collection for development of the hydraulic model consisted of continuous and spot discharge measurements, topographic survey, water surface profile measurements, spot velocity measurements, velocity profiles, and substrate classification.

3.3.1 Discharge measurements

Discharges were measured during site visits conducted between June 2004 and April 2006 to describe how flows change throughout the Beaver Creek watershed over time and to develop rating curves at the project sites. Continuous records of depth were obtained from three pressure transducers and converted to continuous records of discharge using the rating curves. Each site had one pressure transducer installed to develop detailed records of discharge near the rock vortex weirs. See Chapter 2 for more information on discharge from spot measurements and the pressure transducer records. Measured flows on Beaver Creek in the vicinity of the Lower Stokes, Thurlow, and Upper Stokes project sites are shown in Figure 2.6, 2.12, and 2.19.

3.3.2 Ground survey at project sites

Ground surveys were conducted at four locations for the Methow Project. The locations included three primary sites at Lower Stokes, Upper Stokes, Thurlow, and a fourth site at Fort-Thurlow. Full ground surveys were performed at Lower Stokes, Thurlow, and Upper Stokes. These surveys included measurement of at least 18 cross sections, detailed topography, weir crest profiles, thalweg profiles, and water surface profiles at each site. A reconnaissance level survey was performed at Fort-Thurlow to outline structures and locate the stream alignment. The instrument used was a robotic total station (Leica TCA 1105

Plus). Results and additional methods for the ground survey are shown in Appendix B. Horizontal and vertical control for survey was set to arbitrary datums.

Data from ground survey were processed in AutoCAD 2005 (Autodesk, San Rafael, California) to determine channel cross sections, thalweg profiles, water surface profiles, and to model topography of the rock vortex weirs with digital terrain models (DTMs). More details on ground surveys and data processing are provided in Appendix B.

3.3.3 Water surface profile measurements

Water surface profiles were measured to develop rating curves for hydraulic parameters and to calibrate hydrodynamic models. Measurements were taken by pressure transducers, visual observations of staff gages, and ground survey of water surface profiles. The installation and maintenance of the pressure transducers and data loggers are discussed in Chapter 2. The pressure transducer depth and discharge data were combined with data from staff gages strategically placed adjacent to the rock vortex weirs to measure hydraulic drop over the weirs. These staff gages were located directly upstream of the weirs and within the energy dissipation pools of the weirs. Each staff gage was mounted to a T-post vertically driven into the gravel-cobble bed a minimum of 0.5 m (1.5 feet). Staff gages were oriented so the flat sides were approximately parallel to the direction of flow to improve accuracy of readings. A typical installation of staff gages near a rock vortex weir is shown in Figure 3.10. Visual readings were performed during summer field work by the UI-CER and monthly by USGS-CRRL personnel on site during fall, winter, and spring.

Figure 3.10. Typical installation of staff gages at rock vortex weir. Staff gages were oriented parallel to flow path to reduce hydraulic forces and to facilitate visual observation of staff readings from shore.

Staff gage measurements and observed differential hydraulic drops over the rock vortex weirs are shown in Appendix C. The minimum and maximum measured hydraulic drops at the rock vortex weirs at Lower Stokes were 0.11 and 0.33 m (0.35 and 1.09 feet), for discharges ranging from 0.10 to 0.77 m^3/s (3.39 to 27.09 cfs). These data were used to develop rating curves and time series for the hydraulic parameters, to evaluate fish passage effectiveness (Chapter 5). For all the rock vortex weirs modeled, hydraulic drop decreased with increasing discharge, as expected.

3.3.4 Measurement of spot velocities

To determine specific energy and maximum velocities in the vicinity of the rock weirs, spot velocities were measured using the Sontek ADV. Monitoring locations were sampled at 0.6 of total depth at specific locations measured in relation to the weir crest. Data at each location included water depth and 3-dimensional velocity at 0.6 depth (V_x, V_y, V_z). Velocity measurement locations on the weir crests were chosen based on observation of focused flows over the tops of rocks and between rocks. Each sampling location was documented for

future recovery. A discharge measurement was also performed during spot velocity measurements.

Spot velocity measurements at the rock vortex weir crests for all weirs at all project sites ranged from 0.3 to 1.8 m/s (1.0 to 5.9 feet per second) for discharges from 0.07 to 0.77 m^3/s (2.6 to 27.1 cfs). Velocity at the crest increased with increasing discharge, as expected.

3.3.5 Measurement of velocity profiles

Velocity profiles were measured near the rock vortex weirs to characterize velocity distributions upstream of the weir, at the weir crest, within the weir pool, and downstream of the weir. Each velocity profile consisted of sampling three velocities at 0.2, 0.6, and 0.8 total depth. Velocities were measured using a Sontek Handheld Flowtracker ADV flow meter and saved to a data recorder that logs velocity in three orthogonal directions (i.e., V_x, V_y, V_z). Upstream of each rock vortex weir, one velocity profile was sampled at the center of the channel, followed by a velocity profile at the weir crest, five velocity profiles across the center of the pool, and one downstream of the pool.

A typical velocity field developed from velocity profile measurements is shown in Figure 3.11. Additional velocity fields for weir pools at Lower Stokes, Thurlow, and Upper Stokes are shown in Appendix D. The velocity field shown in Figure 3.11 was measured in the pool below weir 1 at Upper Stokes. The longitudinal velocity, V_x, is presented as a contour plot of equal velocities (isovels). The lateral and vertical components of velocity, V_y and V_z, are plotted as vectors. A central core with highest velocity is shown near the surface. The pool also shows strong transverse flows up to 1/3 the magnitude of the longitudinal flow velocity (V_y and V_z versus V_x). The margins of the pool show slower velocities, due to surface roughness from substrate and boundary effects. Velocity within the pool changes direction frequently due to turbulence, and it appears to form a clockwise rotation, with a trend towards the left bank.

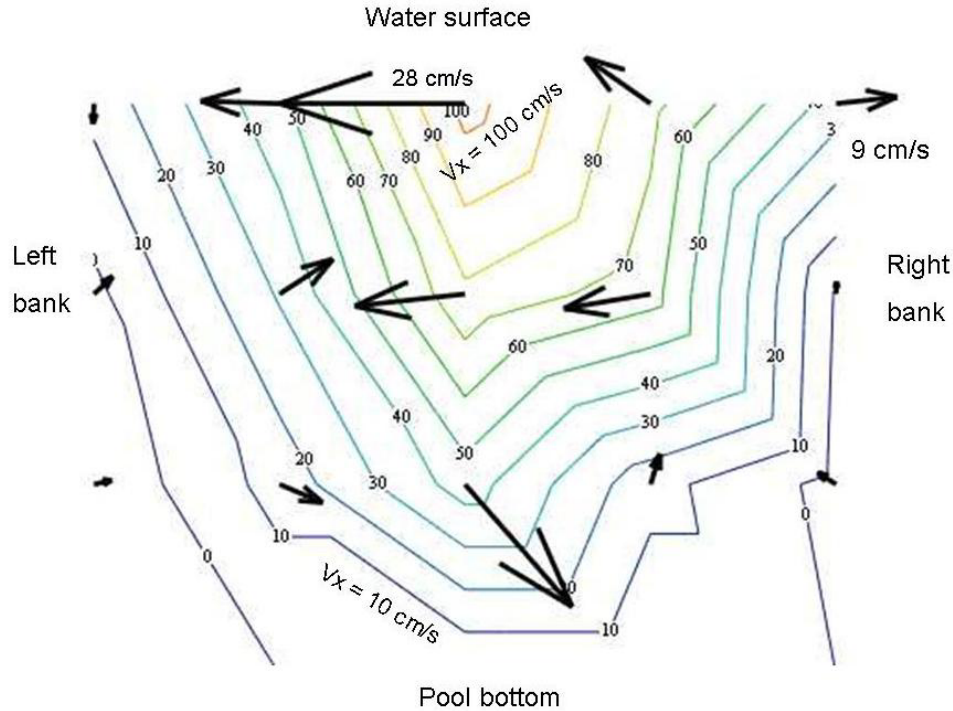


Figure 3.11. Typical velocity field in weir pool at Upper Stokes, weir 1 at a discharge of 0.56 m^3/s. Contours indicate measured velocity in the longitudinal direction (V_x) and vectors represent measured velocity in the lateral and vertical direction (V_y and V_z). Contours and vectors not to scale spatially. Velocity vectors for V_y and V_z scaled by relative magnitude to each other.

3.3.6 Substrate Classification

Wolman Pebble Counts were performed at three locations at each site to characterize bed substrate. At Lower Stokes, Thurlow, and Upper Stokes, in 2004 and 2005, Wolman Pebble Counts were performed upstream of the project sites, just upstream of the rock vortex weirs, and downstream of project site. Results from Wolman Pebble Counts for substrate characterization at the project sites are shown in Appendix E.

3.4 Development of hydraulic models for weirs at Lower Stokes project

A spreadsheet-based model was developed to simulate flow mechanisms over rock vortex weirs as water stage increases. Using a linear decoupling approach, four key flow modes

were identified as additive elements. In order of increasing flow, these modes are 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). Each flow mode exerts increasing influence that successively controls the flow characteristic, as shown by a measured stage versus discharge curve. A conceptual model is shown in Figure 3.12. Each individual mode of the hydraulic model was calibrated by varying selected parameters and coefficients until the net calculated stage versus discharge curve matched data from field measurements. Initiation of flow modes and transitions between modes were determined from weir geometry, relative roughness relationships, and field observations. Each flow mode was calibrated by varying the coefficients used in the general formulations. More details on transitions and controlling parameters are given below. Formulae for each flow mode were drawn from traditional theories and general formulations (Chow 1959).

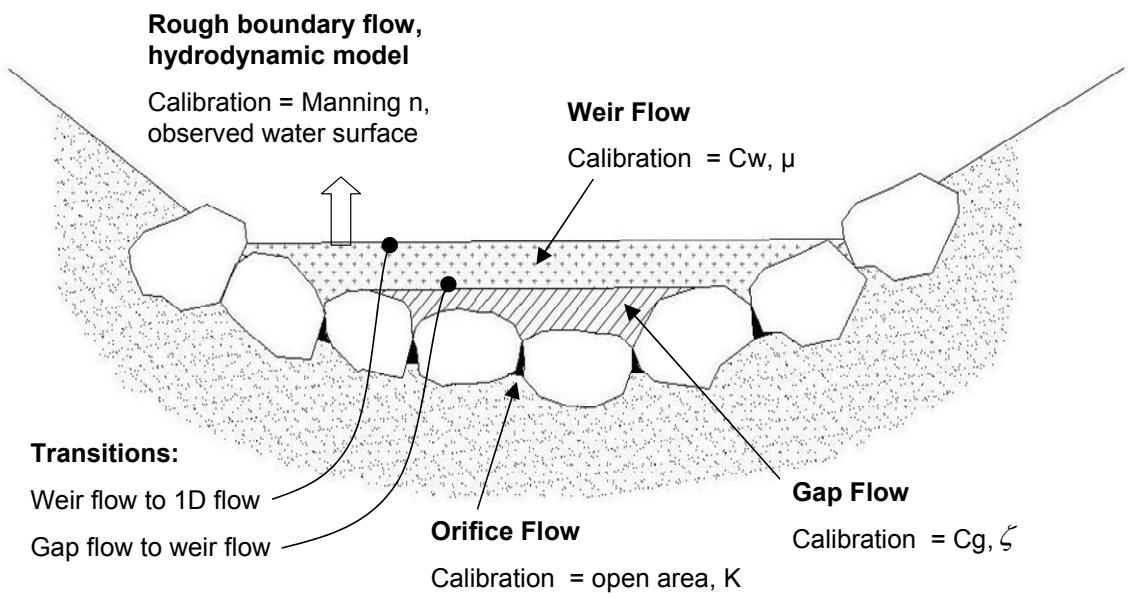


Figure 3.12. Conceptual cross section of hydraulic model.

3.4.1 Orifice flow

The first mode of the hydraulic model estimates flow through interstitial spaces between and below the large rocks in the weir crests. A detailed view of orifice flow is shown in Figure

3.13. The basic form of the orifice flow equation, assuming velocity is small and approximately the same upstream and downstream of the weir crest, is (Chow 1959).

$$Q_{orifice} = \sqrt{2g \cdot h_{drop}} \cdot A_{eff} \cdot K \tag{3.1}$$

Where:
g = Acceleration of gravity, 9.81 m/s^2

h_{drop} = Pressure head, estimated by measured differential water surface between headwater at rock vortex weir crest and tailwater elevation in pool, in m (Figure 3.13)

$A_{eff} = \Sigma A_i$, Total effective flow area in rock orifices and subflow, calibration term, in m^2

K = Loss coefficient, fixed at 0.6, includes friction and geometry (Chow 1959)

The minimum recommended value of the K coefficient of 0.6 was used in Equation (3.1) to reflect high losses due to friction and geometry of the interstices in the boulders (Chow 1959). Differential head, h_{drop}, was calculated based on a rating curve developed from field observations of discharge and staff gage readings. Linear fits of stage versus discharge for the staff gages upstream and downstream of the weir were developed. By taking the difference between the two lines, a hydraulic drop versus discharge relation was established.

In this study, orifice flow has only a minimal contribution to the overall stage versus discharge relationship, as all the weirs have a layer of geotextile installed upstream in the stream bed to effectively seal sub-surface interstices. Orifice flow begins at the minimum elevation of the boulder crest and is estimated as a dominant component of total flow up to about 0.014 m^3/s (0.5 cfs). Seepage and hyporheic flow are also considered to be part of orifice flow, although are assumed minimal for these installations with geotextile liners. At discharges greater than 0.014 m^3/s, gap flow is estimated to dominate the stage versus discharge relationship.

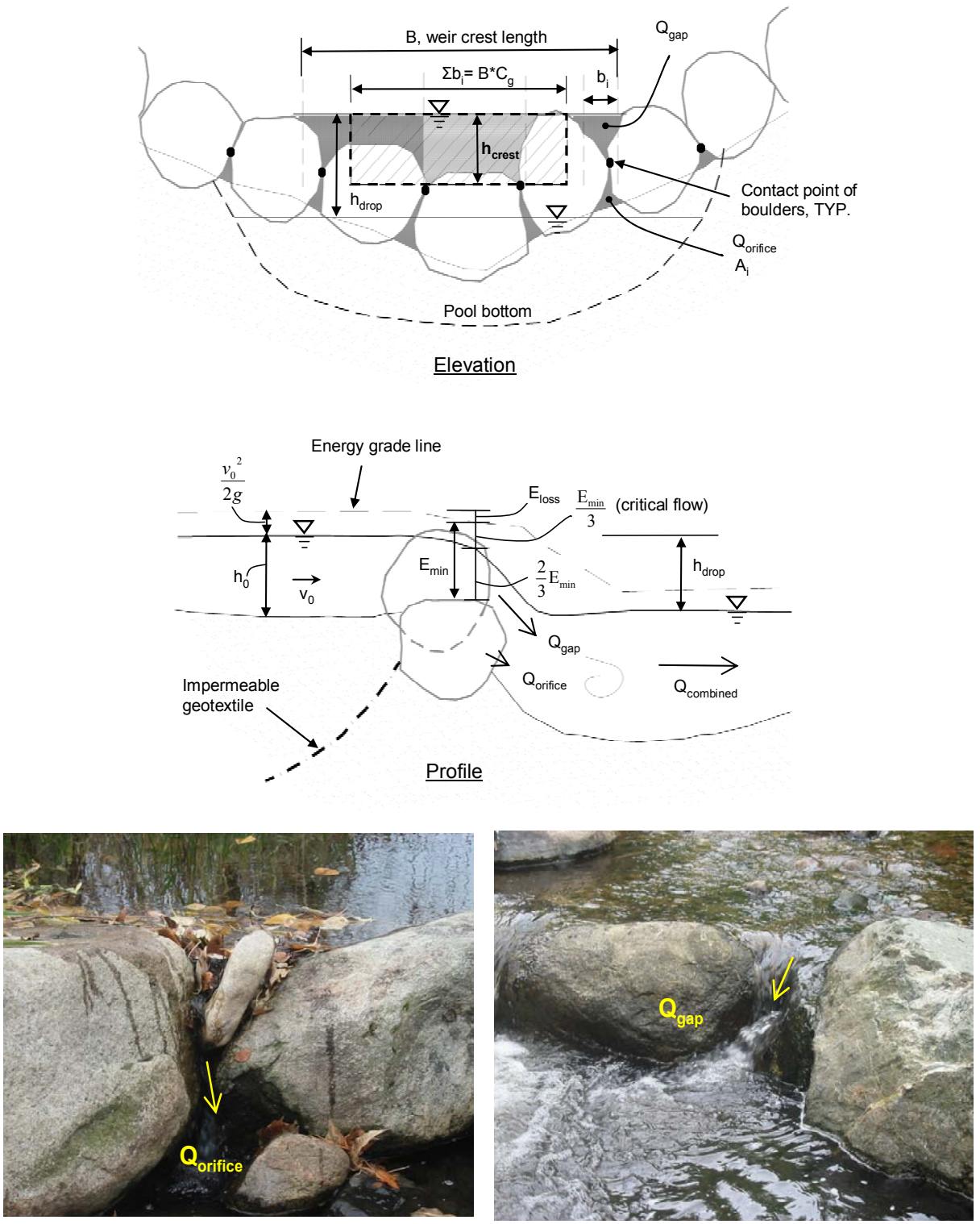


Figure 3.13. Hydraulic models for orifice flow and gap flow. Schematics show typical elevation and profile of rock vortex weir crest. Photos show typical orifice and gap flows.

3.4.2 Gap flow

Coincident with the onset of orifice flow, gap flow was assumed to start. As water stage increases above the cracks in the boulders of the rock vortex weir crest, gap flow becomes a dominant component to total modeled flow, $Q_{combined}$ (Figure 3.13).

Gap flow is effectively a balance of specific energy upstream to specific energy and critical flow in the spaces between the boulders of the weir crest, plus friction losses (DVWK 1996), as shown in Equation (3.2) and Figure 3.13.

$$E_0 = h_0 + \frac{v_0^{\ 2}}{2g} = E_{\min} + E_{loss} \tag{3.2}$$

Where:

E_0 = Specific energy upstream of gap flow, in m

h_0 = Head at a location just upstream of the boulders forming weir crest, based on field observation of staff gages, in m

v_0 = Velocity at a location upstream of the boulders forming the weir crest, based on discharge, assumed to be negligible in upstream pool, in m/s

g = Acceleration of gravity, 9.81 m/s^2

E_{min} = Minimum energy to force flow through gap based on upstream conditions, in m

E_{loss} = Energy loss at weir crest in boulder gaps, in m

Minimum specific energy, E_{min}, at the weir crest was determined by assuming critical flow at the weir crest, where critical depth (h_{crest}) is twice velocity head (Chow 1959).

$$h_{crest} = \frac{2}{3} \cdot E_{\min} \tag{3.3}$$

and

$$\frac{v_{crest}^{\ 2}}{2g} = \frac{1}{3} \cdot E_{\min} \tag{3.4}$$

Energy loss at the weir crest was modeled as a sharp-edged inlet loss with a friction coefficient (Chow 1959).

$$E_{loss} = \xi \cdot \frac{v_{crest}^{\ 2}}{2g} = \xi \cdot \left(\frac{1}{3} \cdot E_{\min} \right) \tag{3.5}$$

Where:

ξ = Sharp-edged inlet loss coefficient, assumed to be 0.5, no units

v_{crest} = Water velocity at crest in gaps between rocks, in m/s

Substituting Equation (3.5) into (3.2) and solving for E_{min} results in

$$E_{\min} = \frac{E_0}{\left(1 + \frac{\xi}{3}\right)} \tag{3.6}$$

Flow through the gaps can be quantified as

$$Q_{gap} = v_{gap} \cdot A_{gap} \cdot C_g \tag{3.7}$$

Where:

v_{gap} = Velocity in gap, assumed to be critical flow velocity and equal to v_{crest}, in m

A_{gap} = Area of flow between crest boulders, sum of individual gaps in boulders, in m^2

C_g = Contraction and roughness coefficient used to calibrate gap flow (Figure 3.13), no units

Velocity in gaps can be determined from Equation (3.4) as

$$v_{gap} = \sqrt{\frac{2}{3} \cdot \mathrm{g} \cdot E_{\min}} \tag{3.8}$$

Total flow area for gap flow can be described as (Figure 3.13)

$$A_{gap} = \Sigma b_i \cdot h_{crest} \tag{3.9}$$

Where:

Σb_i = Total effective width of gaps derived from weir geometry and total profile length of weir crest, B (oblique alignment, Figure 3.13 and Figure 3.14), in m

By combining Equations (3.2) and (3.6) to (3.9), and rearranging terms, gap flow, Q_{gap}, can be expressed as measured parameters and one calibration term, C_g.

$$Q_{gap} = \left(\frac{2}{3} \cdot \frac{h_0 + \frac{v_0^{\,2}}{2g}}{\left(1 + \frac{\xi}{3}\right)} \right)^{\frac{3}{2}} \cdot \sqrt{g} \cdot B \cdot C_g \tag{3.10}$$

Where:

B = Total profile length of rock vortex weir crest, from weir geometry (Figure 3.14), in m

For gap flow, losses due friction and contraction were accounted with a calibration term C_g, which accounts for angled wing walls on the weir, gaps that are not parallel to the main flow direction, contraction within the gaps, irregular gap shapes, and surface roughness of the crest rocks (Figure 3.13 and Figure 3.14).

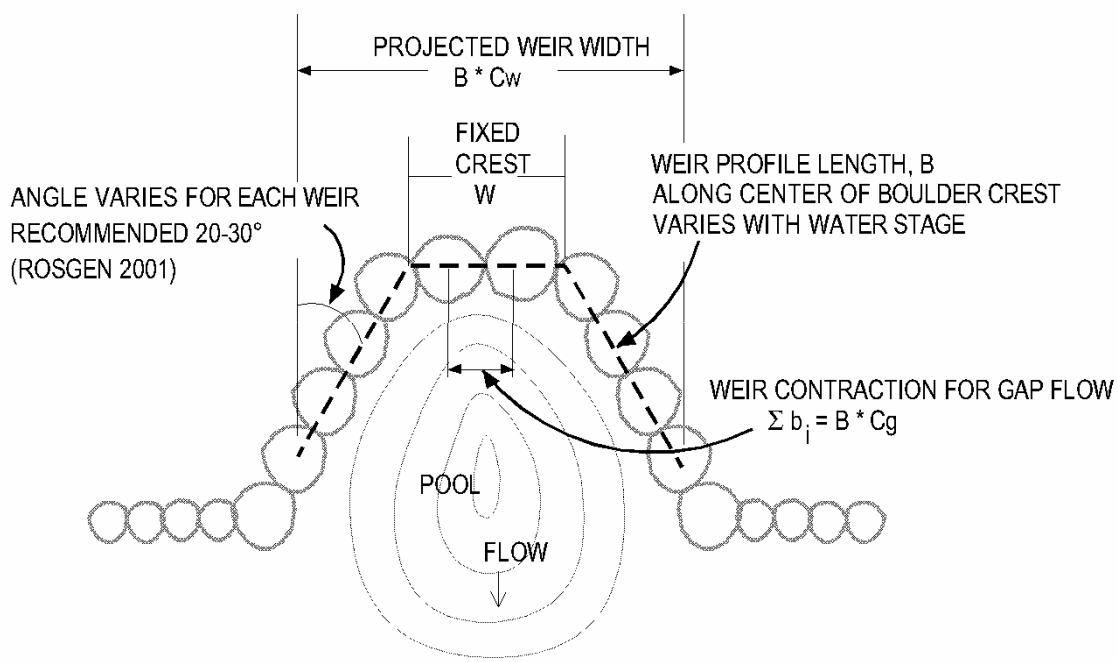


Figure 3.14. Contraction coefficients for gap flow and weir flow.

To calculate Q_{gap} in Equation (3.10), total weir profile length, B, was determined by developing estimates of weir length as a function of water stage using ground survey data. A trapezoidal weir centerline was digitized in plan, based on survey points located on the

upstream and downstream faces of the crest rocks. This line was then used as an alignment to calculate the rock crest profile from offset survey points. The ground survey measured elevations of crest stones as well as the joints between rocks. The result was a normalized profile along the center of the weir crest. For reference, an estimate of the original trapezoidal design was overlaid on the weir crest profile (Figure 3.15).

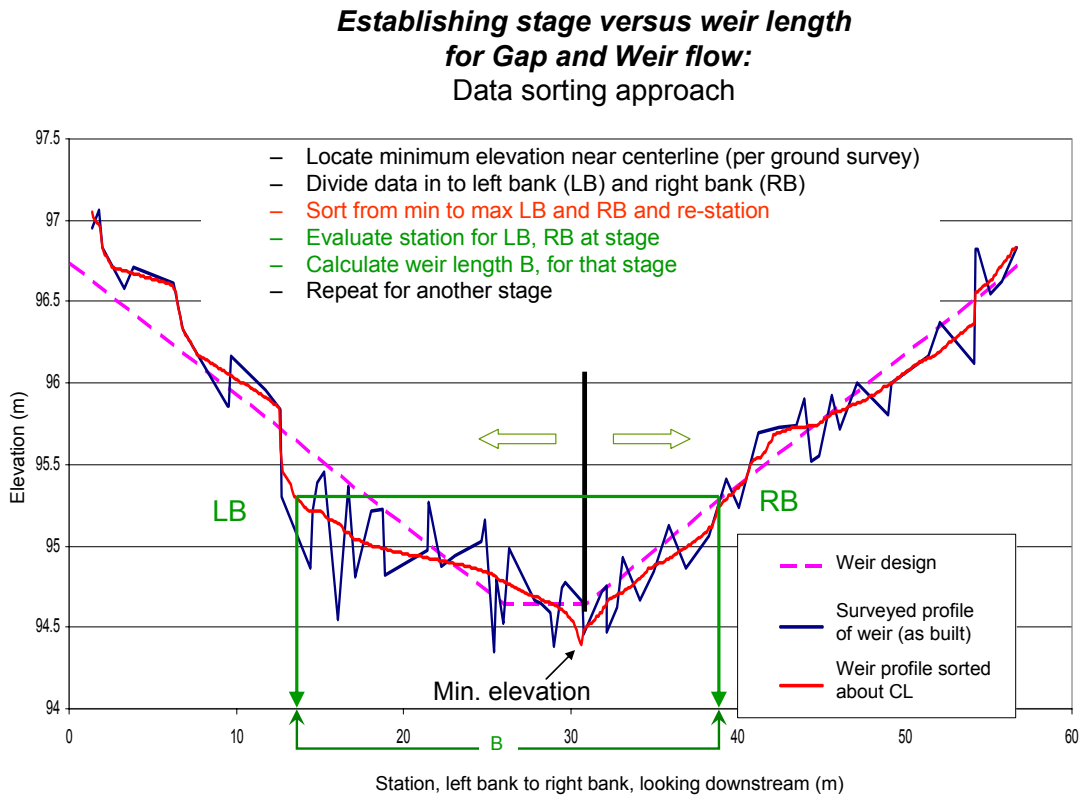


Figure 3.15. Processing of weir profile data for calculation of weir length versus stage relationship. Typical weir cross section shown, not to scale.

As outlined in Figure 3.15, surveyed data were processed to calculate weir profile length, B, as a function of elevation. Based on ground survey notes and the minimum elevation, a center point on the weir was located and used as a basis to re-sort the profile from low to high points for the left bank and right bank. Irregularly spaced profile points were interpolated to equal intervals and sorted so that the low points were in the center and high points were outboard from the thalweg. This effectively aggregated low spaces in cracks to the center of the weir profile. The result was a profile that presented a consolidation of low

spots in the center, and higher elevations radiating from the center. Using this sorted profile, calculations of weir profile length were performed for a range of water stages to determine a weir profile length versus stage relation for the weir.

Using the re-sorted weir profile, calculations of weir length, flow area, and depth versus stage were developed for use at critical parameters in the hydraulic model. The C_g coefficient for the gap flow equation was adjusted to account for moving low points in cracks to a consolidated area in the center.

Calibration of gap flow was achieved by adding the orifice flow ($Q_{orifice}$) to gap flow (Q_{gap}) and comparing the total modeled flow ($Q_{combined}$) to measured flow. Parameterization of gap flow was performed by changing the contraction coefficient, C_g in Equation (3.10). All other terms were either fixed or defined by observations related to discharge. For example, h_0 and v_0 were based on field observations of discharge and staff gages.

3.4.3 Transition from gap flow to weir flow

An empirical approach was used to estimate the stage where weir flow initiates designated as a height above the weir crest, H_{T1} (Figure 3.16). Data from the sorted weir profile were used to estimate a ratio of flow depth to width. Conceptually, weir flow has a higher ratio of flow width to flow depth than gap flow, which is constrained by flow passing between crest boulders. Weir flow was assumed to begin about where the water surface starts to rise above the boulder crests and form more of a sheet flow, drowning the roughness from the crest boulders. For each weir, the ratio of weir width to flow depth was plotted against discharge and inspected for a point of inflection or a flattening (Figure 3.16), which indicates a possible transition to another flow mode. The stage associated with this point of inflection was applied to initiate the weir mode of the model. The resulting total discharge (orifice + gap + weir flow), as modeled, was compared to measured stage versus discharge to confirm the fit, as driven by the power relationship in the weir equation (Chow 1959). If the stage

was too low, a vertical shift in stage was applied to the initiation of weir flow, until the modeled response matched the measured stage versus discharge.

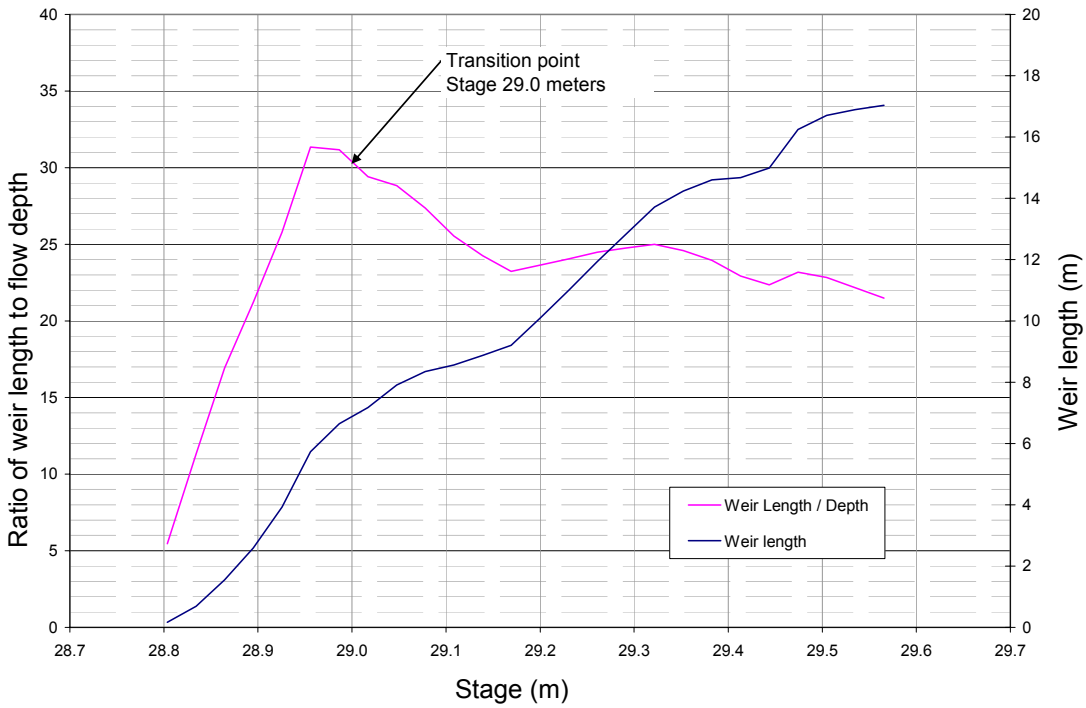


Figure 3.16. Determination of stage for transition from gap flow to weir flow (h_{T1})

Once weir flow was initiated, gap flow characteristics were assumed to change due to submergence. To compensate for submergence, gap flow would convert from the formulation in Equation (3.10) to a cross section averaged velocity with a fixed flow area (Figure 3.17), as given by Equation (3.11):

$$Q_{gap} = V_{weir} \cdot A_{gap*} \tag{3.11}$$

Where:

Q_{gap} = submerged gap flow, in m^3/s

V_{weir} = velocity in weir flow region in m/s = weir flow (m^3/s) / flow area (m^2)

A_{gap*} = fixed submerged flow area in m^2, area below transition stage to weir flow at H_{T1}

Conceptual representations of the fixed flow area for submerged gap flow, and the stage for transition from gap flow to weir flow are shown in Figure 3.12 and Figure 3.17.

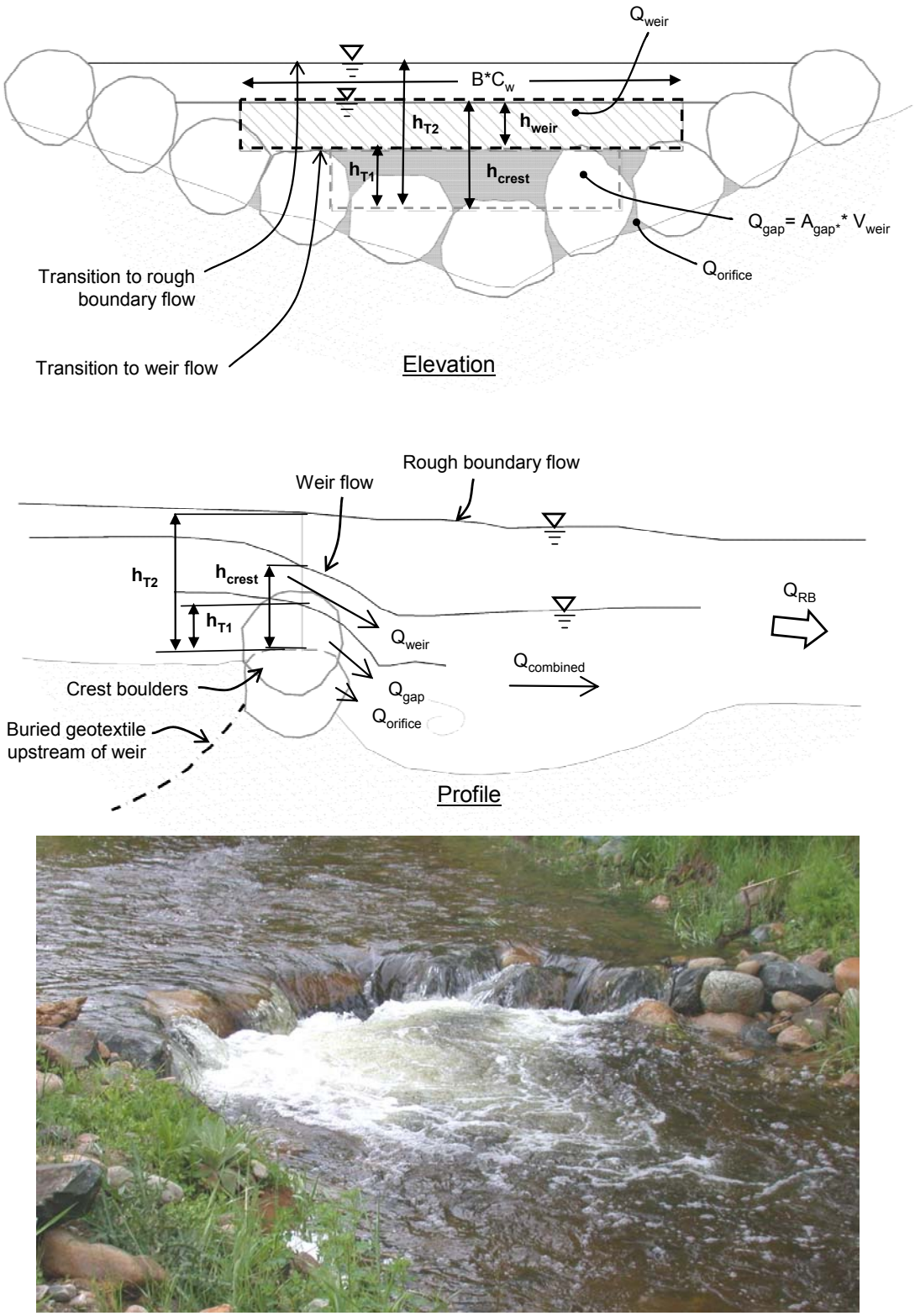


Figure 3.17. Hydraulic model for weir flow and transition to rough boundary flow. Schematics show typical elevation and profile of rock vortex weir crest. Photo shows typical weir flow over rock vortex weir at a field site.

3.4.4 Weir flow

Weir flow, the third mode of the hydraulic model, initiates at the threshold height of H_{T1} (Figure 3.17). Given models for orifice flow and gap flow, weir flow was added to the total calculated flow $Q_{combined}$, which was calibrated to match measured discharge (Figure 3.17). The general form of the Poleni equation from Chow (1959) was used to model weir flow, with a slight modification that included a contraction coefficient, C_w, which accounts for contraction due to weir length perpendicular to the channel flow direction. The modified Poleni equation is as follows:

$$Q_{weir} = \frac{2}{3} \cdot \mu \cdot C_w \cdot B \cdot \sqrt{2g} \cdot h_{weir}^{1.5} \tag{3.12}$$

Where:

Q_{weir} = Discharge for weir flow, in m^3/s

μ = Weir coefficient, function of the geometry, varies from 0.6 to 0.8, calibration parameter

C_w = Contraction coefficient for weir crest profile length, calibration parameter

B = Weir profile length along boulder crest, function of water stage and weir geometry, in m

g = Acceleration of gravity, 9.81 m/s^2

h_{weir} = Water depth at the rock vortex weir crest for weir flow, calculated as depth above transition from gap flow to weir flow (H_{T1}, Figure 3.17), in m

As described above for gap flow, a stage versus weir width relationship was established by processing cross section profile data (Figure 3.15). The total weir profile length, B, was calculated at a given water stage (increasing as water surface elevation increased).

Final calibration and parameterization of weir flow was achieved by iterating values of the weir coefficient, μ, until the total modeled flow matched measured flow. The coefficient C_w in Equation (3.12) is a contraction coefficient to account for projection of the trapezoidal weir crest length, B, to a length perpendicular to the channel (Figure 3.14). The value of C_w changes with depth and is a function of the wing wall angle, eventually converging to a relatively constant value when the base width, W, of the trapezoid is outweighed by total weir length (Figure 3.14).

3.4.5 Transition from weir flow to rough boundary flow

The threshold from weir flow to rough boundary flow, H_{T2}, occurs when the water surface profile is a continuous slope through the rock vortex weir, and downstream control dominates, eliminating the hydraulic jump over crest boulders. The rock vortex weir effectively becomes a submerged roughness element and the tailwater has a continuous influence on the headwater throughout the structure (Figure 3.17). Rough boundary flow was assumed to occur only in high discharges. The transition was estimated by applying relative roughness of the boulders in the weir crest to flow depth over the weir. Rough boundary flow was assumed to begin when relative roughness, the ratio of total water depth to surface features, is about 3.0–5.0 (Chow 1959). For example, if a boulder crest had rocks that protrude into the channel by 0.2 m, then rough boundary flow would begin approximately from 0.6 to 1.0 m above the bed elevation.

3.4.6 Hydrodynamic modeling of rough boundary flow

The fourth and final mode in the hydraulic model is a rough boundary flow, modeled using a hydrodynamic model, based on the St. Venant equations (DHI Water and Environment 2003) and the Manning equation for open channel flow to establish channel roughness. The hydrodynamic model MIKE 11 from the Danish Hydraulics Institute (DHI Water and Environment 2003) was applied as the rough boundary model. In rough boundary flow, the rock weir effectively becomes drowned, and it acts as a roughness element to create a sloping water surface over the drowned weir crest (Figure 3.17).

Boundary conditions (i.e., water surface elevation downstream and discharge upstream) were used to set up a MIKE 11 model. Cross sections and overbank channel definitions were input to the model. Contraction and expansion coefficients were also input. Reach lengths and Manning's n were input for each cross section.

Cross sections for the MIKE 11 hydrodynamic model were developed based on ground survey data measured in 2005 (Appendix B). Stations and elevations on the cross section were calculated in AutoCAD using perpendicular projection to a straight line formed by cross section endpoints. Longitudinal stations, or chainages, were determined from the stream centerline and applied to the cross section definition. Cross sections measured at the weir crests were simplified to facilitate hydrodynamic model algorithms. Left bank and right bank for the cross sections were defined based on ground survey notes and inspection of the cross section. To stabilize the rough boundary model, at least four additional cross sections were interpolated from surveyed cross sections on the upstream and downstream ends of the study reach.

Contraction and expansion coefficients of 0.1 and 0.3, respectively, were used as default values to stabilize the standard step algorithms in the rough boundary model. At the rock vortex weirs, the contraction and expansion coefficients were adjusted to calibrate the model and account for increased roughness and energy losses at the rock vortex weirs.

Manning's n was initially estimated as a global value for the stream reach, with higher roughness values at the locations of the rock weirs, due to bed roughness and increased turbulence.

The Manning equation is:

$$Q = \frac{1}{n} \cdot R^{2/3} \cdot S^{1/2} \cdot A \tag{3.13}$$

Where:

n = Manning's roughness coefficient

R = Hydraulic radius, in m

S = Channel slope

A = Cross section area of flow, m^2

Upon completing the model set up, simulations were run at a minimum time interval of one second. This fine time resolution allowed the model to simulate water surface profiles on the

fine scale of the rock vortex weir. Simulations were run at steady state (constant flow) until the water surface level stabilized. Water surface profiles from the model were exported and compared to measured water surface profiles. Discrepancies were reduced by adjusting Manning's n, contraction and expansion coefficients, and re-running the model. Simulations were only run and calibrated for measured low flows, since data were not available for higher flows. Manning's n, or channel roughness, changes with water depth, so water surface observations at high flows are important to calibrate the model further and provide a reliable water surface calculation at higher flows.

3.5 Results of hydraulic models for weirs at Lower Stokes project site

Two types of models were developed for the rock vortex weirs: spreadsheet models for three modes of flow over the weir crest, and rough boundary models for the fourth mode. This section presents results from the spreadsheet models and the rough boundary model.

The hydraulic models developed for the weirs at Lower Stokes are shown in Figure 3.18 to 3.20. A significant amount of information is presented in these figures to consolidate weir geometry with modeled and measured flows at each stage. The cross sections shown in Figure 3.18 to 3.20 illustrate the irregularity of the weir crests in relation to ranges and magnitudes of orifice, gap, and weir flows.

A summary of calibration coefficients for each model is shown in Table 3.1. Orifice flow was assumed to be very small, if not negligible, due the impermeable geotextile installed under the stream bed, upstream of the weirs, and field observations at low flows. The assumed flow area represented eight cracks between the boulders, 80 mm long and 10 mm wide, resulting in a typical maximum flow of about 0.007 m^3/s, diminishing as differential head over the weir decreased with increasing discharge (Equation (3.1)). The entrance loss coefficient for orifice flow, K, was selected as the minimum recommended value of 0.6, to reflect maximum friction losses for flow between boulders (Chow 1959).

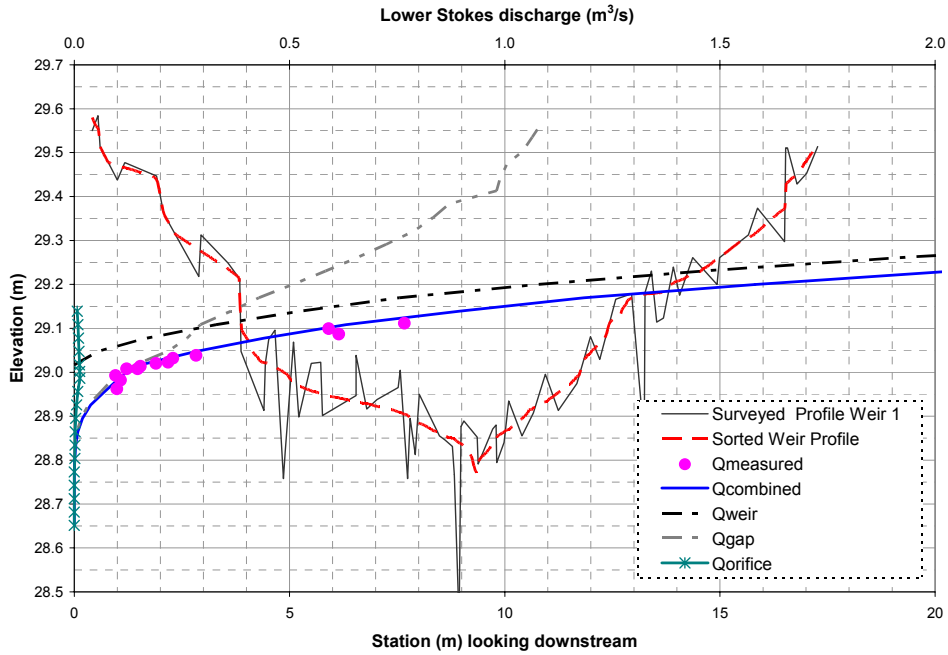


Figure 3.18. Hydraulic model at Lower Stokes, weir 1. Cross section is overlayed on plot of elevation (stage) versus discharge for hydraulic model. Axis for cross section station is on the bottom and axis for discharge is on top. Sorted weir profile reflects re-organization of cross section survey data to show central low spot and gradation profiles of the wing walls of the weir crest. Plots of 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 as stage increases are shown.

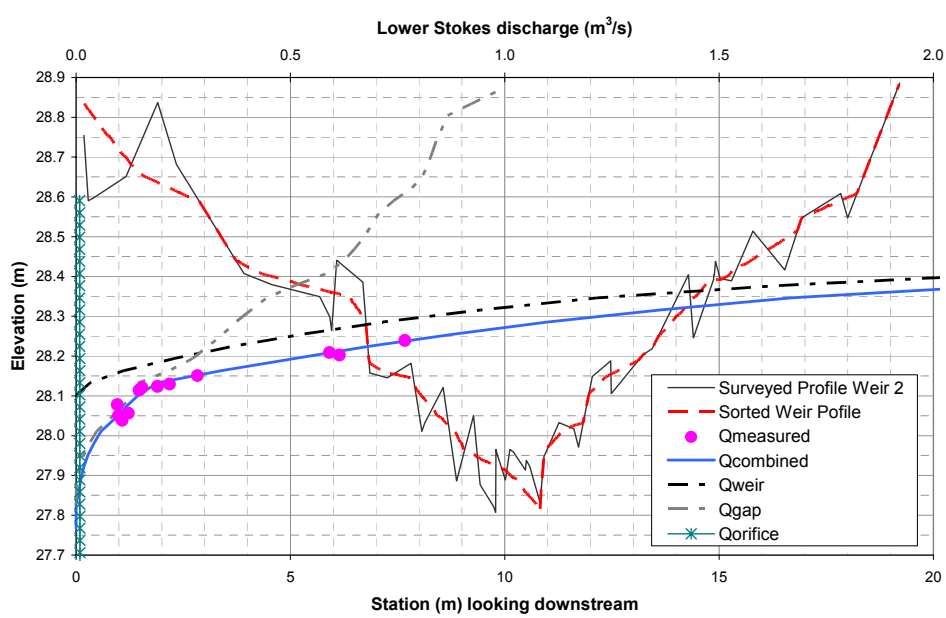


Figure 3.19. Hydraulic model at Lower Stokes, weir 2. See Figure 3.18 for a description of symbols and axis labels.

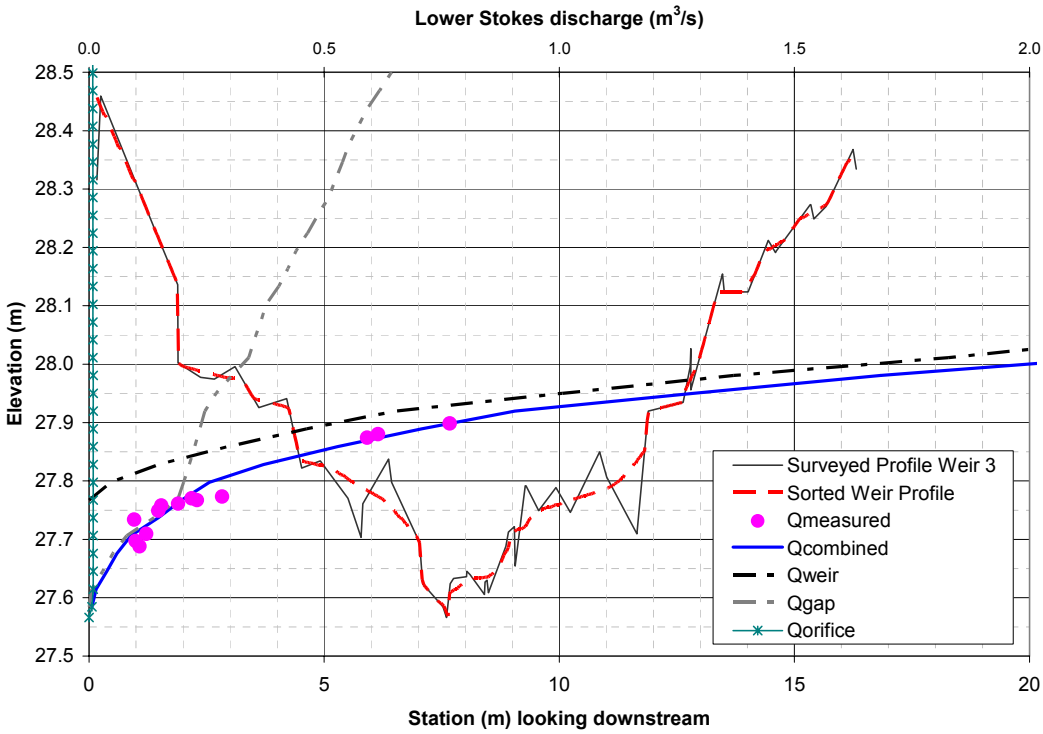


Figure 3.20. Hydraulic model at Lower Stokes, weir 3. See Figure 3.18 for a description of symbols and axis labels.

Table 3.1. Calibration of hydraulic models for rock vortex weirs at Lower Stokes.

	Lower Stokes (calibration site)		
Weir geometry, as built	**Weir 1**	**Weir 2**	**Weir 3**
Crest width, W (m)	1.5	1.5	1.5
Average wing wall angle (plan), degrees	32	28	30
Wing wall slope (profile)	9%	10%	9%
Orifice Flow			
K, loss coefficient	0.60	0.60	0.60
Open area (m^2)	0.007	0.007	0.007
Gap Flow			
Zeta ξ, friction factor	0.50	0.50	0.50
C_g, contraction factor for gaps	0.10	0.17	0.45
Weir Flow			
μ, weir coefficient (0.5 to 0.8 recommended)	0.80	0.70	0.80
C_w, contraction coefficient Determined by weir geometry	*ranges from 0.42 to 1.00, varies according to crest profile length*		
Transitions, estimated			
Gap to weir flow, discharge, (m^3/s)	0.15	0.15	0.20
Gap to weir flow, depth, (m)	0.37	0.34	0.34
Weir to rough boundary flow, (m^3/s)	2.6	2.2	1.7
Weir to rough boundary flow, depth, (m)	0.6	0.6	0.4

Gap flow was assumed to initiate concurrently with orifice flow at zero depth on the weir. The calibration coefficient ξ was kept constant at 0.5, for sharp-edged entrance losses (Chow 1959 and DVWK 1996). Calibration of gap flow to measured values was achieved by iterating the weir crest contraction coefficient C_g. For Lower Stokes, C_g varied over a wide range from 0.10 to 0.45, likely due to irregular boulder placement at each weir crest.

The transitions from gap flow to weir flow ranged from depths of 0.34 to 0.37 m at the Lower Stokes weirs. Initial estimates of the transition point were based on plots of the ratio of weir length to depth versus stage and the locations of the points of inflection (Figure 3.21). The initial estimates for transition points were used to initiate weir flow in the hydraulic model spreadsheet. The total modeled flow, $Q_{combined}$, was compared to measured data. If $Q_{combined}$ differed from measured flow, the transition points (stages) were adjusted until the modeled flow $Q_{combined}$ matched measured flows. The data suggest that the transition stage from gap to weir flow varied approximately 0.05 m vertically from the initial estimate from the point of inflection in Figure 3.21. Weir 2 presented a different result, without a clear point of inflection for the length to depth versus stage relationship. The transition point for weir 2 was selected based on iterations to match $Q_{combined}$ to measured flows. The result for weir 2 was a point on the climbing limb of the length/depth ratio versus stage relationship. For all three weirs, the curves for ratio of length to depth versus stage appear to converge to a value of approximately 20, which is attributed to the constant slopes of the weir crest profile design, S (Figure 3.3).

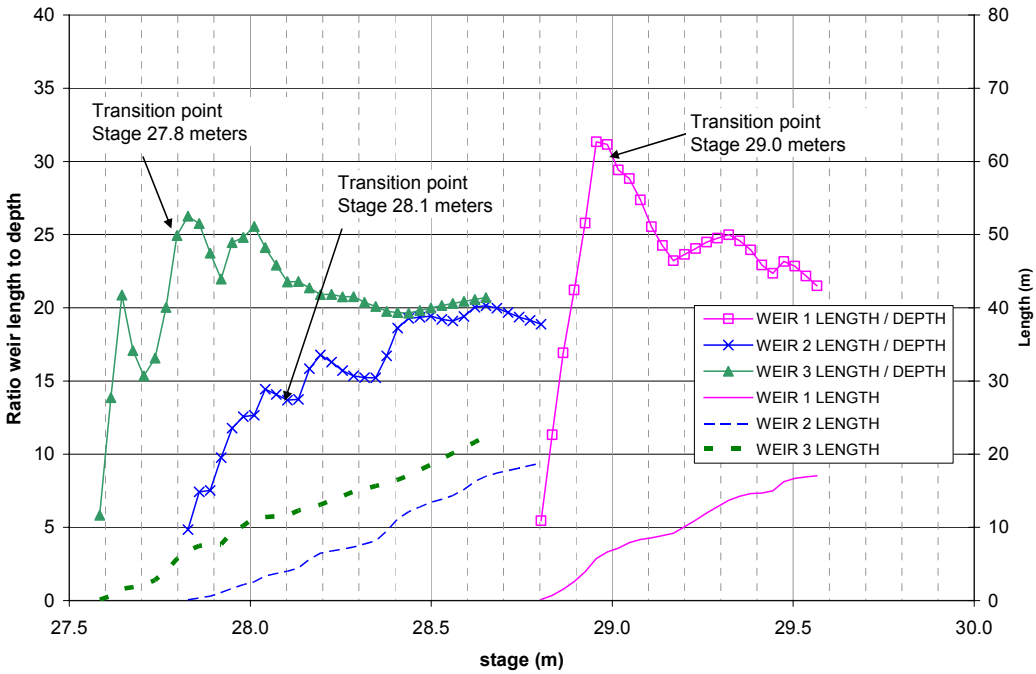


Figure 3.21. Calculated weir length-stage relationship and transition points from gap to weir flow, Lower Stokes project site.

Weir flow was calibrated with two coefficients, μ and C_w. The weir coefficient μ was adjusted until $Q_{combined}$ matched measured flow. Larger values of μ produced higher flows per change in stage in Equation (3.12). The resulting weir coefficient μ varied from 0.7 to 0.8 for weirs 1, 2, and 3 at Lower Stokes. These values for μ are relatively high, resulting in higher flow per change in stage. The coefficient C_w was included to correct for projected width transverse to the channel. The value of C_w varies based on center crest width W and the plan angles of the wing walls (Figure 3.3 and Figure 3.14). The value of C_w varied from 0.42 to 1.0 (Figure 3.22). The following equation was used to calculate C_w as a function of base width, W, and weir profile length, B:

$$C_w = \frac{W + (B - W) \cdot Sin(\alpha)}{B} \tag{3.14}$$

Where:

B = Total length of weir profile, varies with water stage, in m

W = Base width of trapezoidal weir crest, in m

α = Angle of wing wall relative to stream bank, in degrees

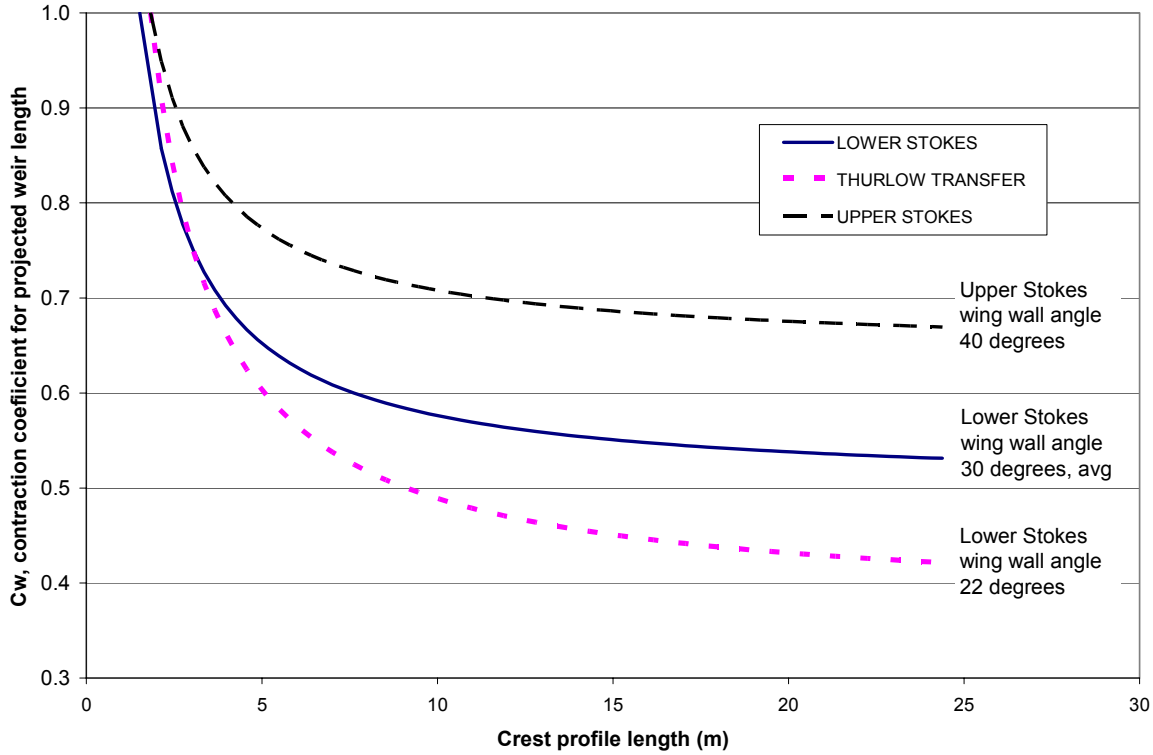


Figure 3.22. Contraction coefficient of weir crest profile length to projected weir length.

The final modeled values for $Q_{combined}$, and the components $Q_{orifice}$, Q_{gap}, and Q_{weir}, are shown in Figure 3.18 to 3.20, and Appendix F. Overall, the first three modes modeled the full range of measured flows well. Gap flow calculations accounted for flows below the transition to weir flow, where the weir equation significantly diverges from measured flows, around 0.15 to 0.20 m^3/s (Table 3.1).

Transitions from weir flow to rough boundary flow were calculated between 1.7 and 2.6 m^3/s (60 to 92 cfs), when relative depth (water depth divided by bed roughness) was estimated as 4, which is between 3 and 5 (Chow 1959). Additional field observations at the rock vortex weirs would help identify the stage where rough boundary flow begins at each weir.

The final mode of the hydraulic model at the weir crest, rough boundary flow, was developed as a separate model that overrides $Q_{combined}$ and treats the weir as a drowned roughness element. Water surface profiles generated for low flow observed in July 2005 from the MIKE 11 model are shown in Figure 3.23. Water surface elevations for high flow were not available for calibration, so those water surface profiles are not shown. The primary calibration step involves adjusting Manning's n at each section to match observed water surface elevations. An initial estimate of Manning's n was 0.04 for the Lower Stokes site. After running the model, an area downstream of the weirs required an increase in Manning's n to 0.06 to match observed water surface elevations. At the locations of the rock vortex weirs, Manning's n was increased to 0.12. Contraction and expansion coefficients, utilized by the rough boundary model MIKE11, were programmed as 0.1 and 0.3, respectively, through the reach and as 0.4 and 0.6, respectively, at the rock vortex weirs. Increased values for contraction and expansion coefficients are recommended at channel constrictions, such as bridges and culverts (COE 2002). The rock vortex weirs were modeled as straight, broad-crested weirs at elevations 0.20 m above the lowest measured point on the weir crest, based on findings from the hydraulic model for the weir flow mode. Additional cross sections were interpolated upstream and downstream to stabilize the model calculations.

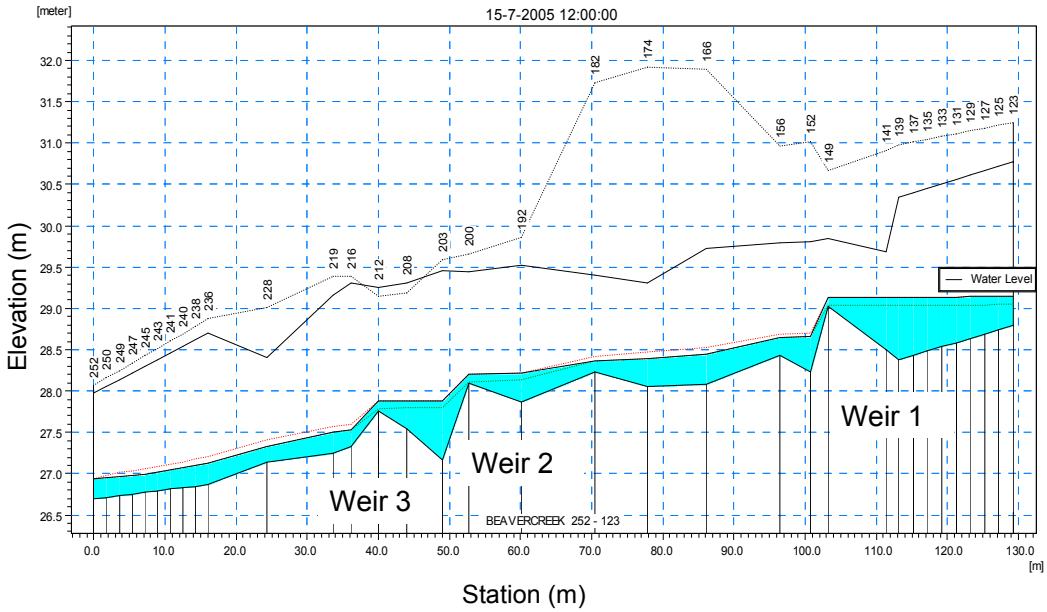


Figure 3.23. Water surface profile from hydrodynamic model analysis for Lower Stokes at low flow.

3.6 Rating curve development for hydraulic parameters to evaluate fish passage at rock vortex weirs at Lower Stokes project site

Rating curves for hydraulic parameters versus discharge were developed to generate time series for hydraulic parameters (NMFS 2000, WDFW 2003, and Appendix A). Continuous estimates of discharge from the pressure transducers (Chapter 2) and the following ratings curves were used to develop time series for hydraulic parameters (Chapter 5). The four recorded hydraulic parameters were hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation factor, and average velocity over the rock vortex weir.

3.6.1 Rating curve for hydraulic drop versus discharge

The primary design factor for the rock vortex weirs was a minimum drop of 0.24 m, considered suitable for upstream passage by leaping fish (WDFW 2003 and McLaughlin, personal communications, 2006). Differential stage or hydraulic drop was determined as an empirical relationship to discharge and the weir geometry. Data for the hydraulic drop versus discharge relationship was collected as visual observations of staff gages and the pressure transducer staff gage. Differences in the staff gages determined hydraulic drop and the pressure transducer staff gage readings determined discharge. Each set of observations formed rating points that contributed to the construction of a fitted rating curve. These curves were then applied to the chronological records of discharge (Chapter 5).

The rating curves for hydraulic drop versus discharge for the rock vortex weirs at the Lower Stokes project site are shown in Figure 3.24. Differential stage or hydraulic drop is plotted against discharge, demonstrating a hydraulic drop of about 0.27 m during low flow and a reduction in the drop to a value of about 0.11 m for higher flows, depending on the weir geometry. At weir 1, hydraulic drop varied the most in relation to discharge, compared to weirs 2 and 3 at Lower Stokes (Figure 3.24), dropping below the fish passage guideline of 0.24 m at a discharge of approximately 0.15 m^3/s. At weirs 2 and 3 the hydraulic drop varied less per change in discharge (Figure 3.24), with the hydraulic drop for weir 3 generally below the guideline (meeting the guideline) and the hydraulic drop for weir 2 slightly above the guideline of 0.24 m (not meeting the guideline).

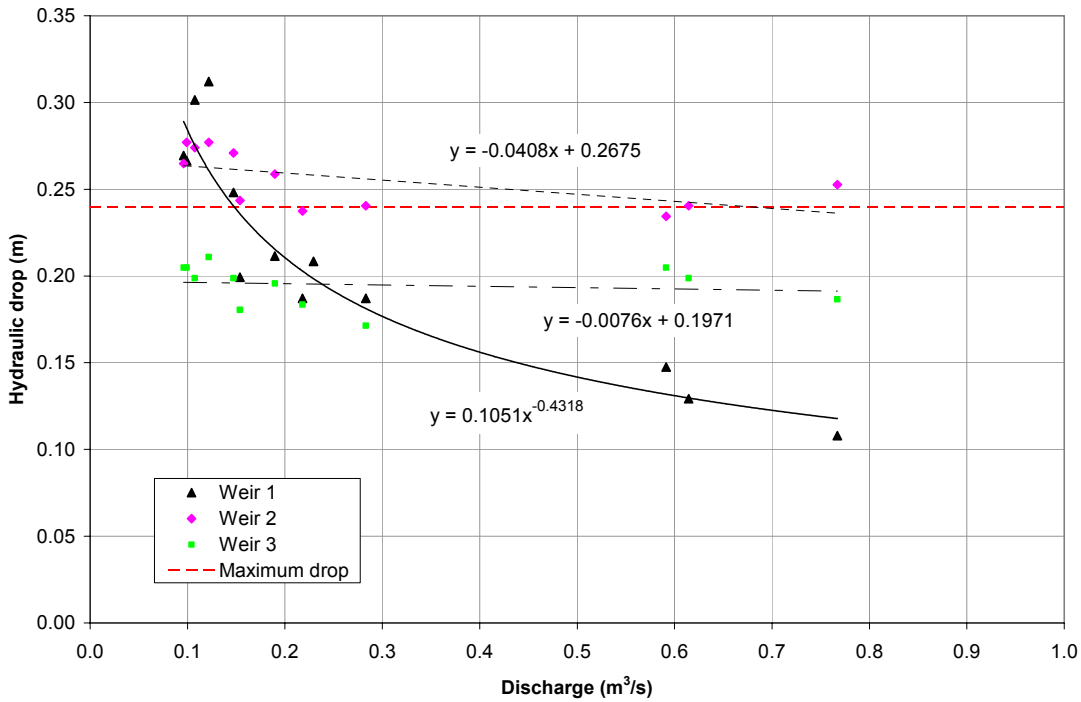


Figure 3.24. Rating curves for hydraulic drop versus discharge at Lower Stokes weirs 1, 2, and 3. Maximum hydraulic drop of 0.24 m shown (WDFW 2003). Regression fits for lines shown.

3.6.2 Rating curve for ratio of pool depth to hydraulic drop versus discharge

Another criteria for fish passage compared the ratio of pool depth to hydraulic drop, which is important hydraulic parameter for leaping fish (Stuart 1962, Pearson 2005). Fish regulations require that the pool depth is at least greater than 1.5 times hydraulic drop (NMFS 2000). Pool depth was calculated based as the difference between the staff gage reading observed in the pool and the surveyed elevation of the bottom of the pool from the 2005 ground survey. The resulting rating points of ratio of pool depth to hydraulic drop versus discharge then composed a rating curve for this hydraulic parameter (Figure 3.25). A linear fit was applied to these rating points and then applied to the chronological record of discharge (Chapter 5). The weirs at Lower Stokes generally met NMFS (2000) fish passage guidelines, including low flows, when the ratio exceed the minimum value of 1.5 (NMFS 2000). As with hydraulic drop (Figure 3.24), weir 1 at Lower Stokes again showed more variation as a

function of discharge. This is implied since hydraulic drop is factored into calculation of the ratio of pool depth to hydraulic drop.

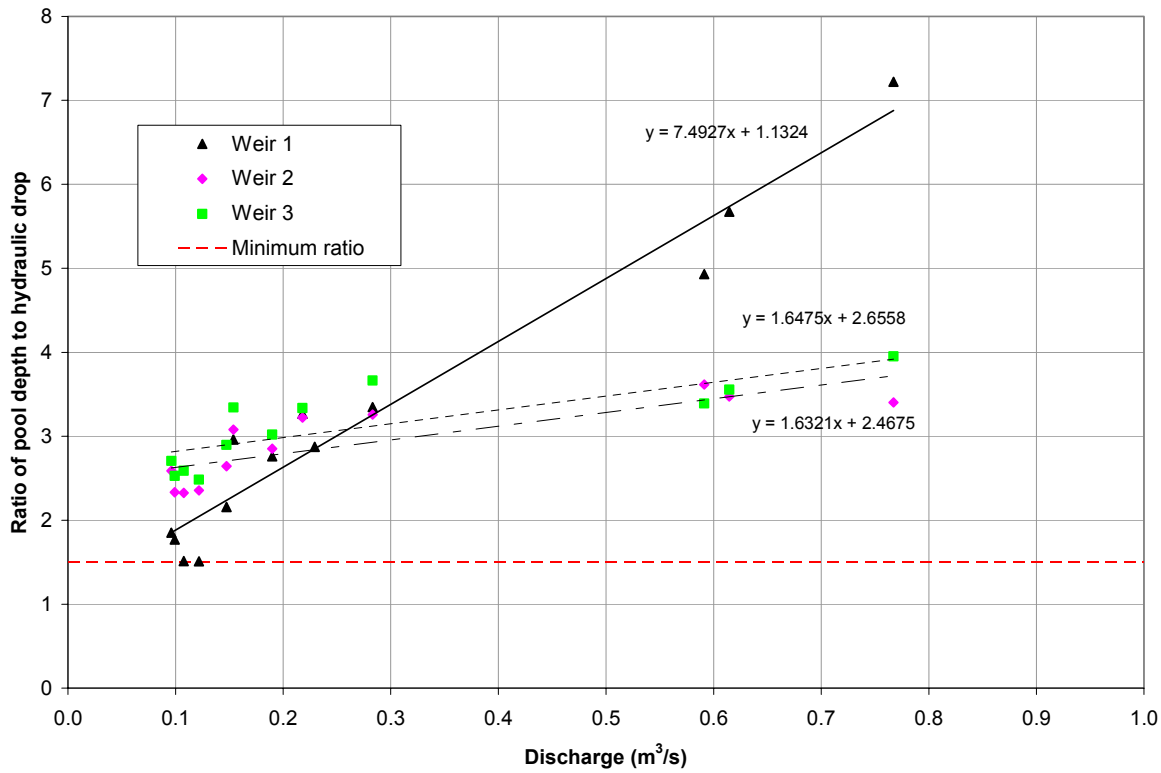


Figure 3.25. Rating curves for ratio of pool depth to hydraulic drop versus discharge at Lower Stokes weirs 1, 2, and 3. Minimum recommended ratio of 1.5 shown (NMFS 2000).

3.6.3 Rating curve for energy dissipation factor versus discharge

Criteria for the fish passage guidelines (NMFS 2000,WDFW 2003, and Klavas, personal communications 2006) state that energy dissipation and turbulence per unit volume, calculated as the energy dissipation factor (EDF), should not exceed a value of 250 W/m^3. High levels of turbulence in the pools may disorient migrating fish and impede upstream passage (WDFW 2003). The EDF is calculated as follows:

$$EDF = \gamma \cdot \frac{Q \cdot D_s}{V_p} \tag{3.15}$$

Where:

EDF = Energy dissipation factor, suggested to be less than a value of 250 (W/m^3)

γ = Unit weight of water

Q = Discharge from continuous record at pressure transducer, in m^3/s

D_s = Differential hydraulic drop at weir determined from staff gage observations, in m

V_p = Volume of pool determined from observation of staff gages and pool volume rating curves developed from topographic survey, in m^3

The volume of the pool was estimated as a stage versus storage relationship calculated from a digital terrain model derived from 2005 ground survey points (Appendix B). The pool volume available for EDF is limited to a region 3 m longitudinally downstream of the weir crest (Hegberg et al. 2001). This limit was intended to restrict pool volume in EDF calculations and quantify turbulence to a region where water plunges over the rock vortex weir crest.

Given Equation (3.15) and a set of staff gage observations, the EDF and discharge were determined and developed into rating points for an EDF versus discharge relationship (Figure 3.26.). A linear fit was applied to the EDF versus discharge relation and then applied to the period of record for discharge, resulting in a continuous record of EDF at each rock vortex weir (Chapter 5).

As shown in Figure 3.26, as discharge increased, EDF increased. To determine EDF, weir pool volume as a function of stage was required (Appendix B). Also, the hydraulic drop was a factor in EDF as shown in Equation (3.15). A reversal in behavior at the weirs occurred, namely, weirs 2 and 3 showed more variation as a function of discharge, compared to weir 1, which demonstrated a relative flat relationship to discharge (Figure 3.26). At weirs 2 and 3, the maximum recommended value of 250 W/m^3 was exceeded at discharges of 0.31 and 0.48 m^3/s, respectively (Figure 3.26).

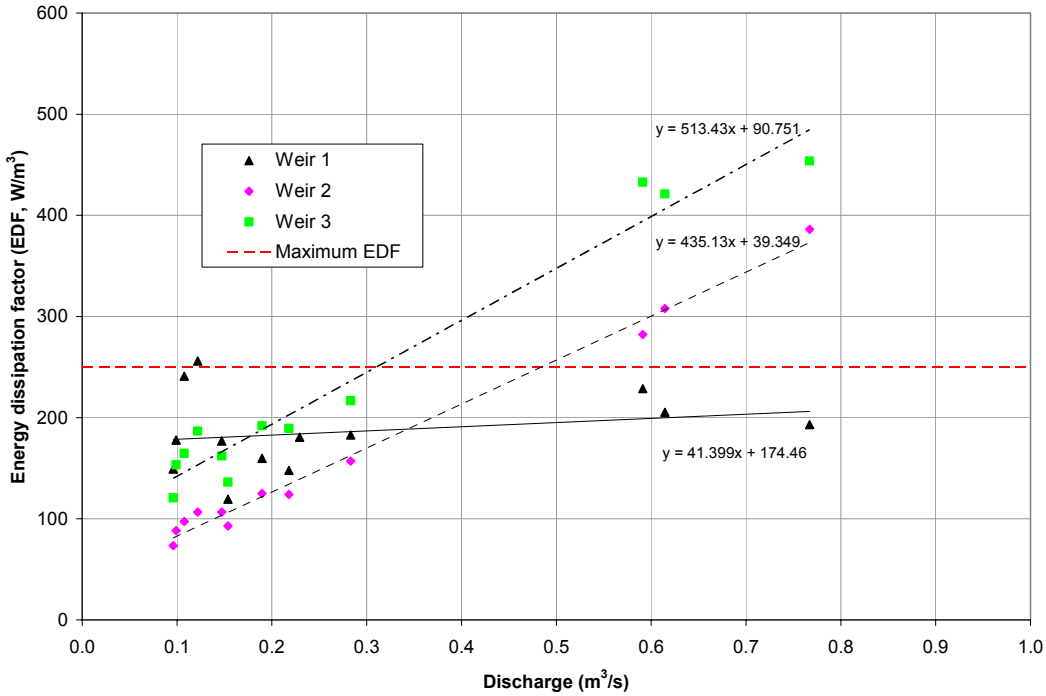


Figure 3.26. Rating curve for energy dissipation factor versus discharge at Lower Stokes weirs 1, 2, and 3. Maximum recommended value of 250 W/m^3 shown (WDFW 2003).

3.6.4 Rating curve for average velocity versus discharge

Results from the four-mode hydraulic models at the Lower Stokes rock vortex weirs were used to construct curves that estimated average velocity as a function of discharge (Figure 3.27). According to WDFW (2003), a maximum cross section averaged velocity of 0.37 m/s is an important guideline for upstream passage of juvenile fish at culverts.

The rating curve for average velocity versus discharge was developed by using model results of discharge and flow area. Velocity was calculated as discharge divided by flow area, according to the four-mode hydraulic model. Rating points were calculated for a range of water stages. Given water stage, the hydraulic models at the rock vortex weirs were used to calculate discharge and flow area. These calculations were developed into a rating curve with a log(velocity) versus log(discharge) relationship (Figure 3.27). The rating curve for average velocity versus discharge was applied to the continuous records of discharge at the project sites to generate a record of average velocity at the weir crests (Chapter 5).

Estimated average velocities over the rock vortex weir crests typically met WDFW (2003) guidelines below discharges of 0.53, 0.34, and 0.07 m^3/s for weirs 1, 2, and 3 at Lower Stokes, respectively. Average modeled cross velocities at weirs 2 and 3 were typically higher than weir 1 by about 0.1 to 0.3 m/s, according to log-log regressions of average modeled velocity versus discharge.

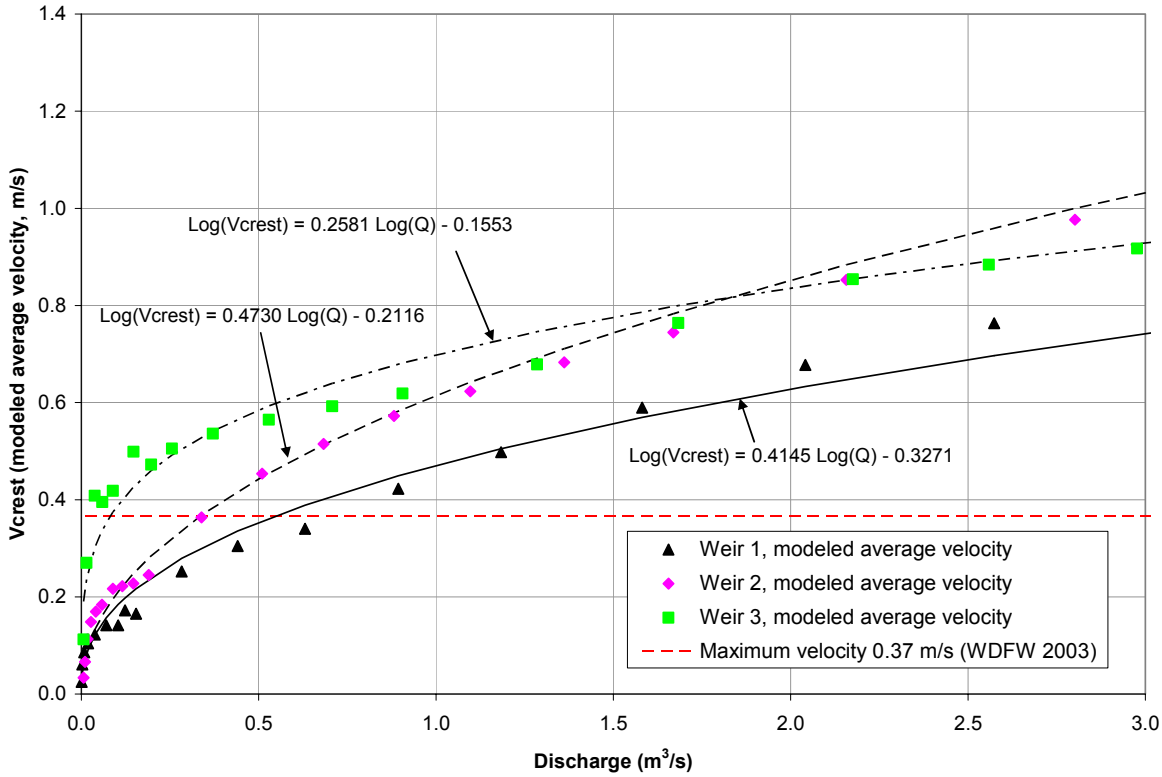


Figure 3.27. Rating curves for average velocity versus discharge at Lower Stokes weirs 1, 2, and 3. Maximum recommended velocity of 0.37 m/s shown (WDFW 2003).

3.7 Example calculation of time series for hydraulic parameters at Lower Stokes project site using rating curves

Four rating curves for hydraulic parameters were generated for each rock vortex weir. Rating curves were calculated at each weir for hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation factor, and average velocity over the weir (Figure 3.24 to 3.27). Each curve used discharge as the dependent variable.

Continuous records of discharge were input to the rating curves for the hydraulic parameters, resulting in time series of hydraulic parameters for Lower Stokes. An example of an estimated time series of hydraulic drop is shown in Figure 3.28. The hydrograph is also shown in Figure 3.28 to demonstrate the time periods that estimated flows are calibrated and within the low and high fish regulation flows (Q_{low} and Q_{fp}), as developed in Chapter 2. When the estimated discharge is greater than Q_{low} of 0.1 m^3/s and less than Q_{fp} 3.5 m^3/s, the hydraulic parameters should comply with the thresholds, shown as red dashed lines in Figure 3.28. When the estimated discharge is outside the calibrated range, all data should be considered provisional. Further presentation and discussion of the time series for the hydraulic parameters, as developed from the rating curves in this chapter, are in Chapter 5.

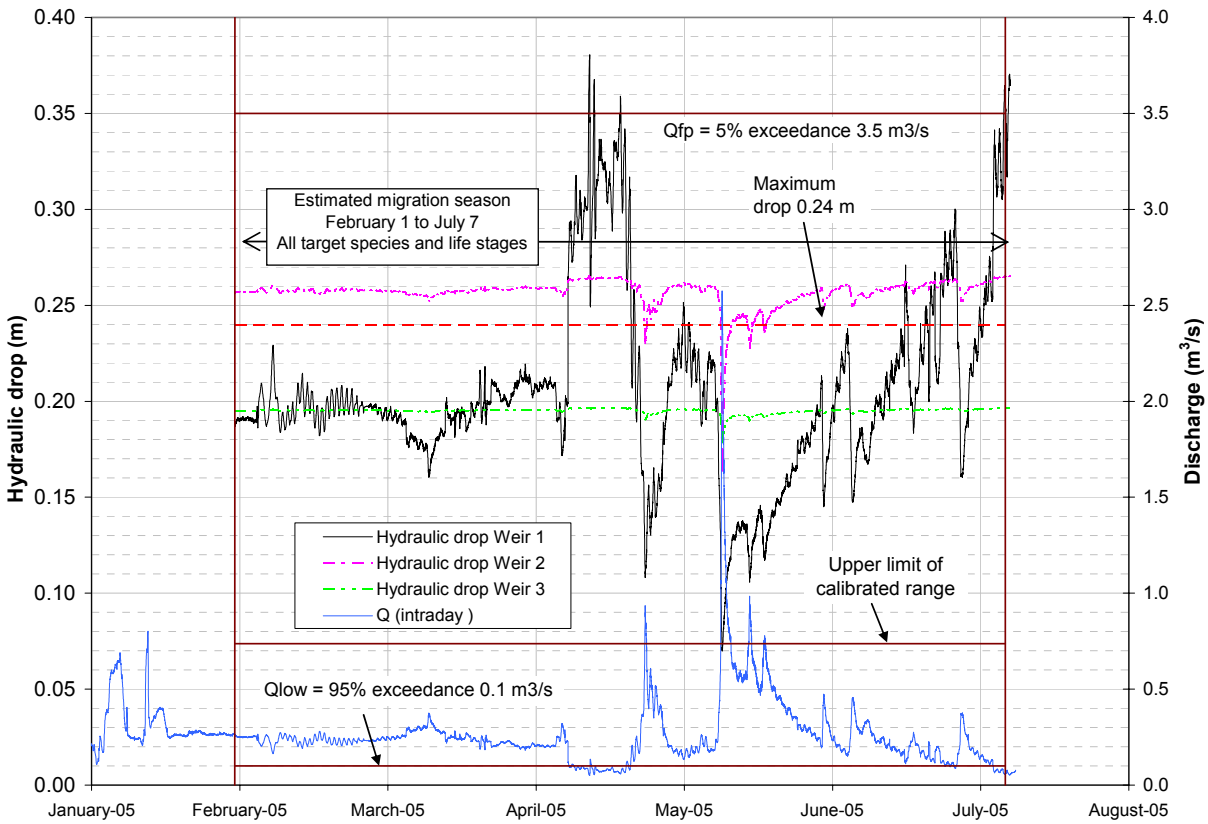


Figure 3.28. Estimated hydraulic drop at rock vortex weirs at Lower Stokes during migration season.

3.8 Hydraulic model validation and rating curve development at Thurlow and Upper Stokes project sites

To validate modeling methods and calibration terms developed for the Lower Stokes site, the same procedures to set up hydraulic models at the rock vortex weirs were performed at the Thurlow and Upper Stokes project sites. Resulting calibration terms from Thurlow and Upper Stokes were then compared to data from the models at Lower Stokes.

The Thurlow project site is about 1 km upstream from Lower Stokes, and the Upper Stokes Site is about 2 km upstream of Lower Stokes. At each site, the original diversion barrier was replaced with two different types of weirs. The downstream weir was an 'A' weir with two crests and the upstream weir was a 'V' weir (single rock vortex weir, Rosgen 1996) (Figure 3.5 and Figure 3.7). The single rock vortex weir ('V' weir) was used to validate model methods at Lower Stokes, since an 'A' weir (double weir) likely creates different hydraulics, beyond the scope of this thesis.

Data were collected at each of the sites to develop four-mode hydraulic models. These data included continuous flow records, staff gage readings at the rock vortex weirs, velocity profile and spot measurements, substrate classification by Wolman Pebble Counts, and topographic surveys measured by a robotic total station. Data collection and hydraulic model development were repeated according to methods described above for the weirs at Lower Stokes.

The values of the coefficients for the spreadsheet-based weir models at Thurlow and Upper Stokes were used to validate coefficients determined at the Lower Stokes project site (Table 3.2). Resulting models are presented in Figure 3.29 to 3.35.

Table 3.2. Calibration and validation of hydraulic models for rock vortex weirs at Lower Stokes, Thurlow, and Upper Stokes. Data from Lower Stokes repeated for comparison to Thurlow and Upper Stokes validation sites.

	Calibration site			**Validation sites**	
	Lower Stokes			**Thurlow**	**Upper Stokes**
Weir geometry, "as-built"	**Weir 1**	**Weir 2**	**Weir 3**	**Weir 1**	**Weir 1**
Crest width, W (m)	1.5	1.5	1.5	1.8	1.8
Average wing wall angle (plan), degrees	32	28	30	22	40
Wing wall slope (profile)	9%	10%	9%	7%	11%
Orifice Flow					
K, loss coefficient	0.60	0.60	0.60	0.60	0.60
Open area (m^2)	0.007	0.007	0.007	0.007	0.007
Gap Flow					
Zeta ξ, friction factor	0.50	0.50	0.50	0.50	0.50
C_g, contraction factor for gaps	0.10	0.17	0.45	0.07	0.15
Weir Flow					
μ, weir coefficient (0.5 to 0.8 recommended)	0.80	0.70	0.80	0.50	0.57
C_w, contraction coefficient Determined by weir geometry	*ranges from 0.42 to 1.00, varies according to crest profile length*				
Transitions for four-mode hydraulic model, estimated					
Gap to Weir Flow, discharge, (m^3/s)	0.15	0.15	0.20	0.09	0.07
Gap to Weir Flow, depth, (m)	0.37	0.34	0.34	0.21	0.18
Weir to rough boundary flow, (m^3/s)	2.6	2.2	1.7	3.3	3.5
Weir to rough boundary flow, depth, (m)	0.6	0.6	0.4	0.6	0.6

The weirs at Thurlow and Upper Stokes have slightly different "as-built" geometries (Table 3.2), which was estimated based on ground survey. The weir at Thurlow has wing walls of 22 degrees (versus 30 degrees at Upper Stokes) in plan, and it has a flatter crest profile slope (7 percent versus 9 percent). The weir at Upper Stokes has a flatter plan angle of 40 degrees and weir crest profile slopes of 11 percent, which are comparable to those at the weirs at Lower Stokes. Each of these factors may affect the hydraulics at the weir.

Calibration of orifice flow for the weir models at Thurlow and Upper Stokes was the same as Lower Stokes. The coefficient of discharge was assumed to be 0.6 and the open area was 0.07 m^2.

To calibrate gap flow at the Thurlow weir, a smaller contraction coefficient value (C_g) of 0.07 was required, likely because the weir had a steeper plan angle of 22 degrees for the wing walls (Figure 3.3). The C_g coefficient at Upper Stokes of 0.15 was comparable to values at Lower Stokes.

Transition from gap flow to weir flow occurred at more shallow depths for Thurlow (0.21 m) and Upper Stokes (0.18 m), than for the weirs at Lower Stokes (0.34 to 0.37 m). Field observations indicated that the weirs at Thurlow and Upper Stokes had smaller gaps between the boulders forming the weir crest, possibly creating conditions for weir flow at a lower stage above the weir crest, relative to the weirs at Lower Stokes. The weirs at Thurlow and Upper Stokes also had deeper low flow notches.

For weir flow, the models for Thurlow and Upper Stokes reported lower weir coefficient values of 0.50 and 0.57, respectively, than for Lower Stokes. The data also show weir flow starting at a vertical datum closer to the weir crest. The results from the four-mode spreadsheet model suggest that the smaller weir coefficients (μ), are attributed to increased higher friction and closer proximity to roughness and turbulent effects from the crest boulders. For Thurlow, the minimum value for μ of 0.5 did not account for friction and losses, suggesting a lower value for higher friction or contraction losses. These data on the low weir coefficients are not surprising as the fishway design guidelines in WDFW (2004) suggest a total weir coefficient (fixed coefficients * μ) for straight weirs constructed of log sills is 1.5 (2.7, English units) (Equation (3.12)). The total weir coefficient at Thurlow is 1.5 (metric units), which includes projection of the trapezoidal crest geometry, adjusted by the C_w coefficient. This is comparable to total weir coefficient for straight log weirs from WDFW (2004).

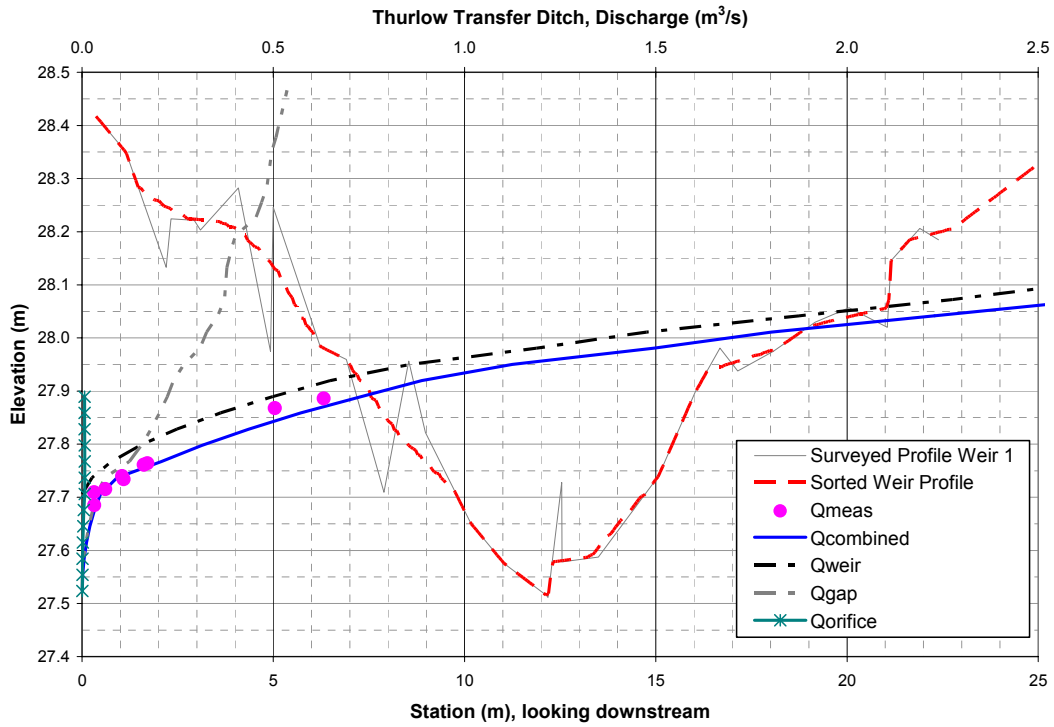


Figure 3.29. Hydraulic model at Thurlow weir 1.

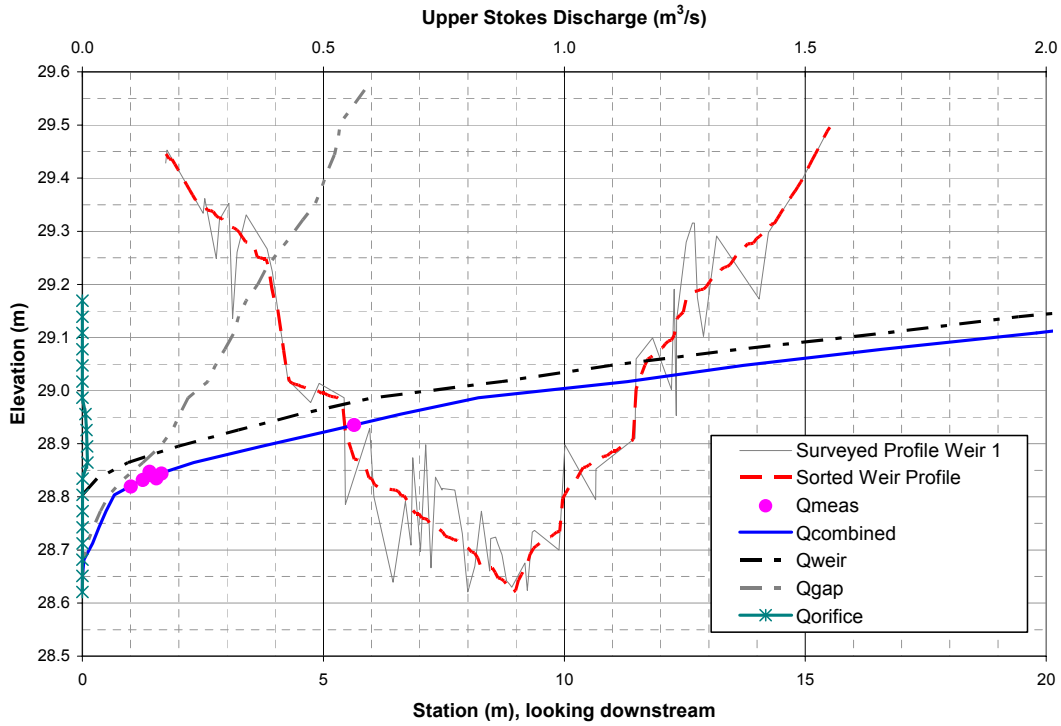


Figure 3.30 Hydraulic model at Upper Stokes weir 1.

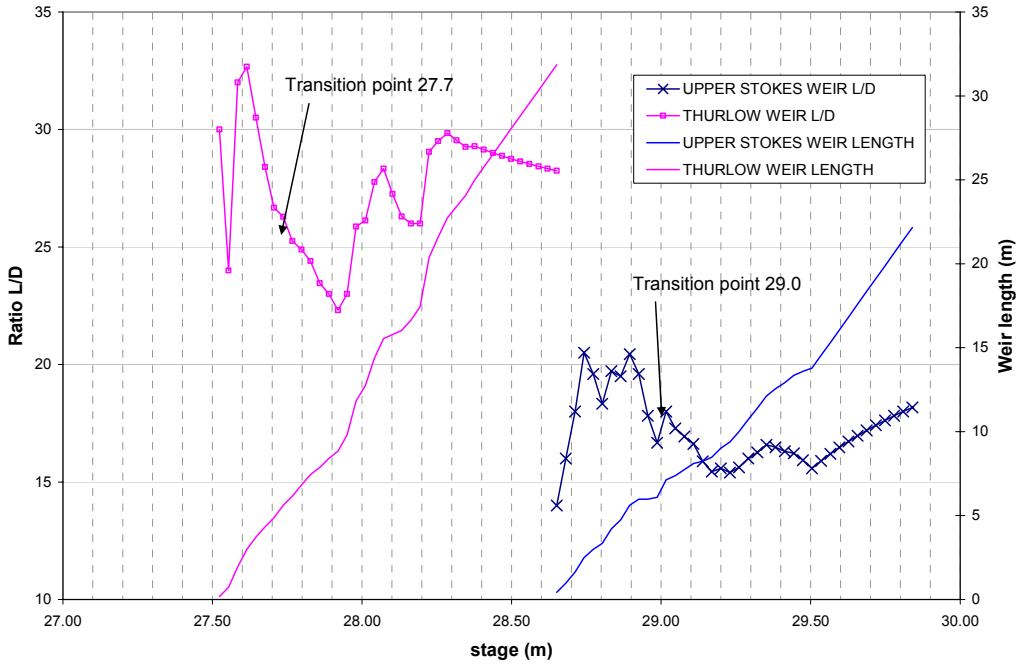


Figure 3.31. Transitions from gap flow to weir flow at Upper Stokes and Thurlow.

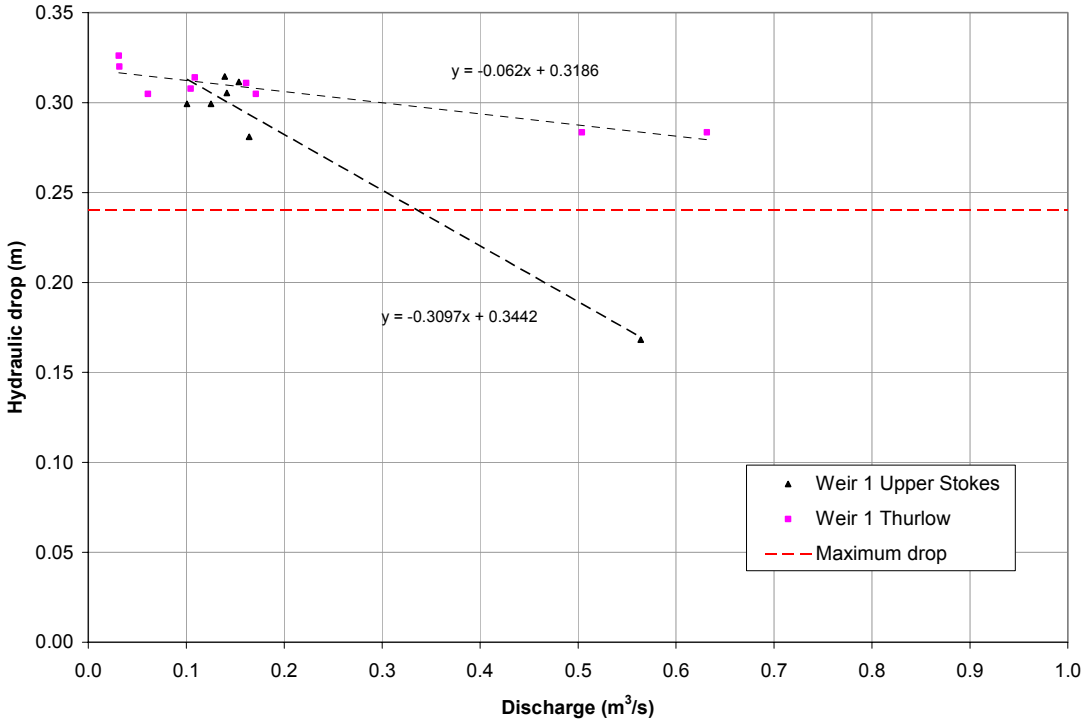


Figure 3.32. Rating curve for hydraulic drop versus discharge at Thurlow and Upper Stokes.

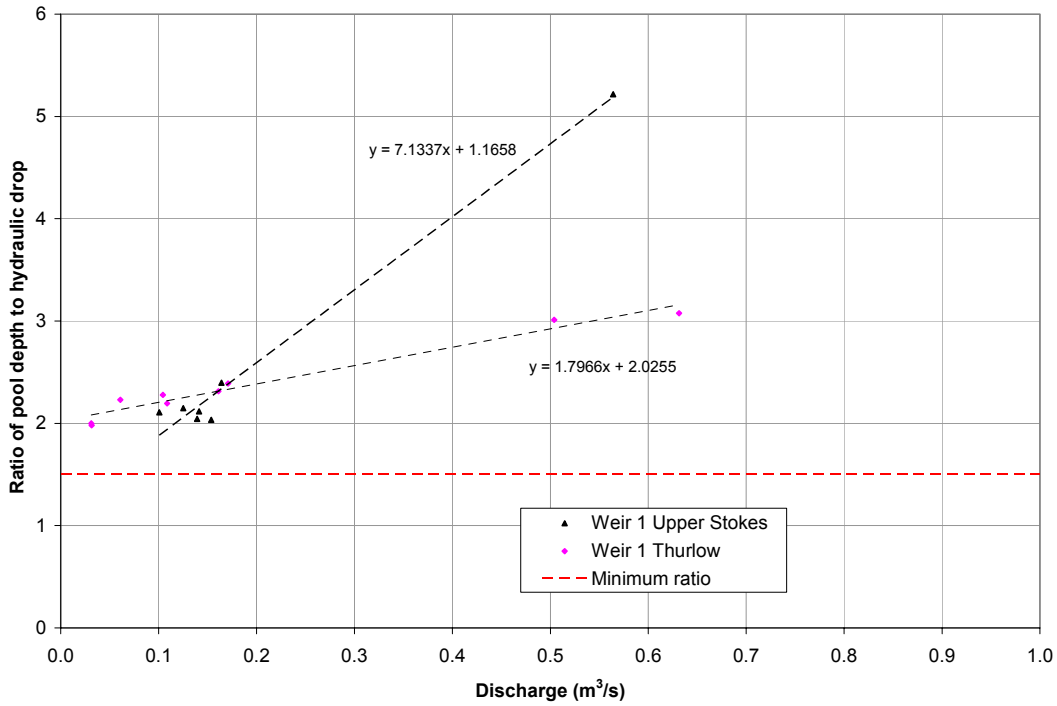


Figure 3.33. Rating curve for ratio of pool depth to hydraulic drop versus discharge at Thurlow and Upper Stokes.

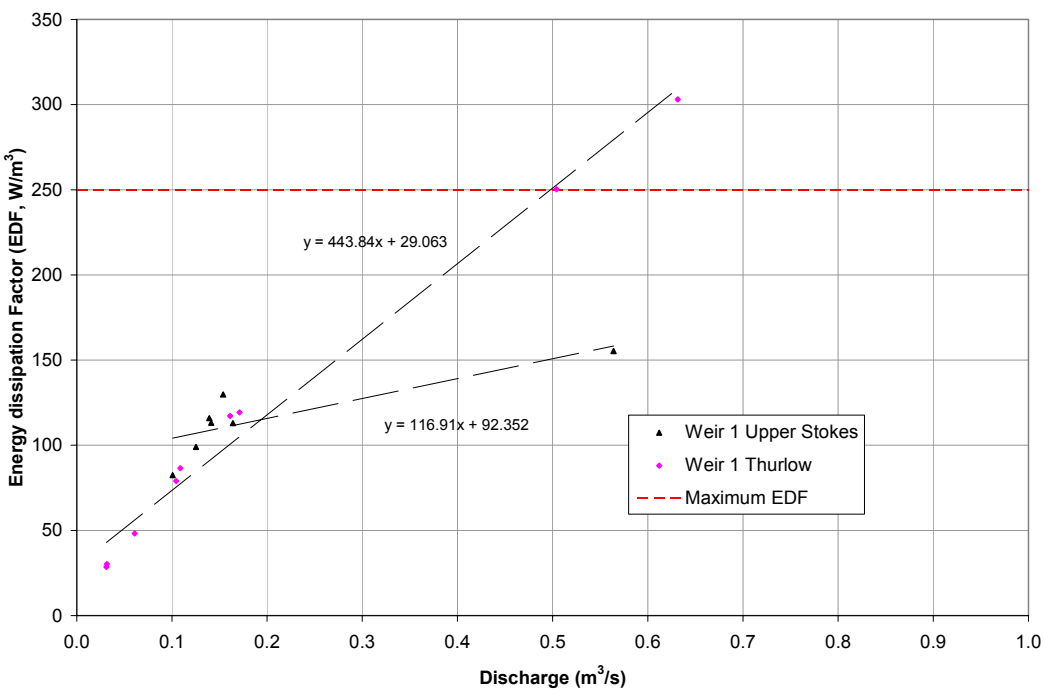


Figure 3.34. Rating curve for energy dissipation factor versus discharge at Thurlow and Upper Stokes.

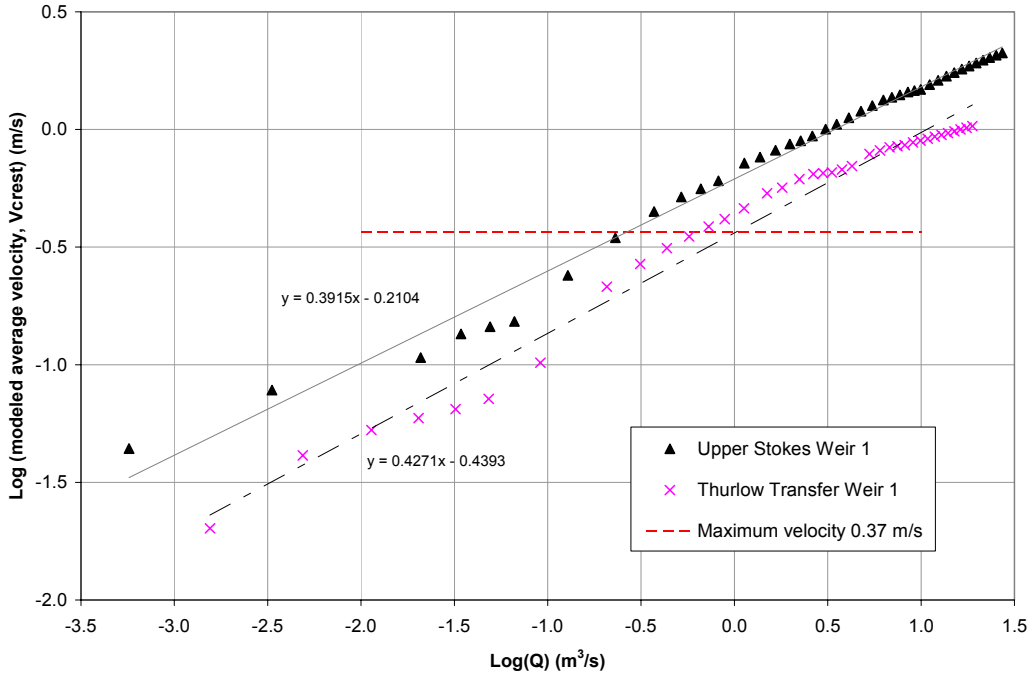


Figure 3.35. Rating curve for average velocity versus discharge at Thurlow and Upper Stokes.

3.9 Discussion

Hydraulic models were developed in this thesis to compute key hydraulic parameters important for fish passage at rock vortex weirs. The models enable computation of hydraulic conditions (velocity, hydraulic drop, turbulence, and pool depth) at the weir crest, where fish would attempt to swim through or leap the weir. High levels of roughness, contraction, and surface friction at the weir crest were quantified by coefficients in a four-mode hydraulic model, especially in the calibration terms used to replicate gap flow.

Two types of models were developed. A spreadsheet-based model was applied to describe three modes of flow over a rock vortex weir: orifice flow, gap flow, and weir flow. The fourth flow mode was rough boundary flow, calculated by the second type of model, a numerical hydrodynamic model, which utilized the St. Venant equations (DHI Water and Environment 2003). Building on the spreadsheet model for hydraulics at the rock vortex weirs, and field observations, rating curves were developed for hydraulic parameters of fish

passage. These rating curves were also modeled in spreadsheet to facilitate synthesis to continuous records of discharge, resulting in continuous time series of hydraulic parameters (Figure 3.28, Chapter 5). These time series allow assessment of weir performance through an entire migration season as well as at specific times of known fish passage (Chapter 5).

For the four-mode model (Figure 3.12), the flow active at the lowest water stage is $Q_{orifice}$, which is also the smallest flow. As water stage increases, Q_{gap} initiates and dominates the discharge. At some stage above the weir crest, Q_{weir} initiates and begins to dominate the total discharge. Ultimately, the weir drowns out by tailwater or downstream control, resulting in rough boundary flow over a drowned weir. The four-mode hydraulic model did not account an intermediate stage of downstream tailwater or control affecting critical flow at the rock vortex weir crest. The gap flow and weir flow modes in the four-mode hydraulic model were developed based on free overflow on the boulders forming the weir crest, with critical flow at the weir crest. The intermediate mode likely occurs at higher flows, which were not observed during field data collection. Also, since the intermediate flow mode occurs at some unknown higher stage and discharge, it was more likely that the intermediate flow mode describes a condition outside of the high design flow for fish passage, Q_{fp}, from WDFW (2003) (Chapter 2), and therefore less important to the thesis study. Additional data collection during high flows would facilitate development of this intermediate flow mode and clarify its relevance to fish passage flows.

The first mode of the four-mode hydraulic model, orifice flow, was nearly negligible at the rock vortex weirs, due to the type of weir construction at the study sites. Nevertheless, the framework set in the thesis can accommodate weirs with larger interstitial spaces and increased orifice and hyporheic flow.

The second mode of the four-mode hydraulic model, gap flow, effectively explained low flows near the weir crest due to high friction losses. Application of the weir equation at these low stages significantly overestimated the discharge versus stage relationship, warranting another formulation, such as gap flow. To account for gap flow, the C_g varied from 0.07 to 0.45, to account for contraction and friction losses. Weirs with steeper plan

angles had greater contractions of weir length, as shown in Figure 3.3. By using estimates of flow area versus discharge for the range of gap flow, better estimates of cross section averaged velocities were applied to the weir rating curve.

Calculation of the transition stage from gap flow to weir flow was less apparent. Initial estimates of the point of inflection on the weir length to depth ratio curves were useful, but inspection of the plots of modeled flows versus measured flows was more useful, as the length to depth ratio curve for a given weir does not always have a point of inflection. Another approach is to estimate the stage of the transition based on the height above the bottom of the weir crest. The data developed for this thesis indicate that weir flow initiates from 0.18 to 0.37 m above the crest, or at an average vertical shift of 0.23 m. This stage was equivalent to a discharge between 0.07 and 0.20 m^3/s.

The third mode in the spreadsheet-based model, weir flow, initiated at the transition height h_{T1} (Figure 3.17). Calibration of this mode was achieved by projecting weir length perpendicular to the channel and iterating the weir coefficient. As shown in Table 3.2, the weir coefficient, μ, was estimated from 0.5 to 0.8. When values for μ are relatively high, there appears to be less friction at the initiation of weir flow, due to less friction at a water-water interface, rather than a water-fixed boundary interface. Also, the transition from gap to weir flow is a moving boundary, augmenting the movement of water in the weir equation. Alternatively, for lower values of μ, it appears the transition from gap flow to weir flow is also lower, likely due to roughness from the weir crest (Table 3.2). For one model (Thurlow, weir 1), weir flow still overestimated measured flows, even with the smallest recommended value of 0.5 for μ. The findings in this thesis indicate that further study is necessary to better define the value of μ as it varies with depth, but a workable value between of 0.5 and 0.8 could be assumed for the purpose of analyzing fish passage, in settings similar to those described in this thesis.

The transition to rough boundary flow from weir flow, h_{T2}, was more difficult to estimate for two reasons (Figure 3.17). Observations and measurements of high flows are required to calibrate a model, and these data are sometimes difficult to collect. Also, each rock vortex

weir has unique hydraulics as the stage increases and includes increased stream power and influences from reach-level characteristics. For practical purposes, the transition to rough boundary flow was estimated using a relative roughness of 3 to 5, where the transition depth is 3 to 5 times the scale of the bed roughness (Chow 1959, COE 2002). For a typical installation of rock vortex weirs, with 1 m diameter crest stones, the surface roughness varied from 0.10 to 0.15 m, which resulted in values of the transitions to rough boundary flow (h_{T2}) from 0.4 to 0.6 m above the weir crest. Discharge associated rough boundary flow is comparable to the high flow requirement for fish passage, Q_{fp}, and is likely only applicable for a very short period during extreme flow events.

A large number of field observations of high flows are required to properly calibrate a numerical hydrodynamic model, such as MIKE 11, for rough boundary flow at rock vortex weirs. If these data were available, the hydrodynamic model could be calibrated by adjusting contraction and expansion loss coefficients and Manning's n. However, with regard to upstream fish passage, development of a hydrodynamic model for high flows is less critical because current fish passage guidelines at culverts (NMFS 2000 and WDFW 2003) only require 5- to 10-percent exceedance criteria, well below the transition to rough boundary flow and the application of a hydrodynamic model (Figure 2.23 and Table 3.2).

To formulate a rough estimate of discharge over rock vortex weirs, as simple trapezoidal model of the weir could be assumed. The value of μ in Equation (3.9) could be assumed to be between 0.5 and 0.8 and the contraction of the weir profile length could be calculated from Equation (3.14). Also, a vertical datum shift of 0.1 to 0.3 m of the simplified trapezoidal model above the minimum weir elevation is suggested. The simple trapezoidal model works more effectively for discharges above 0.1 m^3/s. At lower discharges the weir equation does not account well for high friction losses, where gap flow better describes stage versus discharge.

4. FISH MOVEMENT MONITORING BY USGS-CRRL

In this chapter the natural history and migration periods of species of concern for the study sites are discussed. Methods and equipment for PIT-tagging, fish weirs, PIT-tag antennas, and other equipment used by the USGS-CRRL research team are characterized. Findings on fish movements from the USGS-CRRL are quantified temporally and spatially for PIT-tagged fish near installed rock vortex weirs at the Lower Stokes Project site on Beaver Creek. Given these data, trends in fish movement on Beaver Creek are discussed and records of movement of adults and juveniles for summer steelhead and spring Chinook are used to determine the primary migration season for Beaver Creek.

4.1 Background

Over the period 2004 to 2006, the USGS Columbia River Research Laboratory (USGS-CRRL) monitored fish movement in Beaver Creek. Fish movement was tracked using passive integrated transponder (PIT) tags inserted to the body cavity of captured fish. The work performed during this period included surveys of index reaches, operation of a fish trapping weir in Beaver Creek, and operation of several PIT-tag interrogation systems in Beaver Creek. Findings from the USGS-CRRL studies include reports describing where and when fish were found, how fast they were moving, estimates of physical cues for migration, and the species, age, and size of the fish (Connolly, personal communication 2006).

For this thesis, USGS-CRRL fish movement monitoring data were important for evaluating the effectiveness of upstream fish passage at rock vortex weirs at the Lower Stokes project site. Using actual observations of fish movement, the rock vortex weirs were evaluated to determine if they were facilitating upstream passage of juvenile fish (Chapter 5).

4.2 Natural history of migratory salmonids

Anandromous fish spawn in freshwater and migrate to salt water where they mature and eventually return to freshwater. The downstream migration, rearing behavior, residence time in salt water, and return to fresh water for spawning vary by species (Meehan 1991). These differences in migratory behavior are typically determined by genetics and environmental factors (Meehan 1991). The transition from freshwater to salt water requires physiological changes in fish to adjust to differential salt concentrations between the surrounding environment and their internal circulatory systems (Meehan 1991).

Typical factors that determine times of migration are genetics, temperature, photoperiod, and size (Meehan 1991). Some species of salmon migrate to the ocean soon after emerging from redds. Other species migrate downstream when they reach a certain size, which is influenced by the temperature of their rearing environment (Meehan 1991). Colder streams could delay downstream migration, or smolting, for 1–4 years. Movements downstream and upstream are influenced by avoidance of predators, food supply, and temperature. To avoid predators, newly emerged salmonids primarily move at night in the spring and summer. In general, the size of a particular species of fish will increase as it spends more time in freshwater rearing. Increased size has the added benefit of improving the ability of the fish to avoid predation in the ocean.

For fish that spend the winter in freshwater, their behavior changes from feeding to hiding and conserving energy (Meehan 1991). Fish that are territorial in the summer and congregate together in the winter, seeking pools, brush, interstitial spaces in the substrate, and woody debris for refuge. If space is limited or winter weather is severe, the fish migrate to a larger river system in the fall and early winter.

Upstream migration may be influenced by spawning behavior, improved feeding areas, and better refuge from predators. Similarly, downstream migration can be influenced by these same factors. Juvenile fish move downstream to smolt, seek better food sources, avoid predation, and find better thermal domains. Spawning fish may move downstream to seek

alternate routes, when they encounter an instream barrier, physical or hydraulic (Aarestrup and Lucas 2003).

Many factors determine whether a fish migrates (Meehan 1991). For example, fish may move upstream to seek colder water, suggesting that warm temperatures in the lower part of a stream trigger a fish to move upstream (Meehan 1991). A benefit of moving upstream for a juvenile fish would be improved growth rates. Growth rates for cold water fish cease when exposed to temperatures of 20 ºC or greater, which is attributed to increased metabolic rates at higher temperatures (Bell 1991 and Lang et al. 2004).

For a stream with fish barriers, repopulation of the upstream reach may not be immediate after barrier modification or removal, due to the varying life cycles of anandromous fish, which could be as long as seven years for steelhead trout (Meehan 1991). Also, salmon are known to occupy and adapt to regional disturbances within a watershed, so a reach of stream may not receive fish until a regional disturbance in another part of the watershed forces salmon to seek alternative habitats. Regardless, re-opening a historic reach of stream previously restricted by a man-made barrier provides habitat that can provide enhanced food sources, refuge from predators, and reproduction (Meehan 1991).

4.3 Species of concern in the Methow River basin

4.3.1 Bull trout

Bull trout in the Upper Columbia Distinct Population Segment within the Methow River basin are listed as threatened under the Endangered Species Act (ESA). Four general forms of bull trout are recognized, varying by behavioral or life history pattern: *anandromous, adfluvial, fluvial,* and *stream-resident* (Andonaegui 2000). All forms are considered supported in the Methow River basin, except anandromous. The *adfluvial* form matures in lakes and ascends to tributary streams to spawn. The juveniles remain at the spawning grounds for one to three years. *Fluvial* forms mature in rivers and small tributaries to spawn

and rear. Both *adfluvial* and *fluvial* bull trout make extensive migrations, reach sexual maturity at age five to six, and grow to more than 10 kilograms. *Stream-resident* bull trout remain in headwater tributaries throughout their lives and seldom migrate, growing to about 0.35 m. The diet of juvenile bull trout is aquatic invertebrates, eventually becoming more piscivorous as they mature (Andonaegui 2000).

Bull trout generally prefer cold water, which is generally found in the headwaters of the Methow River basin. They are strongly influenced by temperature for all forms and life stages (Andonaegui 2000). Spawning is highly dependent on temperatures, and typically occurs between mid-September and October. Sites for redds are positively associated with bounded alluvial valley segments with cover for hiding, coarse substrate size, and stream reaches of positive groundwater exchange, or upwelling through the gravel (Andonaegui 2000, Baxter and Hauer 2000). Redds located near groundwater seeps utilize hyporheic exchange to keep the streambed warmer in the winter and cooler in the summer (Baxter and Hauer 2000). Bull trout are especially vulnerable to sediment accumulation during snowmelt or degraded water quality (e.g., post forest fire). After emergence, fry remain in hiding in the gravel for about three weeks. Fry less than 0.10 m mostly remain on the bottom near the margins of fine detritus, near the surface of the substrate. Juveniles typically seek hiding near boulders, large wood debris, pools, or overhanging banks (Andonaegui 2000).

Within the Methow River basin, a limited population of bull trout persists in the Gold and Beaver creeks (Connolly, personal communications 2006). Historically, bull trout were located in the headwaters of Beaver Creek, but they have been extirpated in places, likely due to competition from brook trout (Andonaegui 2000). Bull trout can coexist successfully with salmon and steelhead, as they occupy different niches. The strength of bull trout distributions tends to reflect habitat quality (i.e., a denser distribution of bull trout indicates a more pristine habitat) (Andonaegui 2000).

4.3.2 Spring Chinook

In the Methow River basin, spring Chinook spend one or more years in freshwater, and they are considered "stream-type" versus "ocean-type" salmonids (Andonaegui 2000). They are listed as endangered under the ESA (Northwest Power and Conservation Council 2004). Counts of spring Chinook moving upstream at Wells Dam, on the Columbia River just downstream of the confluence of the Methow River, have declined from historic runs of 3976 fish in 1977 to 191 fish in 1999 (Andonaegui 2000). In addition, according to Chapman et al. (1995), productivity of upper Columbia River spring Chinook has declined by at least 43-percent from the 1950s to the 1980s. Declines in the Methow River basin are attributed industrial development, agriculture, forestry, and private development (Northwest Power and Conservation Council 2004). Given this history, there is concern for extinction of spring Chinook species (Andonaegui 2000).

Adult spring Chinook enter the Methow River from mid-May through July and spawn from late July through September. The eggs remain in the substrate and incubate through the winter. Young fry emerge in April and May and most will migrate out the following spring. During the summer, chinook feed and then transition to seeking pools in the winter. Spring Chinook tend to rear where they spawn, and then disperse into adjacent tributaries. Juvenile spring Chinook have been observed at the mouth of Beaver Creek. Adult Chinook are the largest of Pacific salmon and have been documented to grow to more than 50 kilograms, but are typically about 18 kilograms (Meehan 1991).

4.3.3 Summer steelhead trout and rainbow trout

Summer steelhead trout are named for the timing of their return to freshwater from salt water, from June to September (Meehan 1991). After returning to freshwater, they tend to winter in large rivers and continue their journey to spawning grounds in early spring (February through June). Their life cycles and migration patterns are regionally complex, driven mostly by environmental factors (i.e., stream flow, lunar cycle, temperature, and

photoperiod) and partially by genetics. Wild summer steelhead trout are listed as endangered in the Methow River basin under the ESA and only sustain themselves at threshold population size today (Northwest Power and Conservation Council 2004). Counts of wild steelhead at Wells Dam, just below the mouth of the Methow River, have declined to about 432 wild fish versus 4138 hatchery fish (12-percent) in 1999 (Northwest Power and Conservation Council 2004). The majority of the summer steelhead population is hatchery fish. According to WDFW et al. (1990), from 1982 to 1986, natural summer steelhead represented 3-percent of the total summer steelhead run in the Methow River basin. Stocks today remain hybridized and potential loss of biodiversity of the tributary stocks has not been determined (Andonaegui 2000).

Behavior of summer steelhead is highly dependent on temperature. Specific behaviors, such as time to emergence (incubation), emergence of fry from gravels, and length of time juveniles reside in freshwater before moving downstream, are all highly dependent on temperature. Smoltification of steelhead may take 1–7 years, depending on temperature making them highly dependent on freshwater habitat. They also typically spend three or more years in the ocean maturing before returning inland to spawn (Andonaegui 2000).

Spawning grounds for steelhead trout are difficult to observe, as they spawn during high spring flows with low visibility. Summer steelhead trout have substantial post-spawning mortality, which increases with longer upstream migrations (Meehan 1991).

Concerns for summer steelhead survival include high levels of fine sediments, disturbances to redds by freshets, and maintenance of adequate flows. Survival rates are less than 50-percent from egg to emergent fry, less than 20-percent for their first year, and less than 2-percent for fish that must travel long routes and pass dams (Meehan 1991).

Rainbow trout are steelhead trout that are resident fish, and no longer anandromous (Andonaegui 2000). They can be found above and below barriers in the Methow River Basin. Rainbow trout typically feed on insects and are not especially large when they mature (less than 2 kilograms), relative to summer steelhead. In the juvenile stage, distinguishing

between rainbow trout from steelhead trout is difficult to impossible, as they are technically the same species.

4.3.4 Westslope cutthroat trout

Cutthroat trout are often associated with bull trout, as they are found above and below barriers in the Methow River basin (Meehan 1991). Salmon and steelhead trout are usually restricted to areas downstream of barriers (Meehan 1991). There two life histories of westslope cutthroat trout, migratory and non-migratory (Schmetterling 2001). Cutthroat trout spawn in spring or early summer, usually in small streams, moving through the watershed during high flows. Redds for cutthroat trout are usually near cover or wood debris (Schmetterling 2001). Westslope cutthroat trout mature to an average size of approximately 0.3 to 0.4 m (Schmetterling 2001). Juveniles rear in freshwater streams for two or more years. Some populations remain in the same area for their complete life cycle, while others migrate modest distances (up to 50 km) to lakes, larger rivers, or the ocean. In winter, cutthroat trout reside in pools near cover (Schmetterling 2001).

4.4 Estimated optimum temperatures for migration

In the *Fisheries Handbook of Engineering Requirements and Biological Criteria* (Bell 1991), optimum temperatures for migration and spawning are reported for different species. Preferred temperatures for migration of salmonids are shown in Table 4.1. Temperatures generally preferred by steelhead and Chinook are from 7.2 to 14.4 ºC (Bell 1991). Cutthroat trout prefer a temperature range from 9.4 to 12.8 ºC (Bell 1991). Lethal temperatures for Chinook and steelhead vary from 23.9 to 25.6 ºC (Bell 1991).

Table 4.1. Preferred migration temperatures in ºC (Bell 1991)

Species and life stage	Low ºC	High ºC
Spring Chinook	3.3	13.3
Juvenile Coho	7.2	16.7
Adult Coho	7.2	15.6

4.5 PIT-tag technology

A technology incorporating a passive integrated transponder tag (PIT-tag) was developed to track animal behavior and physiology. Similar marking and tracking systems are used extensively in fisheries and ichthyologic research, as well as for physiological research, game management, food web studies, conservation efforts, and assessment of commercial harvests (Gibbons and Andrews 2004, Connolly et al. 2005).

A PIT-tag is a microchip that is encased in biocompatible glass. The glass serves to protect the electronics and prevent tissue irritation. The tags used in the Methow project were 12 mm, full duplex 134.2 kHz (Connolly, personal communications 2006). The PIT-tag was typically inserted into the body cavity of the fish using a 12-gage needle or by a surgical incision in the skin. Each tag has a microchip preset with a unique alphanumeric code, which is activated when the tagged animal passes through the electromagnetic field generated by a reader or antenna. The chip is passive, permanent, and does not require a power source. A PIT-tag code is comparable to a bar code on a commercial product, or to microchips that are inserted into house pets to aid in their recovery.

The unique code on a PIT-tag identifies an individual within the population, which enables a wide variety of field studies. Recapture and repeated measurements on individuals provide a wealth of information, such as growth rates, health changes, and movement. With respect to this thesis, PIT-tags and the reader system provided information on movement of individual juvenile and adult fish within Beaver Creek and the Methow River basin. In particular, this study focused on movements near the sites of interest, fish barriers, and installed rock vortex weirs. Additional information provided by the PIT-tag readings in the Methow River basin

included fish species, life stage, growth, weight, point of origin (hatchery versus wild, river tributary), and movement within the Columbia River basin.

The technology of PIT-tags and their detection networks provide higher reliability in data collection than other methods. Conventional exterior markings, for example, can wear away, which leads to misread codes or markings (Gibbons and Andrews 2004). The biggest limitation of PIT-tag readers is that their typical detection range is only 0.3 m. However, with innovative designs and multiple lateral antennas, very high detection efficiencies of over 90-percent were reported by Connolly et al. (2005) for PIT-tagged fish.

The data collected in the Methow River basin by PIT-tag readers were coordinated with other fish tracking efforts in the Columbia River basin. The frequencies of the PIT-tags and the reader frequencies for the Methow River project were each selected to match the frequencies used by other readers in the Columbia River basin. With the cooperative effort and effective detection systems in place, the migratory history of an individual anandromous fish, PIT-tagged in the Methow River basin, could be monitored from the headwaters, down the Methow River, in the dams on the Columbia River, to the estuary (where a surface pair-trawl deployment is towed), and to the ocean (NMFS 2004). Also, fish PIT-tagged elsewhere in the Columbia River basin could be detected in the Methow River basin. Data on fish movement were collected—and continue to be collected—on a shared internet data base called PTAGIS, which was established as a depository for fish movement within the Columbia River basin The PTAGIS data base is maintained by the Pacific States Marine Fisheries Commission (PSMFC). Data collected and added to PTAGIS are critical to the continuing efforts to document upstream and downstream migration and fish passage within the Methow River basin and the Columbia River basin, past dams, fish ladders, and other instream challenges to migrating fish.

4.6 USGS-CRRL Methods

The USGS-CRRL installed and maintained four PIT-tag readers and one fish weir along Beaver Creek that measured fish movements above and below the Lower Stokes project site (Figure 4.1). Additional PIT-tag readers and index reaches for fish surveys (Figure 4.1) were located farther upstream in Beaver Creek. Detailed descriptions of the Beaver Creek installations follow.

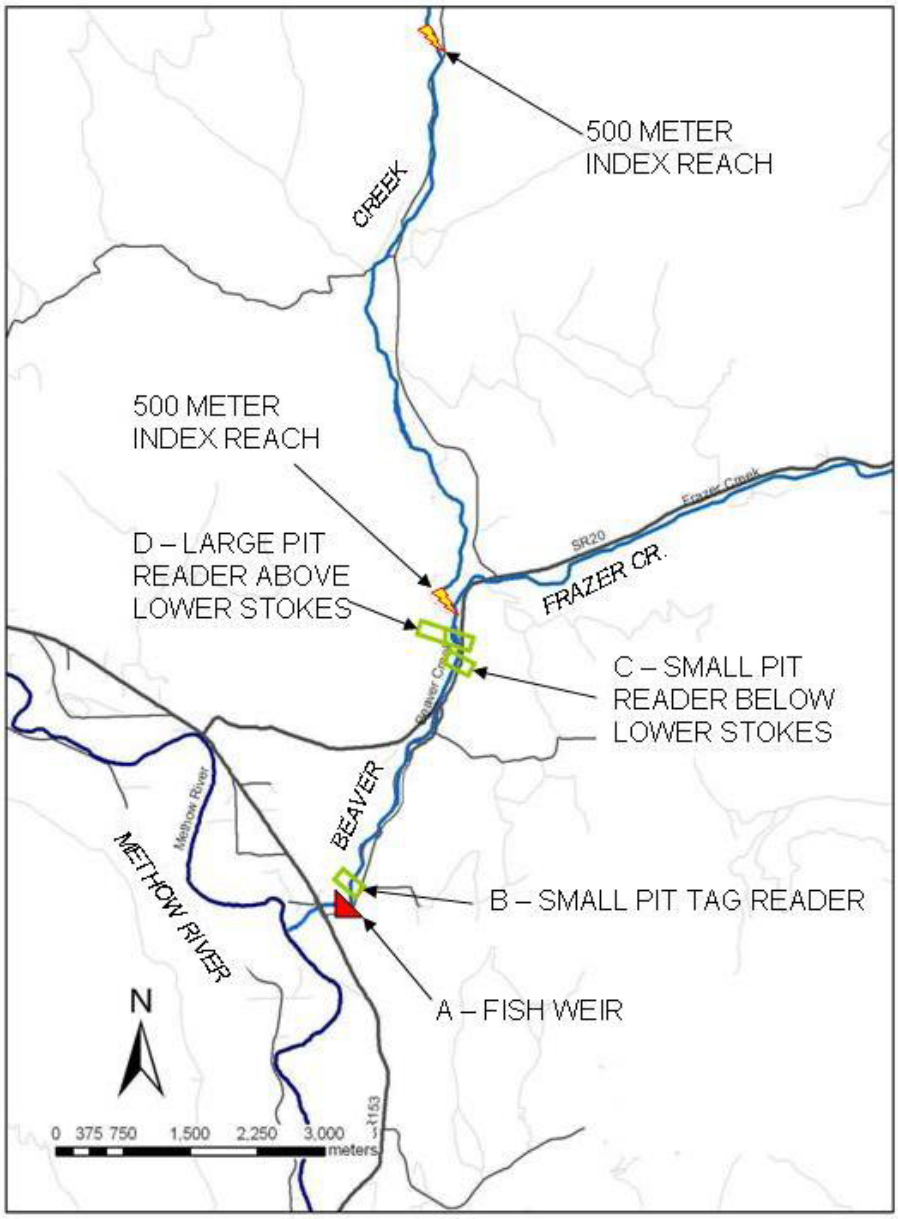


Figure 4.1. Location of USGS-CRRL PIT-tag readers and monitoring weirs in Methow River basin.

4.6.1 USGS-CRRL index reaches and PIT-tagging

The USGS-CRRL conducted multiple pass-removal electrofishing on three 500-meter sites in Beaver Creek (Figure 4.1). The sites were selected from geomorphic analysis (Chapter 2). During index reach surveys and at the fish weirs, fish were captured and PIT-tags were inserted in the body cavities of fish not previously tagged. Most fish greater than 0.07 m (7 centimeters), age-1 or older, were tagged with PIT-tags and released back into the habitat units in which they were captured. At the time of PIT-tagging, the captured fish were weighed, measured for length, sampled for genetics, and identified by species (Figure 4.2). PIT-tags were checked for operation and the unique PIT-tag ID number was entered into a USGS-CRRL database. Total counts of fish PIT-tagged by the USGS-CRRL in the Beaver Creek basin are shown in Table 4.2.

Table 4.2. Counts of fish marked with PIT-tags by USGS-CRRL in Beaver Creek

Year	Rainbow trout/ steelhead	Brook trout	Cutthroat trout	Chinook	Bull trout	Coho	Total Beaver Creek
2004	1,140	112	1	73	1	0	1,327
2005	2,160	200	4	192	12	16	2,584

4.6.2 USGS-CRRL fish weir on lower Beaver Creek

The USGS-CRRL installed a fish weir in October 2004 on a private residence in Lower Beaver Creek, about 3.0 km upstream of the mouth of Beaver Creek and about 2.0 km below the Lower Stokes project site. The fish weir operated with high efficiency by catching almost all fish moving upstream and downstream (Site A in Figure 4.1). Upstream migrants were attracted to a compartment sealed with heavy-duty plastic strips that allowed entrance and deterred exit. Downstream migrants were funneled into a 0.25-m pipe and captured at a separate compartment designated at the downstream cage. The stream channel was sealed off with a series of sliding pickets that conformed to the stream bottom (Figure 4.3).

Figure 4.2. PIT-tag installation and typical measurements by USGS-CRRL.

Figure 4.3. Fish weir on Beaver Creek installed and maintained by the USGS-CRRL.

On a daily basis, the fish weir was cleaned and checked for fish. If fish were caught in the cages, they were checked for PIT-tags (or tagged with a new PIT-tag if necessary), weighed, measured for fork length, sampled for genetics (as needed), and released in the direction they were heading. The two-way fish weir trapped juvenile as well as adult fish. Data from the fish caught in the weir were essential to tracking fish movement near the installed rock vortex weirs.

During the winter, the fish weir on Beaver Creek was removed to prevent damage from ice and snow. The fish weir was removed from December 2004 until March 2005 and from December 2005 until March 2006. In addition, during high flows in spring 2004 and 2005, the fish weir was temporarily dislodged and reset within several days to weeks.

4.6.3 Small PIT- tag readers

A small PIT-tag reader consists of an antenna window about 1.2 by 0.6 m (4 by 2 foot) that was energized by battery power and connected to a recording device (Figure 4.4). The PIT-tag reader was a Biomark FS2001F-ISO with a custom antenna built by USGS-CRRL personnel in Cook, Washington. Whenever a fish with a PIT-tag crossed the window, it sent out a signal that was picked up by the reader and logged into a data recorder. The reader was inspected periodically to download recorded data, change batteries, and secure the device. The efficiency of tracking fish was limited by the partial spanning of the active channel and the detection range of the antenna. Also, during high flow events, the antennas were prone to damage or dislodgement. Such damage to the antennas required maintenance and repair by USGS-CRRL personnel.

Locations of the small PIT-tag readers on Beaver Creek were above the fish weir and about 20 m below the rock vortex weirs at Lower Stokes, identified as Sites B and C in Figure 4.1. Another small PIT-tag reader was located about 7 km upstream of the fish weir on Beaver Creek (not shown in Figure 4.1).

Figure 4.4. Typical USGS-CRRL small PIT-tag reader and data logger.

4.6.4 Large PIT-tag reader

A larger, more complex array of antennas, described as the "large PIT-tag reader", was located at Site D; about 100 m upstream of the rock vortex weirs at the Lower Stokes project site (Figure 4.1). The large PIT-tag reader was installed in October 2004 by Earl Prentice of NOAA Fisheries with assistance from USGS-CRRL personnel. The large PIT-tag reader included six energized antennas connected to a Biomark FS-1001m PIT-tag reader that downloaded data directly into a personal digital assistant. The antennas detected PIT-tagged fish at a distance of 0.15 m or more. The antennas were in an array of six, measuring about 1 by 2 m (3 by 6 feet) each. They were installed to the bed of the channel in three pairs, with spacing at about 10 m between each pair (Figure 4.5). Some of the antennas, called "hybrids", were secured at the upstream end and free at the downstream end to facilitate a floating antenna window, which improved the detection of tagged fish in higher flows. Since multiple antennas spanned the entire channel and provided a floating window, the detection efficiency of the large PIT-tag reader was higher than that of the small PIT-tag readers. In addition, because the antennas were close together, detection records at Site D indicated whether a fish was moving downstream or upstream and the rate that it moved.

4.7 Upstream migration detected on Beaver Creek

About 590 fish were detected at the USGS-CRRL system of readers between deployment on 27 September 2004 and end of operation on 22 November 2005 (Table 4.3). The data in Table 4.3 include upstream and downstream movements across the readers.

A summary of upstream fish migrations from the USGS-CRRL is provided in Table 4.4. Data include the unique PIT-tag number for each fish, species, size, and the movement history of the fish by date, time, and direction. The PIT-tag reader Sites B through D are shown in Figure 4.1. A code for location "X" indicates that a fish originated some location outside of the Beaver Creek system, such as one fish that originated from outside Beaver Creek, traveling from Winthrop, Washington, down the Methow River, past the rock vortex weirs at the Lower Stokes project site, and past the large PIT-tag reader at Site D.

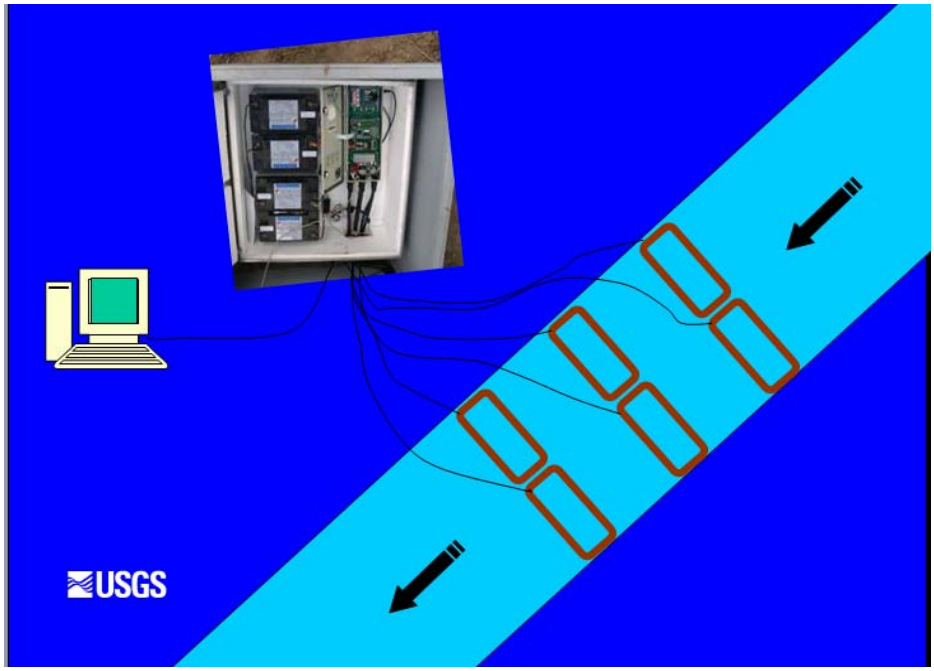


Figure 4.5. Large PIT-tag reader installed and maintained by the USGS-CRRL.

Table 4.3. Total number of fish detected at PIT-tag readers in Beaver Creek.

Location in Beaver Creek	Reader ID	Type of reader *	Date of installation	Total # fish detected
Below South Fork	Site E	small	10/10/2005	3
Above Lower Stokes	Site D	large	9/27/2004	216
Below Lower Stokes	Site C	small	10/6/2005	32
Above fish weir	Site B	small	10/21/2004	339
			Subtotal	590

* Small PIT-tag readers have one antenna and large PIT-tag readers have 6 antennas.

** Data provided courtesy of USGS-CRRL, unpublished data.

A total of 21 rainbow trout / juvenile steelhead, 4 juvenile brook trout, and 4 adult steelhead were detected moving upstream in the Beaver Creek system. These PIT-tag readers indicated these 21 fish successfully passed the rock vortex weirs at Lower Stokes and the double rock vortex weirs at Fort-Thurlow (about 2 km downstream of the Lower Stokes project site and 1 km upstream of the fish weir). The data for rainbow trout and juvenile steelhead were combined, because it was difficult to distinguish between them, as they are the same species. The life history form of these fish could be apparent through genetic testing or by recapture when the fish matures.

Fish movement data are shown in Table 4.4 are plotted in Figure 4.6. All fish movements shown in Figure 4.6 are typically movements from the fish weir (Site A, creek km 1.4) to the PIT-tag reader past the rock vortex weirs (Site D, creek km 4.5), with some minor exceptions (two fish from Site B to Site D, three fish from Site C to Site D). These exceptions could be attributed to partial coverage of the channel by the small PIT-tag reader or fish that squeezed through the pickets of the fish weir and avoided capture and detection. Each horizontal bar shown in Figure 4.6 represents the approximate travel time from Site A to Site D, which varied from 1.2 to 147.0 days (Appendix G). Juveniles typically took longer than adults to move from Site A to Site D.

Table 4.4. Fish detected in Beaver Creek by USGS-CRRL PIT-tag reader network. Sites A, B, C, and D are the fish weir, above the fish weir, below Lower Stokes, and above Lower Stokes, respectively. Stokes is the index reach above the Lower Stokes project site.

				Date and time of detection				
Fish	Length at tagging (mm)	Location of tagging	Date at tagging	Downstream Site A	Site B	Site C	Upstream Site D	Detection locations
Juvenile Steelhead / rainbow trout								
3D9.1BF20A0E70	77	A	4/25/2005	4/25/2005	6/27/2005		6/30/2005 13:04	ABD
3D9.1BF2022650	79	Winthrop	4/22/2005				6/13/2005 4:58	XD
3D9.1BF20A42A3	90	A	4/19/2005	4/19/2005			7/6/2005 7:06	AD
3D9.1BF20A5D2F	107	A	4/13/2005	4/13/2005			5/7/2005 20:53	AD
3D9.1BF20A60B9	123	A	5/26/2005	5/26/2005	5/29/2005		6/25/2005 22:34	ABD
3D9.1BF20BC05E	98	D	5/26/2005		6/16/2005		7/5/2005 21:08	BD
3D9.257C5AB943	125	A	6/27/2005	6/27/2005	6/27/2005		7/1/2005 21:03	ABD
3D9.257C5AEF43	142	A	6/26/2005	6/26/2005			6/30/2005 3:31	AD
3D9.257C5AFAFA	109	A	6/21/2005	6/21/2005	6/21/2005		7/2/2005 20:01	ABD
3D9.257C5B20D4	138	Stokes	6/7/2005			10/8/2005 20:19	10/8/2005 22:39	CD
3D9.257C5CCB7D	117	A	6/21/2005	6/21/2005			7/2/2005 22:23	AD
3D9.257C5D529A	134	A	6/4/2005	6/4/2005	6/4/2005		6/21/2005 4:23	ABD
3D9.257C5D56E8	117	A	6/3/2005	6/3/2005	6/3/2005		7/2/2005 4:36	ABD
3D9.257C5D5E9E	123	A	6/20/2005	6/20/2005			6/25/2005 20:55	AD
3D9.257C5D5F8F	114	A	6/21/2005	6/21/2005	6/21/2005		7/1/2005 21:25	ABD
3D9.257C5D6ABD	136	A	6/27/2005	6/27/2005	6/27/2005		11/21/2005 7:58	ABD
3D9.257C5D862C	123	A	6/18/2005	6/18/2005			6/30/2005 21:39	AD
3D9.257C5DD234	123	A	6/20/2005	6/20/2005	6/20/2005		6/29/2005 0:32	ABD
3D9.257C5DD34E	121	A	6/26/2005	6/26/2005			7/2/2005 14:10	AD
3D9.257C5F5FFE	146	A	7/26/2005	7/26/2005		12/22/2005 17:30	3/31/2006 16:57	ACD
3D9.1BF20A4F65	93	Stokes	4/13/2005			3/8/2006 12:42	4/11/2006 16:01	CD
Brook trout								
3D9.1BF20A47BD	97	A	4/23/2005	4/23/2005	5/3/2005		6/1/2005 22:04	ABD
3D9.1BF20A6CF3	87	Stokes	10/21/2004			10/9/2005 20:39	10/10/2005 5:42	CD
3D9.1BF20B842C		A	3/25/2005	3/25/2005			5/28/2005 2:33	AD
3D9.1BF20BCF2D	119	Stokes	4/13/2005		5/30/2005		6/22/2005 21:22	BD
Adult steelhead								
3D9.1BF15F6E8D	103	Twisp R	5/1/2003		4/7/2005		4/25/2005 9:10	XBD
3D9.1BF1FD915A	637	Weir	5/17/2005	5/17/2005	4/17/2005		4/25/2005 18:18	ABD
3D9.1BF1FDD67F	460	Weir	4/5/2005	4/5/2005	4/23/2005		4/25/2005 14:41	ABD
3D9.1BF1FDDF4F	680	Weir	4/24/2005	4/24/2005	4/25/2005		4/26/2005 7:18	ABD

Data provided courtesy of USGS-CRRL and is provisional and unpublished.

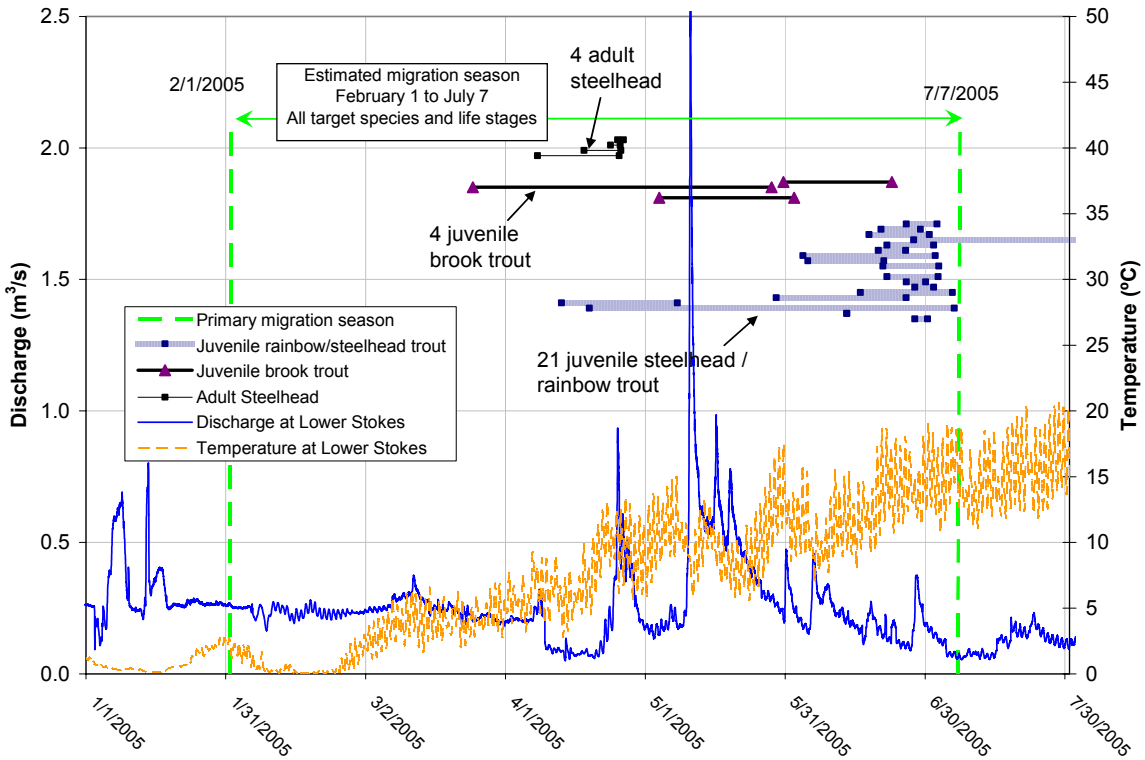


Figure 4.6. Upstream fish movement detected in Beaver Creek from USGS-CRRL combined with estimated discharge at the Lower Stokes project site. From left to right, horizontal bars typically indicate upstream fish movement, from detection time at the fish weir (Site A) or small PIT-tag reader (Site B), to detection time approximately 3 km upstream, about 100 m upstream the rock vortex weirs at Lower Stokes (Site D). Annual migration season estimated from empirical data of fish movement from the USGS-CRRL. Discharge at Lower Stokes estimated from time series of water stage data (from pressure transducers) and rating curves developed from field measurements. Temperature measured by pressure transducer at Lower Stokes.

Adult steelhead moved upstream past the Lower Stokes rock vortex weirs in late April 2005, and the juveniles moved in a cluster from early June to early July 2005 (Figure 4.6). The fastest juvenile fish movement over the rock vortex weirs at Lower Stokes was approximately 2 hours and 20 minutes, according to information from PIT-tag readers at Sites C and D, located directly below and above the rock vortex weirs at Lower Stokes. The

fastest upstream movement by an adult steelhead was a fish that swam from the fish weir (Site A) past Lower Stokes (Site D) in 1.2 days, a distance of approximately 3.2 km.

Additional information on fish movement and detection equipment will be published in an upcoming report and journal article from the USGS-CRRL. The USGS-CRRL will include population estimates and detection efficiencies for the PIT-tag readers in the final reports for the project, as well as additional fish movement records (Connolly, personal communication 2006).

4.8 Discussion

Four adult steelhead moved upstream past the rock vortex weirs in late April 2005 (Figure 4.6), slightly earlier than indicated by Andonaegui (2000), which estimated migration in May to June (early spring). Adult steelhead apparently were triggered to move upstream based on high stream flows, which was suggested by Stuart (1962), who described adult salmonids waiting for optimum high flow conditions to pass obstacles. The adults may have also been swimming upstream to spawn, based on stream temperatures in the range of 3.9 to 9.4 ºC (Table 4.1, Bell 1991) and/or in response to a high flow event in late April.

A total of 19 juvenile steelhead / rainbow trout were detected at Site D, upstream of the rock vortex weirs just after a short flow event that peaked at 0.38 m^3/s on June 28, 2005 (Figure 4.6). This movement of juvenile steelhead / rainbow trout seems to concur with findings from Stuart (1962), which suggested that juvenile fish move upstream past instream barriers during the falling limb of a flood hydrograph. Another possible explanation for the cluster of upstream movement by the rainbow trout / juvenile steelhead was increasing water temperature. According to Bell (1991), the preferred temperature range for steelhead is 7.2 to 14.4 ºC. In late April 2005, the temperature in Beaver Creek was climbing above the preferred range for steelhead, thereby potentially motivating them to move upstream, past the rock vortex weirs, to seek cooler water (Figure 4.6).

A few juvenile steelhead / rainbow trout lingered in the creek and moved at times different from the rest of the group (Figure 4.6). These fish were treated as outliers and were possibly resident rainbow trout that did not respond to the same cues as steelhead.

In addition, four brook trout were detected moving upstream past the rock vortex weirs (Figure 4.6). These fish are an introduced species and not target species for this study, but could be important for further studies on potential negative impacts to native species.

Based on empirical data for upstream fish movements in Beaver Creek, as described above, a primary migration season for adult and juvenile stages of summer steelhead and spring Chinook was considered to be from *February 1 until July 7* each year (Figure 4.6, Connolly, personal communications 2006). The time frame for the primary migration season was important for limiting hydrologic analysis of flow data. According to WDFW (2003), development of the low and high design flows, which define the window for fish passage compliance, should only be developed based on average daily flow data during migration season (Chapter 2).

Data collection for fish movement by the USGS-CRRL is continuing for the Methow River project (Connolly, personal communications 2006). These data are important, as the life cycle of steelhead could be as long as seven years, including rearing, smolting to the ocean, and spawning back to natal areas as mature adults. Extended monitoring by a PIT-tag reader network will provide important information as to whether spawning grounds were opened up above the rock vortex weirs, and whether the young fry successfully return to their rearing areas as adults.

Tagging and tracking fish using PIT-tags and antennas was an effective means to measure fish movement (Connolly et al. 2005). Use of PIT-tags are advantageous since they are placed internally, have longevity in the body cavity of the fish, are effective in hot and cold, and preserve the behavioral aspects of animals (predation, swim speed). Also, the PIT-tag readers are portable and adaptable for installation in natural streams, without requiring a rigid structure (e.g., a bridge or a culvert). The main consideration in PIT-tag reader design

is the requirement that the reader be in close proximity to the fish (0.2 to 0.3 m). Innovative designs from the NOAA fisheries and the USGS-CRRL of "hybrid" PIT-tag antennas, custom PIT-tag antenna arrays, and advanced instrumentation for data collection were fundamental to success of tracking upstream fish movement for this thesis.

5. SYNTHESIS OF MODELED HYDRAULIC CONDITIONS AND FISH MOVEMENT ANALYSIS

In this chapter, calculated hydraulic parameters for fish passage (Chapter 3) are revisited and combined with fish movement data (Chapter 4). Using hydraulic conditions at the rock vortex weirs and detection times of fish, fish passage at the rock vortex weirs was evaluated based on guidelines from NMFS (2000) and WDFW (2003) for fish passage at culverts.

The hydraulic parameters that were combined with USGS-CRRL fish movement data included hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation within weir pools, and average velocity on the rock vortex weir crest. Using these modeled parameters, the effectiveness of rock vortex weirs for fish passage was evaluated and quantified on a scale from A to F by calculating percent of time over the migration season that hydraulic parameters for fish passage met fish passage guidelines for culverts set by NMFS (2000) and WDFW (2003). In addition, sensitivity analysis was performed on discharge measurements to determine the effect of flow measurement accuracy on hydraulic parameter calculations. Based on the results from hydraulic models and weir performance during fish passage, design improvements are suggested for rock vortex weirs for upstream fish passage.

5.1 Summary of fish passage guidelines from NMFS (2000) and WDFW (2003)

Guidelines for fish passage at culverts were used in this thesis to evaluate effectiveness at rock vortex weirs (Appendix A). These data were based on a review of design guidelines from two manuals addressing fish passage at road culverts and communications with WDFW personnel (NMFS 2000, WDWF 2003, and Klavas, personal communications 2006). In place of regulations or design guidelines for rock vortex weirs, these guidelines for culverts were used as criteria for evaluating fish passage effectiveness at the rock vortex weirs.

In WDFW (2003) the "hydraulic design option" for roughened channels was chosen as a template for evaluating the rock vortex weirs. For the hydraulic design option, the structure must be compliant with fish regulations between the 95-percent (Q_{low}) and 10-percent (Q_{fp}) exceedance flows, as applicable to target species and time of year the species migrate. Q_{fp} was further refined to a 5-percent exceedance flow, according to NMFS regional guidelines (Lang et al. 2004), and to satisfy that 90-percent of flows will pass fish (WDFW 2003).

To develop percent exceedance, the annual primary upstream migration period was required as well records of average daily flow (Chapter 2). For the two main species of concern, spring Chinook and summer steelhead, the critical migration period in Beaver Creek for all life stages was consider to be from February 1 to July 7, based on records of fish movement (Chapter 4).

Regarding hydraulic parameters for fish passage, four criteria were selected to evaluate fish passage effectiveness. These criteria, derived from the NMFS (2000) and WDFW (2003) guidelines, should be met during migration season or between the regulatory flows Q_{low} and Q_{fp}, 0.1 and 3.5 m^3/s (Chapter 2). The four criteria used to evaluate fish passage effectiveness at rock vortex weirs, as discussed in Appendix A, were:

- Maximum hydraulic drop of 0.24 m (0.8 feet) (WDFW 2003 and McLaughlin, personal communications, 2006)
- Minimum ratio of pool depth to hydraulic drop of 1.5 (NMFS 2000)
- Maximum energy dissipation factor of 250 W/m^3 (5 ft-lb/s-m^3) (Chapter 3, Equation (3.15)) to quantify turbulences in the weir pool, within 3 m longitudinally downstream of the weir crest (WDFW 2003 and Klavas, personal communications 2006)
- Maximum average cross section velocity of 0.37 m/s (1.2 ft/s) at the rock vortex weir crest (WDFW 2003)

5.2 Synthesis of hydraulic parameters and fish movement

A total of 19 juvenile steelhead (or rainbow trout[1]), four adult steelhead, and four resident brook trout were detected moving upstream past the rock vortex weirs at Lower Stokes during the 2005 migration season, between February 1 and July 7. Fish were detected at a fish weir and PIT-tag readers installed by the USGS-CRRL, located at Sites A, B, or C and subsequent detection at Site D, upstream of the weirs (Chapter 4, Figure 4.1, Figure 4.6, Table 4.4, and Appendix G). Fish were typically detected first at Site A (fish weir) or Site B (small PIT-tag reader just upstream of the fish weir) and then detected upstream at Site D (large PIT-tag reader), indicating that the fish had passed the rock vortex weirs at Lower Stokes, located about 100 m downstream of the large PIT-tag reader at Site D.

To describe site specific conditions during upstream fish passage of individual fish, time series were estimated for four hydraulic parameters (Chapter 3) and combined with fish movement data from the USGS-CRRL (Chapter 4). Individual fish movements were compared to continuous time series of hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation factor (EDF), and average velocity at the weir crest, calculated from the four-mode hydraulic model (Figure 5.1 to 5.4). In addition, the flow hydrograph at Lower Stokes and the high and low flows for fish passage (Q_{fp} and Q_{low}) were combined with the hydraulic parameters and fish movements to indicate when fish passage guidelines from NMFS (2000) and WDFW (2003) should be met (Figures 5.1 to 5.4).

Records of fish movement from the USGS-CRRL reflect a relatively continuous operation of the fish weir at Site A and the PIT-tag readers at Sites B, C, and D, with a short window in May 2005 of non-operation for maintenance. Some PIT-tagged fish were possibly undetected at the PIT-tag readers during that time.

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[1] Rainbow trout are essentially the stream-resident (non-anandromous) form of steelhead. Therefore, records of juvenile steelhead and rainbow trout are combined.

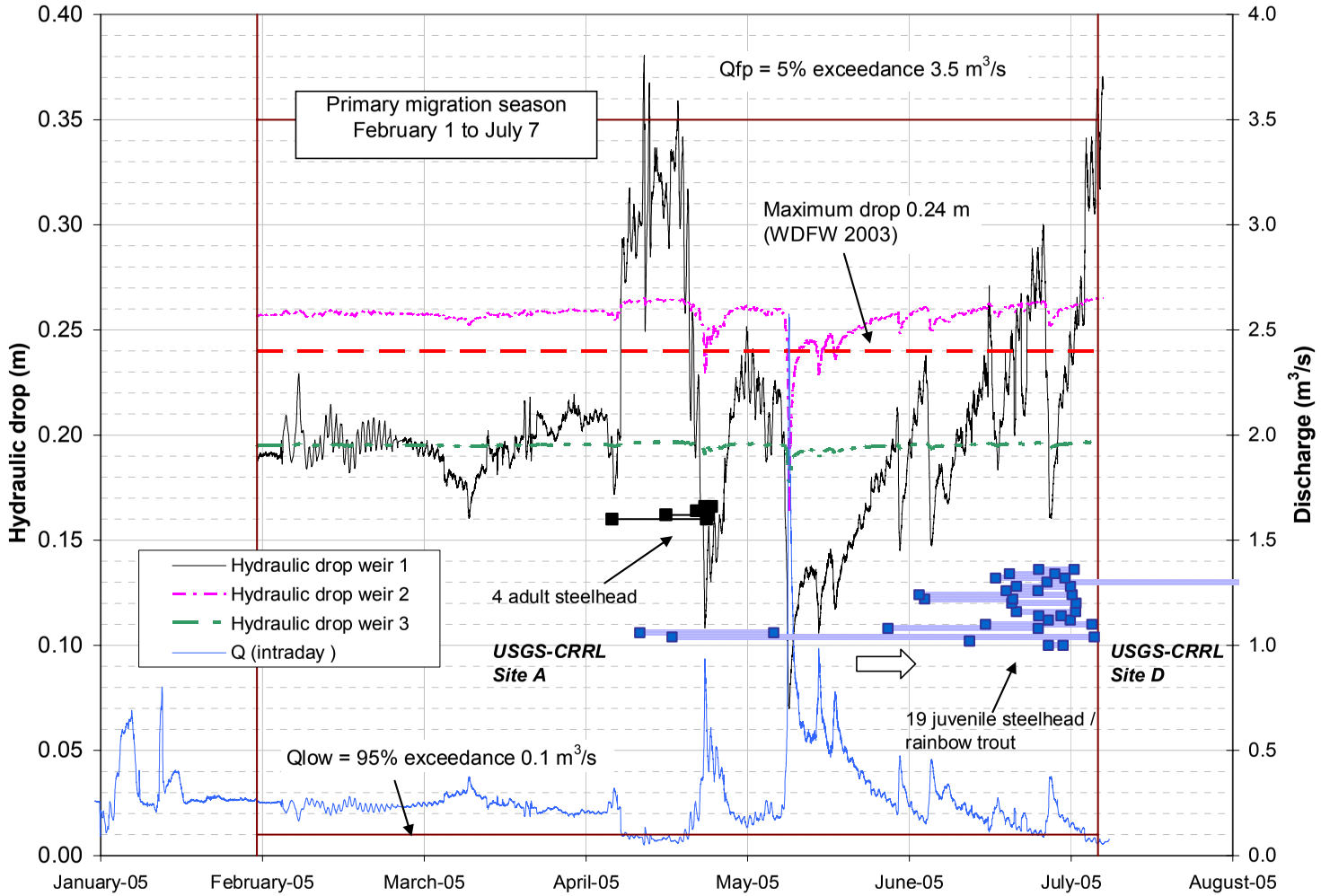


Figure 5.1. Comparison of fish movement to estimated hydraulic drop at rock vortex weirs at Lower Stokes during 2005 primary migration season. Upstream fish movement from USGS-CRRL combined with modeled time series of hydraulic drop. Horizontal bars for fish movement from left to right indicate detection time downstream (Site A or Site B) to detection time upstream, above the rock vortex weirs at Lower Stokes (Site D).

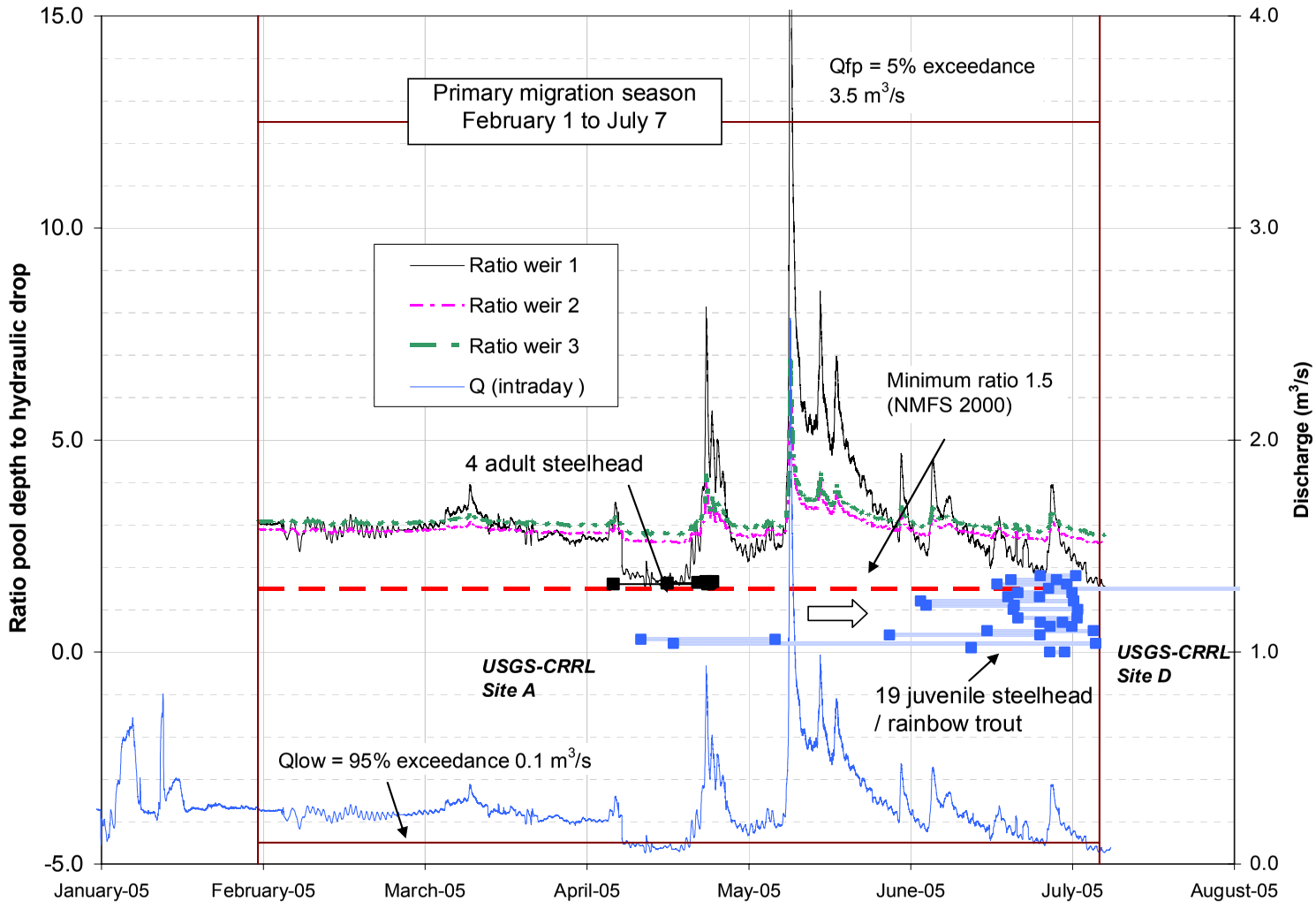


Figure 5.2. Comparison of fish movement to estimated ratio of pool depth to hydraulic drop at rock vortex weirs at Lower Stokes during 2005 primary migration season. See Figure 5.1 for an explanation of symbols.

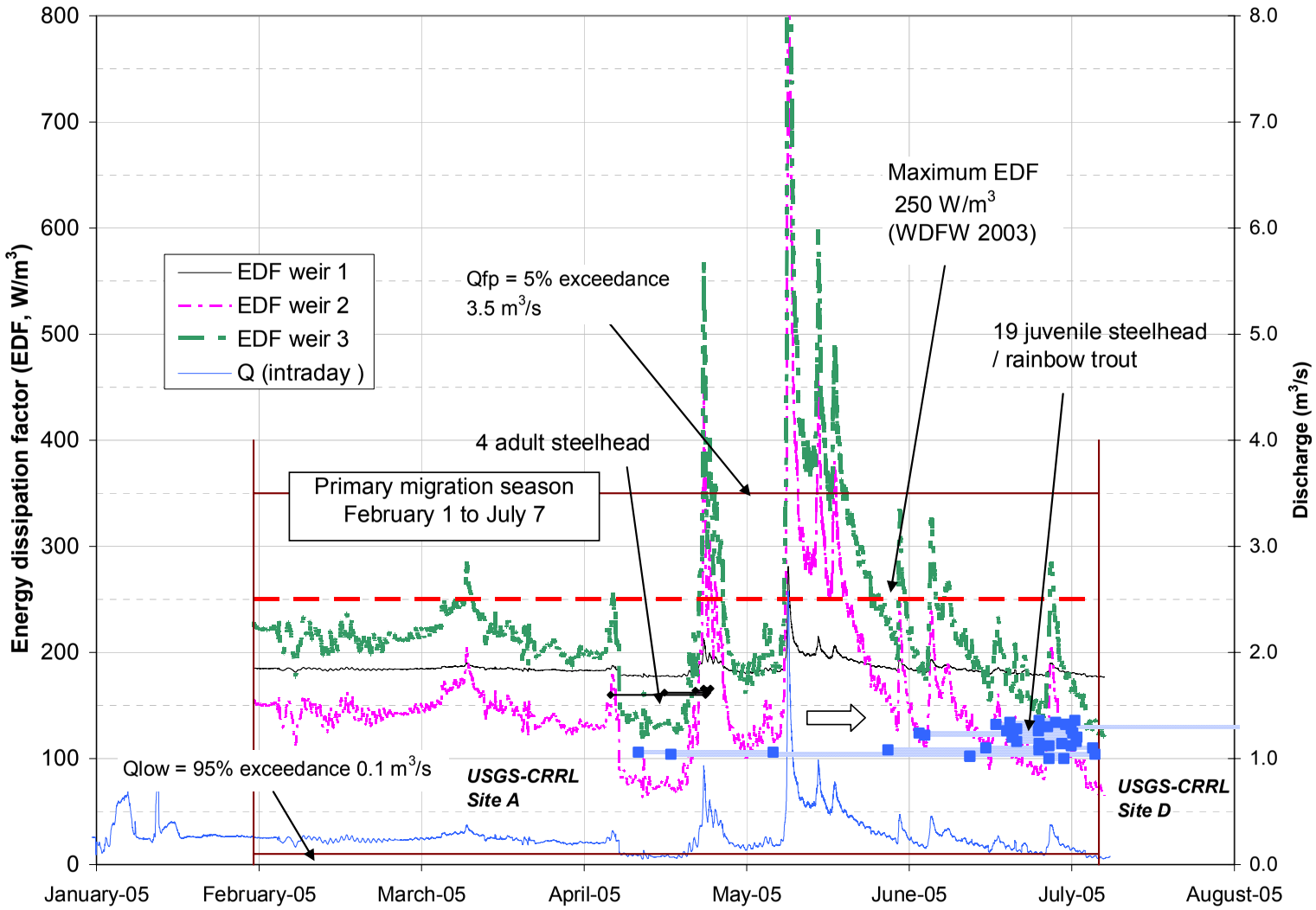


Figure 5.3. Comparison of fish movement to estimated energy dissipation factor at rock vortex weirs at Lower Stokes during 2005 primary migration season. See Figure 5.1 for an explanation of symbols.

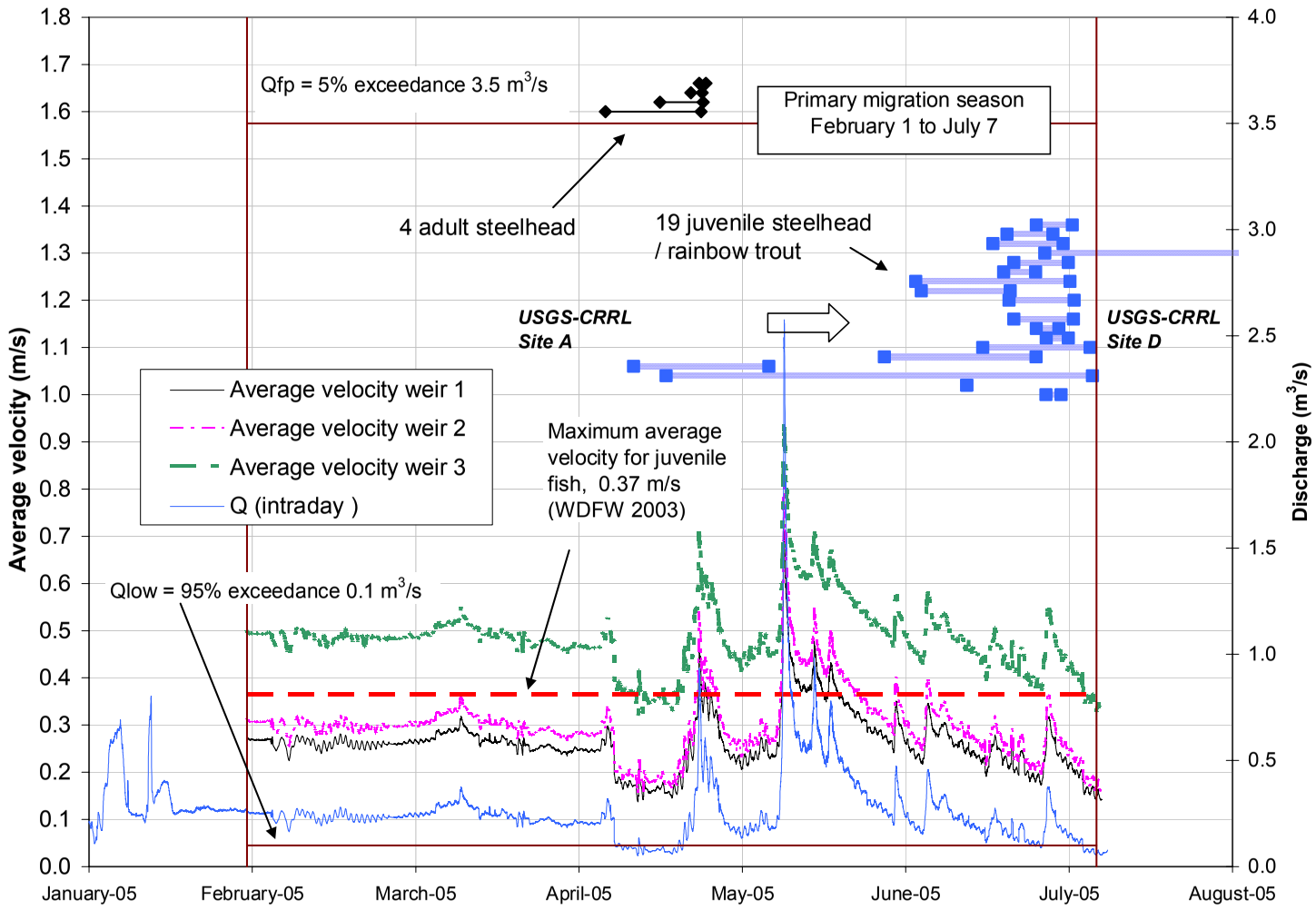


Figure 5.4. Comparison of fish movement to estimated average velocity at rock vortex weirs at Lower Stokes during 2005 primary migration season. See Figure 5.1 for an explanation of symbols.

Estimates of hydraulic parameters were also developed at the Thurlow and Upper Stokes project sites (Chapter 3, Figures 5.5 to 5.8). Fish passage data were not available for the weirs at Thurlow and Upper Stokes. Estimates of hydraulic parameters during the migration season were evaluated to determine potential upstream fish passage at rock vortex weirs at Thurlow and Upper Stokes. Similar to Figures 5.1 to 5.4, the data for hydraulic parameters were plotted with hydrograph data and the upper and lower limits of fish passage flows. This facilitates an evaluation of hydraulic parameters during the migration season in comparison to culvert fish passage guidelines from NMFS (2000) and WDFW (2003).

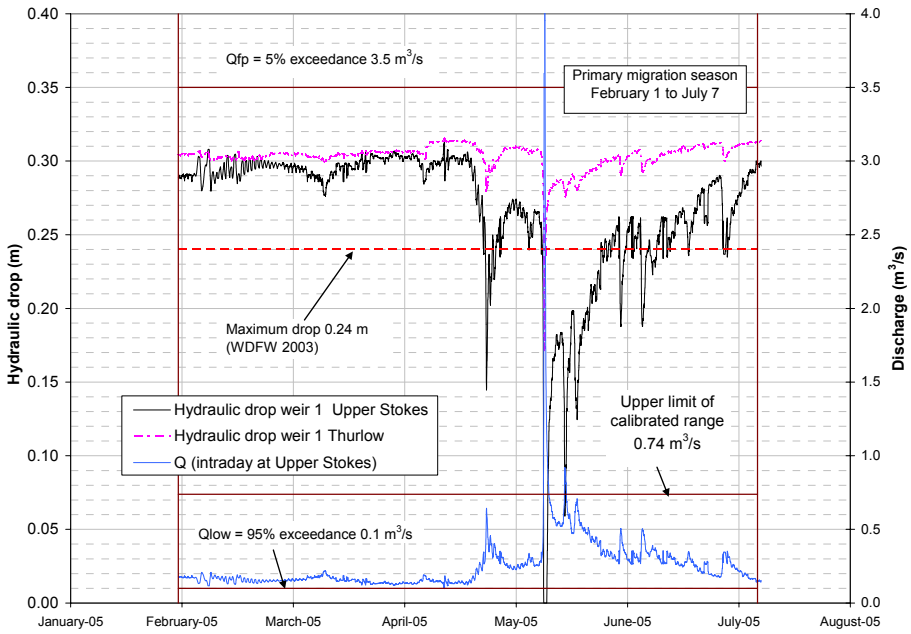


Figure 5.5. Estimated hydraulic drop during 2005 primary migration season at Thurlow and Upper Stokes. No fish movement data available. Data combined with hydrograph in Beaver Creek and upper and lower bounds for upstream fish passage, developed according to guidelines from the National Marine Fisheries Service and the Washington Department of Fish and Wildlife.

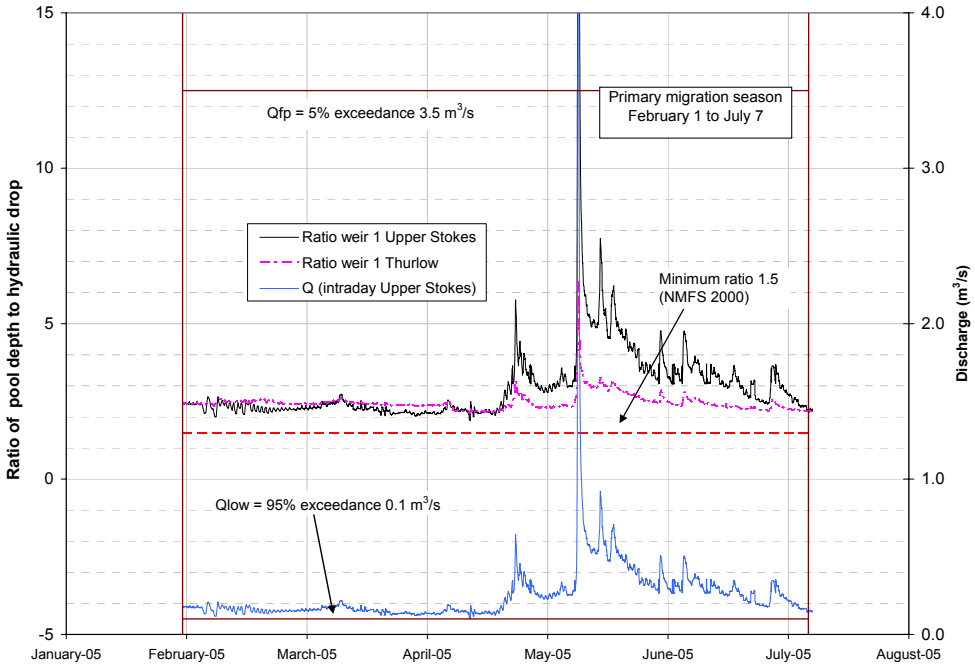


Figure 5.6. Estimated ratio of pool depth to hydraulic drop at Thurlow and Upper Stokes during 2005 primary migration season. No fish movement data available. See Figure 5.5 for an explanation of symbols.

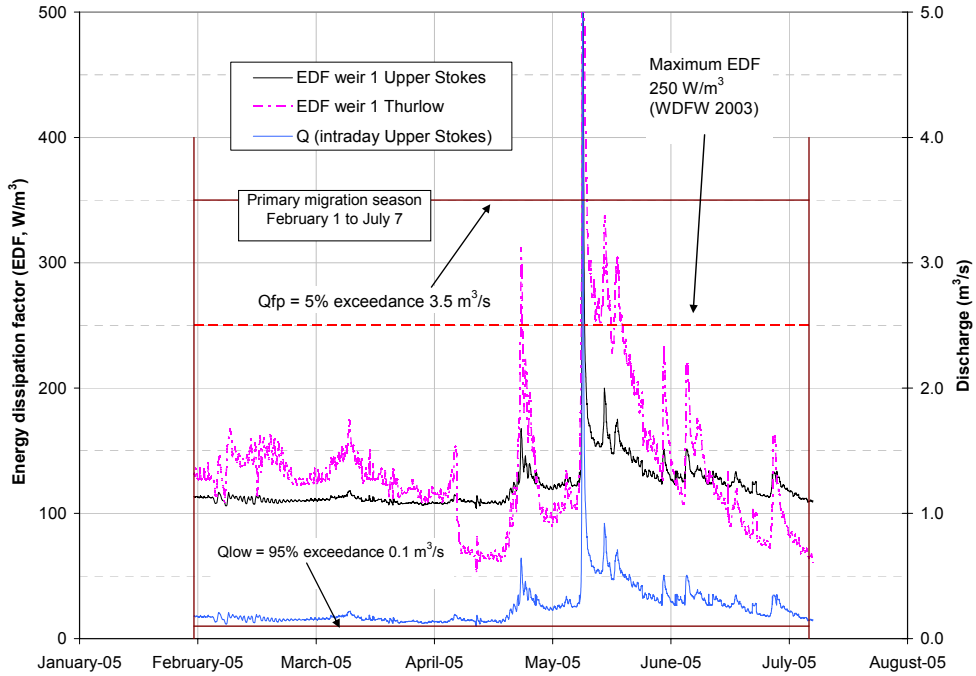


Figure 5.7. Estimated energy dissipation factor at Thurlow and Upper Stokes during 2005 primary migration season. No fish movement data available. See Figure 5.5 for an explanation of symbols.

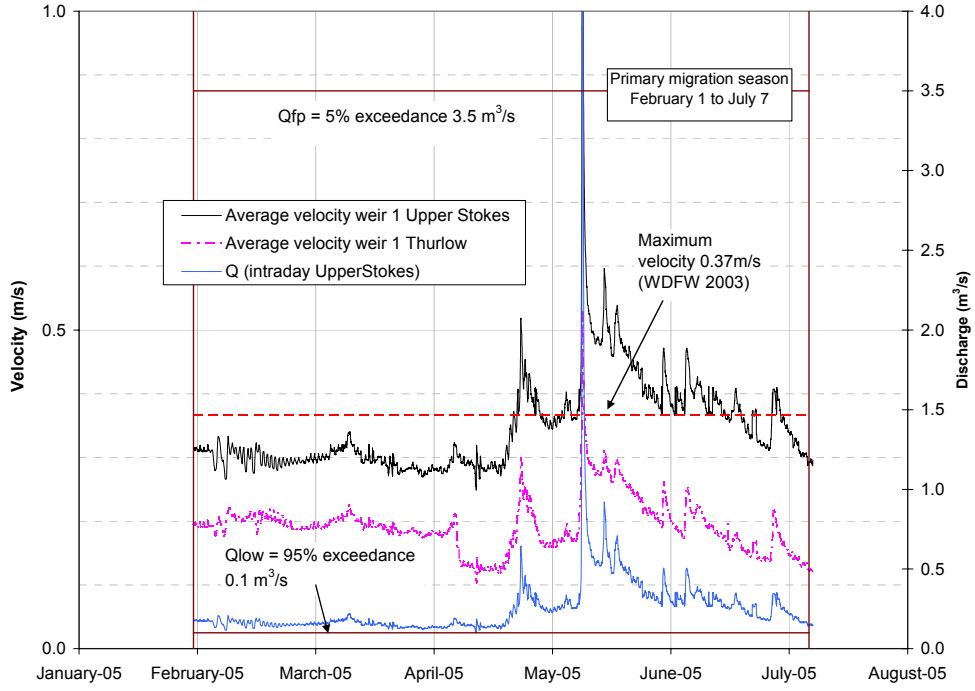


Figure 5.8. Estimated average velocity at Thurlow and Upper Stokes during 2005 primary migration season. No fish movement data available. See Figure 5.5 for an explanation of symbols.

For each fish detected moving upstream, minimum, maximum, average, and end values were calculated for each of the four modeled hydraulic parameters, within the time frame of each individual upstream fish movement, from Site A or Site B to Site D (Figure 4.1, Figures 5.1 to 5.4, Figures 5.9 to 5.12, and Appendix G). Precise times of fish passage at the rock vortex weirs were unknown, since the PIT-tag antennas were not located right at the rock vortex weirs. The minimum, maximum, and average values of the hydraulic parameters define the possible range of estimates, if fish were holding downstream of the rock vortex weirs.

The "end" values were considered the most representative estimates of hydraulic parameters during upstream fish passage, since they were calculated based on detection time at Site D, approximately 100 m upstream of the rock vortex weirs. Also, travel times between Site A or Site B (downstream) to Site D (upstream) ranged from 1 to 147 days, which reflect a

distance of about 3 km (Figure 4.1, Appendix G). Therefore, the estimated hydraulic parameters for the entire time frame of detected fish movement (from Site A or B to Site D) represent a wide range of values, with many days that may not reflect fish passage (Figure 5.9 to 5.12).

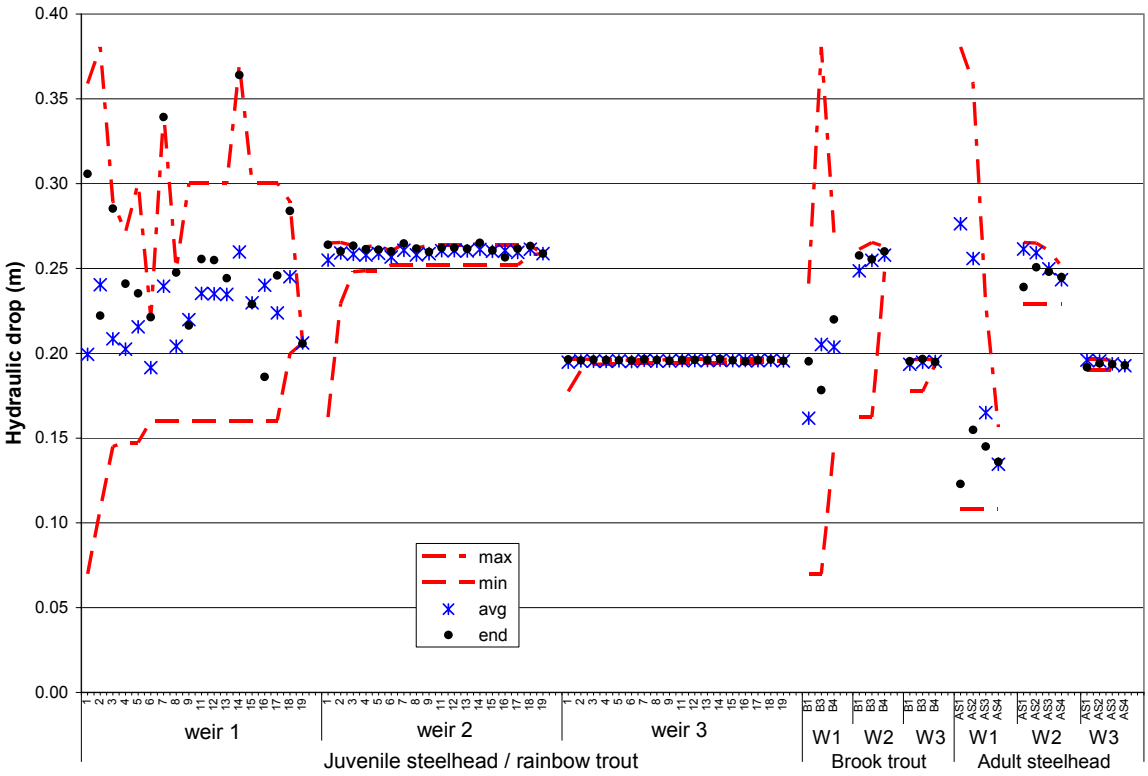


Figure 5.9. Representative statistics on hydraulic drop at rock vortex weirs for individual fish movements at Lower Stokes. Tick marks on horizontal axis identify individual fish and weir that the fish crossed. Data sorted by minimum values for presentation. End values reflect most representative estimate of hydraulic drop (and other hydraulic parameters), since detection at Site D is only 100 m upstream of the rock vortex weirs.

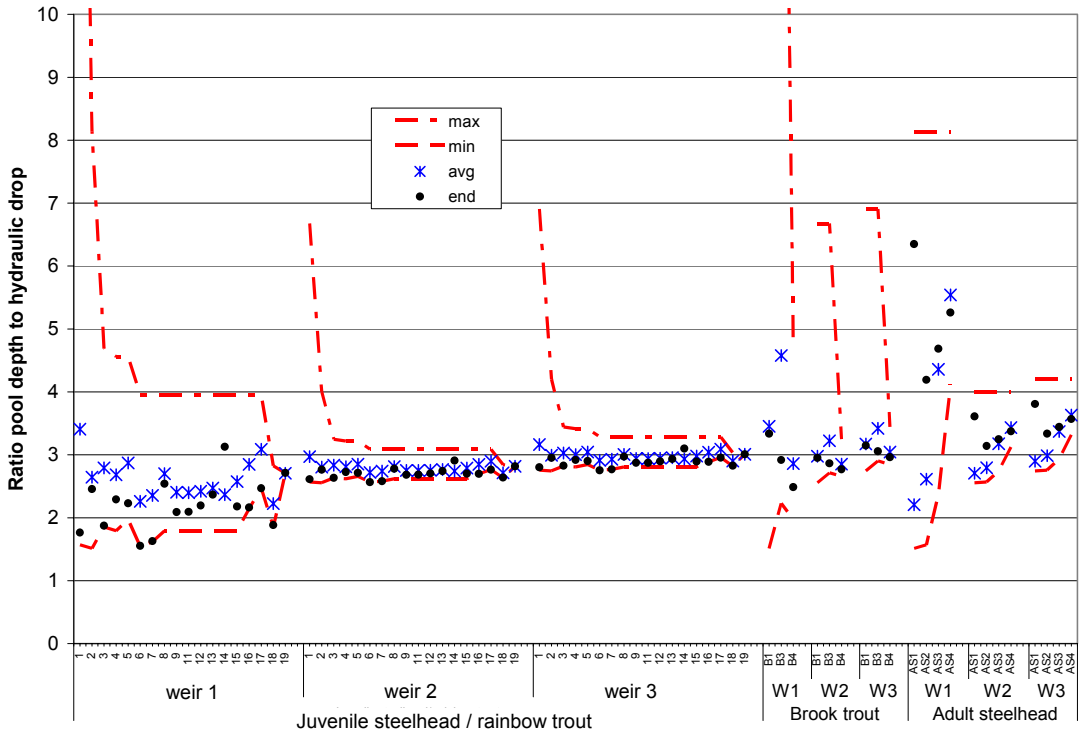


Figure 5.10. Representative statistics on ratio of pool depth to hydraulic drop at rock vortex weirs for individual fish movements at Lower Stokes. See Figure 5.9 for a description of symbols.

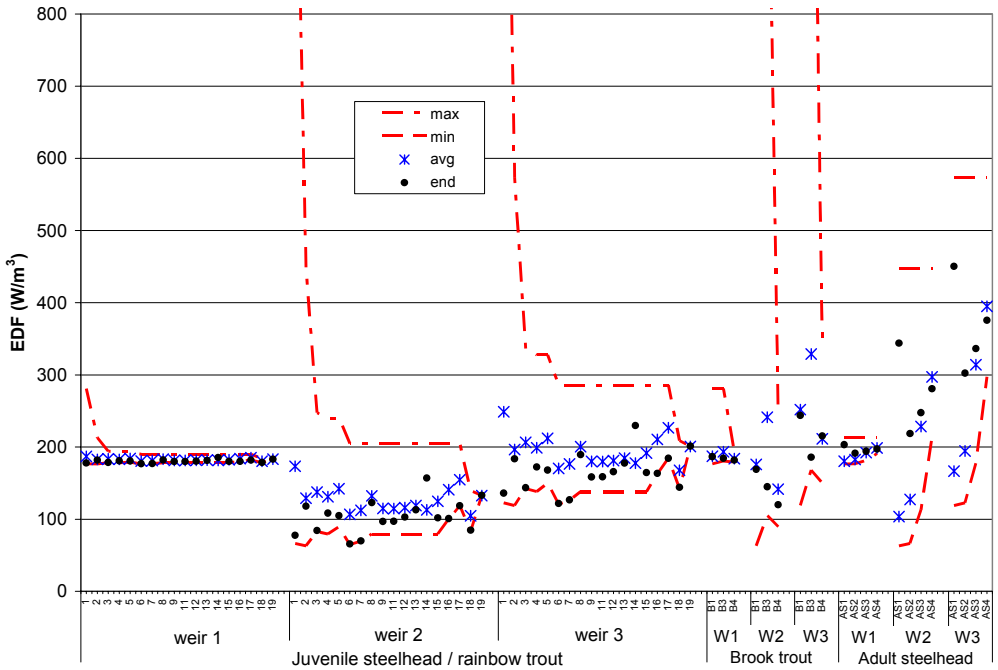


Figure 5.11. Representative statistics on energy dissipation factor (EDF) at rock vortex weirs for individual fish movements at Lower Stokes. See Figure 5.9 for a description of symbols.

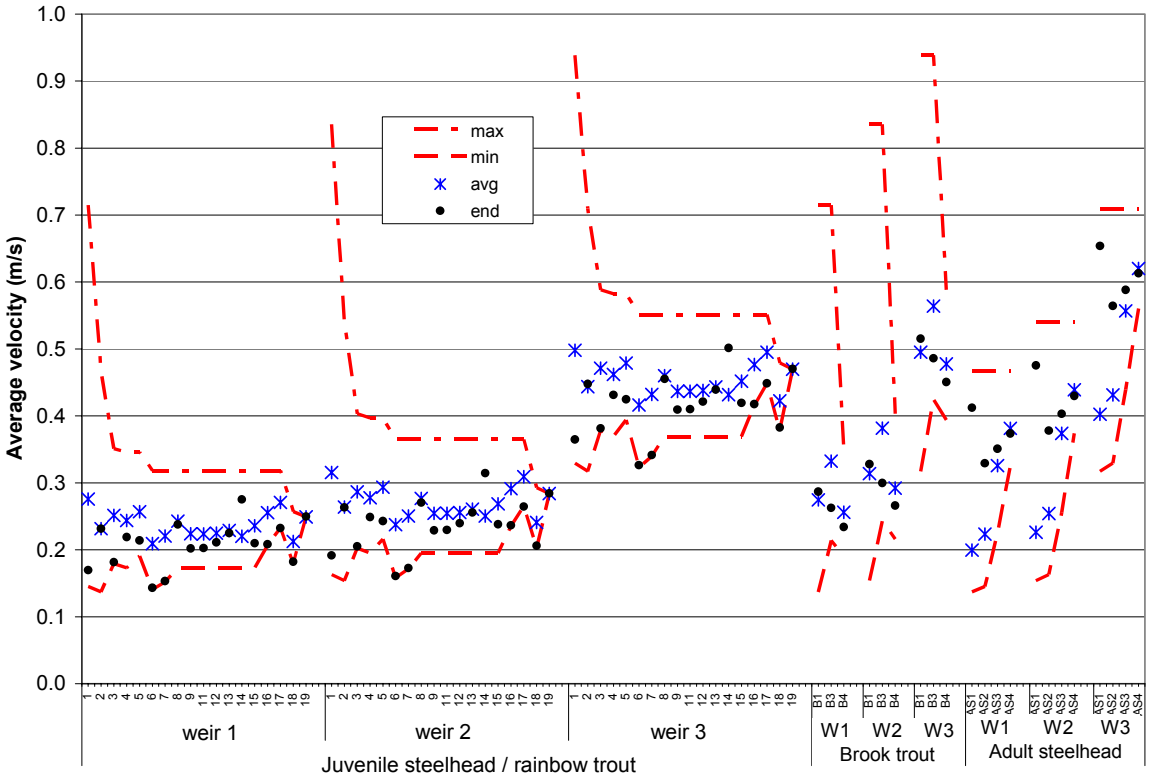


Figure 5.12. Representative statistics on modeled average velocity at rock vortex weirs for individual fish movements at Lower Stokes. See Figure 5.9 for a description of symbols.

To simplify and refine estimates of hydraulic parameters shown in Figure 5.9 to 5.12, fish with travel times from Site A to Site D of less than 5 days were selected and data for these three fish were reported (Figure 5.13 to 5.16). The hydraulic parameters for these three "fastest" fish were considered better estimates during upstream passage, with less diurnal variation from fewer days in the data set. For example, data for estimated hydraulic drop indicates that hydraulic drop varied from 0.11 to 0.27 m during passage for all fish detected moving upstream (Figure 5.5, Appendix G). By selecting fish that spent less than 5 days moving from Site A to Site D, the estimated hydraulic drop was between 0.20 and 0.26 (Figure 5.13).

Of the 19 juvenile steelhead/rainbow trout that moved upstream, fish numbers 1, 7, and 8 demonstrated the fastest travel times from the USGS-CRRL fish weir (Site A) to the large

PIT-tag reader (Site D) of 2.8, 4.1, and 4.1 days, respectively (Appendix G). For these three fish, the data in Figure 5.9 to 5.12 were filtered to data only for fish 1, 7, and 8 (Figure 5.13 to 5.16), which highlight the range of hydraulic conditions within the 2.8 to 4.1 day windows of time.

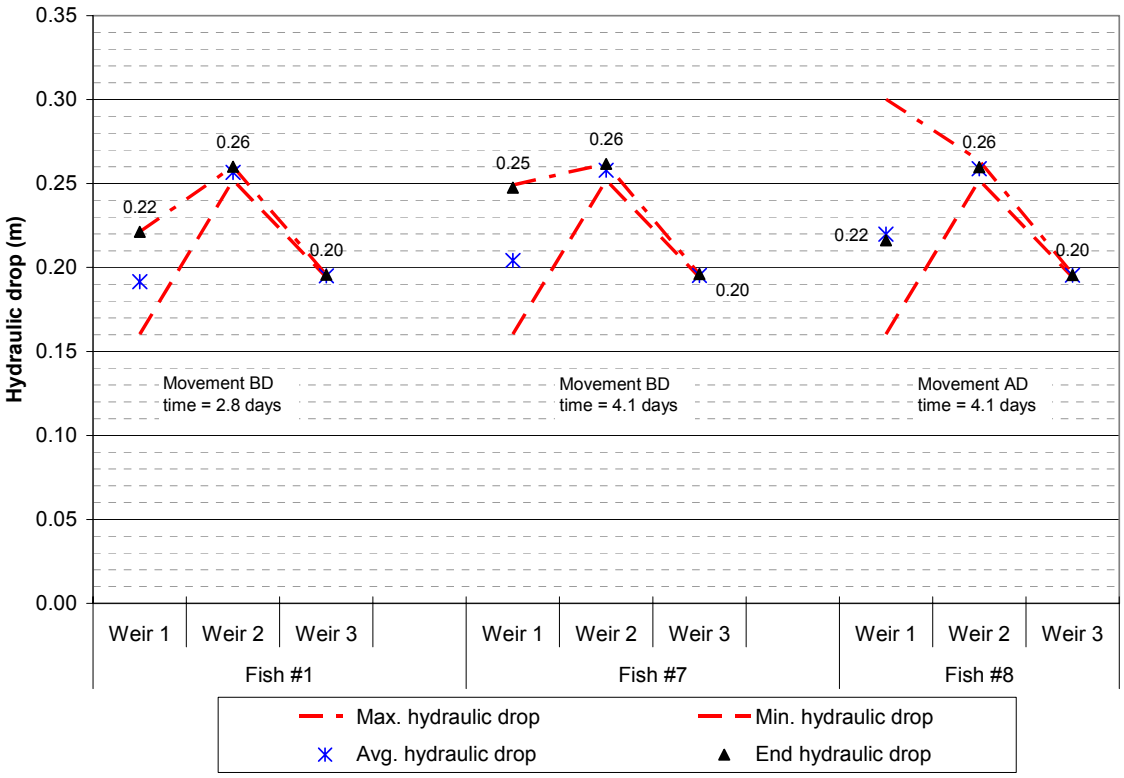


Figure 5.13. Modeled hydraulic drop for selected juvenile fish during passage. Movement AD or BD indicates detection of fish at USGS-CRRL PIT-tag antennas located at Site A or B and Site D, about 3 km upstream, about 100 m past the rock vortex weirs. Tick marks on horizontal axis identify individual fish and weir that the fish crossed at Lower Stokes. Data sorted by minimum values for presentation. End values reflect most representative estimate of hydraulic drop (and other hydraulic parameters), since detection at Site D is just upstream of the rock vortex weirs.

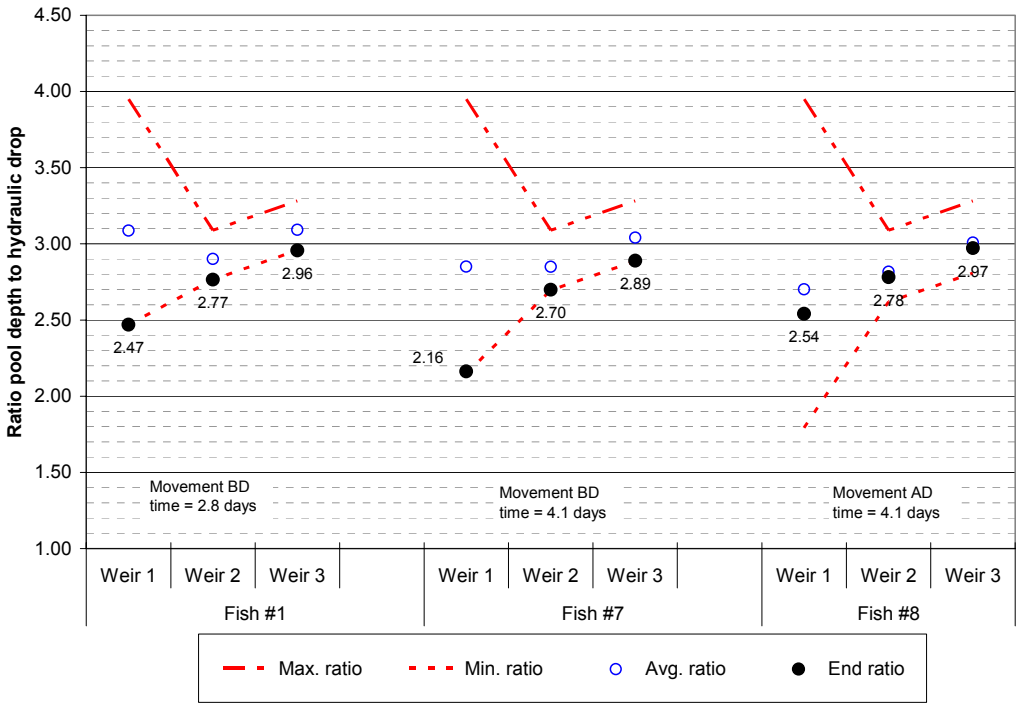


Figure 5.14. Modeled ratio of pool depth to hydraulic drop for selected juvenile fish during passage. See Figure 5.13 for a description of symbols.

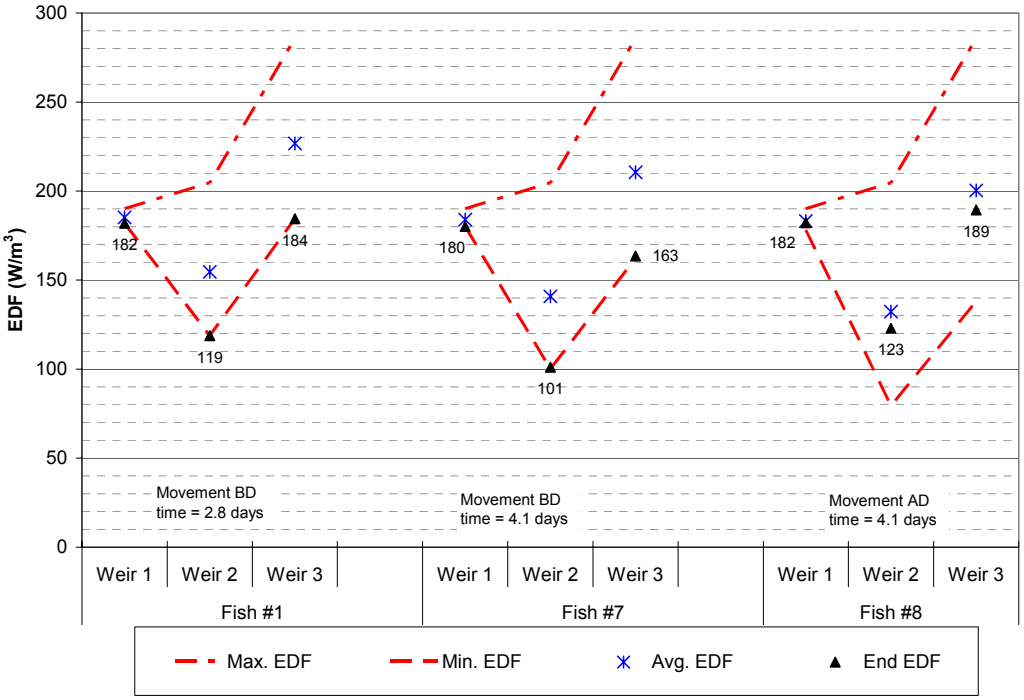


Figure 5.15. Modeled energy dissipation factor for selected juvenile fish during passage. See Figure 5.13 for a description of symbols.

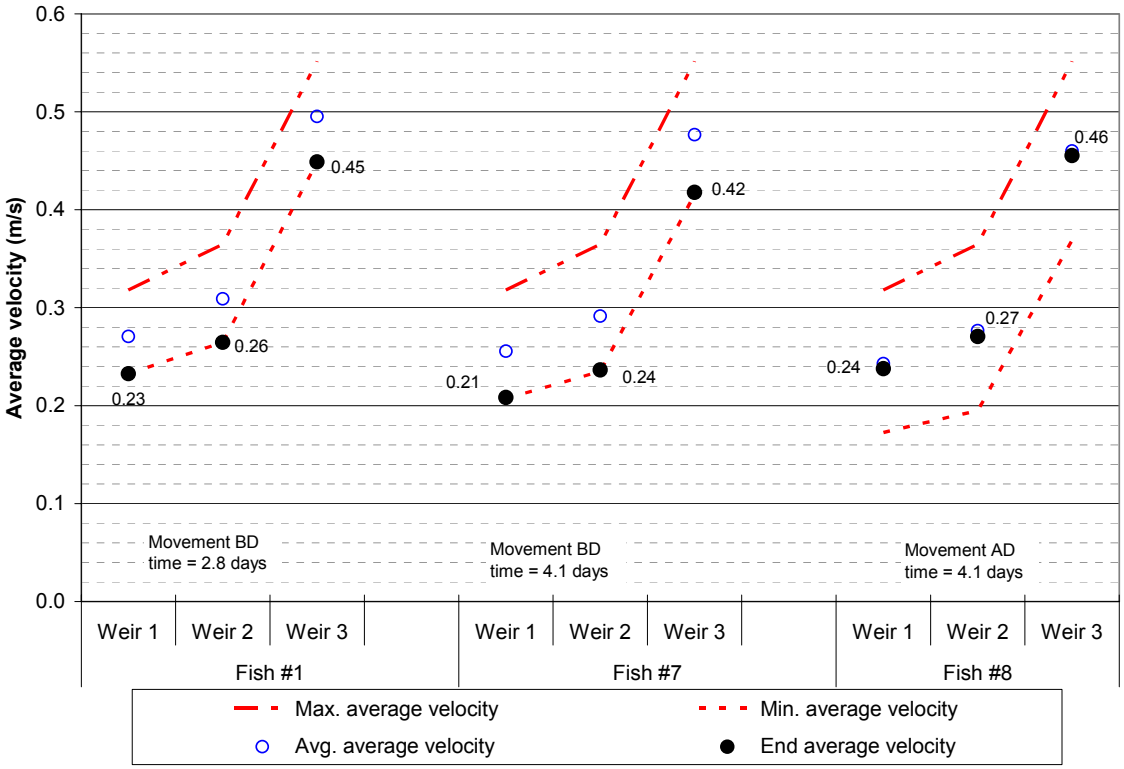


Figure 5.16. Modeled average velocity for selected juvenile fish during passage. See Figure 5.13 for a description of symbols.

5.3 Interpretation of hydraulic model and fish movements and comparison to NMFS and WDFW culvert passage guidelines

5.3.1 Hydraulic drop

Adult steelhead were observed to move past the weirs during higher flows, which coincide with lower hydraulic drops from increased discharge (Figure 5.1). Adult salmonids would not be expected to have difficulty jumping the weirs, other than requiring minimum water depths on the weir crests, although fish are known to jump over the crest entirely (Pearson 2005a). Juveniles moved upstream past the rock vortex weirs in early July, when flows were low and hydraulic drop was higher. From the hydraulic models in Chapter 3, hydraulic drop

was estimated as high as 0.27 m during times of recorded passage for juvenile steelhead / rainbow trout (Figures 5.1, 5.5, 5.9, and 5.13), very close to the fish passage guideline of 0.24 m from WDFW (2003).

According to Lang et al. (2004), the observation that juvenile fish jumped more than 0.24 m is not surprising, since juvenile fish are known to pass boulder weirs with drops as high as 0.30 m. Pearson (2005b) also reported leaping abilities of juveniles up to 3.0 times the fork length of the fish (3L). Data collected by the USGS-CRRL indicate the average length of juvenile fish that passed the rock vortex weirs was 0.15 m (fork length, L), which translates to potential jumping abilities of 0.45 m for the average fork length of juvenile fish, or three times the average fork length (3L). Therefore, for the juvenile fish in this study, the average jumping ability is possibly better than the maximum jump height 0.24 m from fish passage guidelines (NMFS 2000 and WDFW 2003).

Alternatively, using burst swim speeds, juvenile fish possibly swam through the rock vortex weirs through low flow notches, rather than leaping the weirs. This is discussed below in Section 5.3.4, where estimated average velocity at the rock vortex weirs during fish passage is evaluated. The means of that juvenile fish actually used to pass the rock vortex weirs was unknown since the upstream fish movement was detected by antennas, not by visual observation.

5.3.2 Ratio of pool depth to hydraulic drop

Juvenile steelhead / rainbow trout were detected passing the weirs when the ratio of pool depth to hydraulic drop was estimated between 1.6 and 3.1 (Figure 5.2, 5.10, and 5.14, and Appendix G). Adult steelhead passed the weirs when the ratio was between 3.1 and 6.3 (Figure 5.2, 5.10, and 5.14, and Appendix G). The fish passage guideline from NMFS (2000) suggests a minimum ratio of 1.5, so empirical data were consistent with this guideline. The higher ratio for adult steelhead is likely related to deeper water in the weir pools, making the pools more conducive for large fish to pass the structures. Some studies

indicate that the ratio is optimum around 1.25 to 1.50 (Stuart 1962, Pearson 2005b) and that deep pools diminish upwelling from the pool bottom, which is related to successful jumps, based on field studies (Pearson 2005b).

5.3.3 Energy dissipation factor

Juvenile fish were recorded passing the weirs when EDF was estimated between 66 and 230 W/m^3, below the maximum of 250 W/m^3 recommended by WDFW (2003) (Figure 5.3, 5.11, and 5.15). The upper estimate of 230 W/m^3 indicates a possible trend of fish to avoid high turbulence, which is considered to disorient fish (WDFW 2003). According to movement data from fish numbers 1, 7, and 8, when EDF was between 100 and 190 W/m^3, conditions were suitable for passage of juveniles (Figure 5.15). Adult steelhead did not appear to be limited by a higher EDF, as they passed the rock vortex weirs when EDF was between 190 and 450 W/m^3 (Figure 5.3, 5.11, 5.15, and Appendix G).

5.3.4 Average velocity

Juvenile fish were recorded passing the rock vortex weirs when average velocity (cross section averaged velocity at the rock vortex weir) was from 0.14 to 0.47 m/s, according the end point observations (Figure 5.4, 5.12, 5.16, and Appendix G). The estimated values of the average velocity exceed the guideline of 0.37 m/s (WDFW 2003), suggesting fish passage beyond the threshold established by the guideline. The “fastest” fish (fish numbers 1, 7, and 8) appeared to pass the weirs when average velocities were between 0.21 and 0.46 m/s (Figure 5.16). Adult steelhead passed through the rock vortex weirs up to estimated average velocities of 0.65 m/s (Figure 5.12 and Appendix G). According to NMFS (2000), allowable velocities for juvenile salmonids could range from 0.3 to 0.6 m/s. Adult fish could pass with velocities up to 1.83 m/s (WDFW 2003, Appendix A).

Swim speed for salmon could be estimated as 8 to 12 times the fish length (Bain and Stevenson 1999). The average length of juveniles detected as passing the weirs was 0.15 m, so their potential swim speeds could be from 1.2 to 1.8 m/s, well above the estimated average velocities at the weir crests.

5.4 Effectiveness evaluation of hydraulic parameters at rock vortex weirs and sensitivity analysis of discharge

The percentage of time the hydraulic parameters at the weirs met the fish passage guidelines was calculated for the primary migration season, February 1 to July 7. These data are shown in Table 5.1, as developed from the data shown in Figure 5.1 to 5.4. The data in Table 5.1 were developed based on flows that were within the fish regulation flows Q_{low} and Q_{fp} (Chapter 2) and within the calibrated range of the flow measurement instrument (Figure 2.19).

Sensitivity analysis on modeled hydraulic parameters was performed by recalculating percent data in Table 5.1 for accuracy of flow measurement data. According to Sauer and Meyer (1992), field measurements of discharge could vary by as much as ±10-percent. Using this premise of underestimating and overestimating flow by 10-percent, estimated discharge at Lower Stokes was augmented and reduced by 10-percent for the migration season. Then, using the rating curves for hydraulic parameters from Chapter 3, the time series for the hydraulic parameters were recalculated for the two new time series for high and low discharge. Using these upper and lower bounds on hydraulic parameters, as estimated from augmenting and reducing estimated discharge by 10-percent, the percent of time hydraulic parameters met fish passage guidelines was recalculated (Table 5.1).

For a 10-percent increase in discharge, the hydraulic drop decreases, EDF increases, and average velocity increases (Table 5.1). The converse is true for a 10-percent decrease in discharge. The change in percentages of time that hydraulic parameters met fish passage guidelines ranged from 1- to 7-percent (Table 5.1).

Table 5.1. Proportion of time during the primary migration season (February 1 to July 7) modeled hydraulic parameters met culvert passage guidelines (NMFS 2000, WDFW 2003). Data developed within calibrated range of discharge recording instruments. Sensitivity analysis of discharge (Q ±10%) show changes in percent of time hydraulic factors met fish passage guidelines for 10-percent overestimate and underestimate of discharge.

		Percent time within guideline				
		Lower Stokes			Thurlow	Upper Stokes
Hydraulic parameter	Discharge	Weir 1	Weir 2	Weir 3	Weir 1	Weir 1
Hydraulic drop (0.24 m max.)						
	Q+10%	94%	2%	100%	0%	22%
	Q	93%	1%	100%	0%	16%
	Q-10%	91%	0%	100%	0%	11%
Ratio of pool depth to hydraulic drop (1.5 min.)						
	Q+10%	100%	100%	100%	100%	100%
	Q	100%	100%	100%	100%	100%
	Q-10%	100%	100%	100%	100%	100%
Energy dissipation factor (250 W/m^3 max.)						
	Q+10%	100%	91%	75%	93%	100%
	Q	100%	93%	82%	95%	100%
	Q-10%	100%	95%	86%	98%	100%
Average velocity (0.37 m/s max.)						
	Q+10%	93%	86%	0%	100%	63%
	Q	95%	89%	0%	100%	69%
	Q-10%	97%	91%	0%	100%	76%

In addition to sensitivity analysis on discharge, statistics on estimated minimum and maximum values of the hydraulic parameters during the primary migration season were calculated (Table 5.2). These data informed how closely the rock vortex weirs were met the fish passage guidelines for culverts from NMFS (2000) and WDFW (2003). To give a broad range of estimated values for hydraulic parameters, the data in Table 5.2 were constructed from the maximum and minimum values during the full duration of detected fish movement from Site A to Site D, rather than end values, as used above.

Table 5.2. Estimated maximum and minimum values for hydraulic parameters during fish passage. Data developed within calibrated range of discharge recording instruments during primary migration season from February 1 to July 7. Maximum and minimum values estimated from range during entire time of detected migration, rather than end values, to demonstrate the possible range of hydraulic parameters.

	Lower Stokes			Thurlow *	Upper Stokes *
Hydraulic parameter	Weir 1	Weir 2	Weir 3	Weir 1	Weir 1
Hydraulic drop (0.24 m max.)					
max. (m)	0.28	0.27	0.20	0.31	0.31
min. (m)	0.17	0.16	0.18	0.28	0.14
Ratio of pool depth to hydraulic drop (1.5 min.)					
max. (m/m)	20.4	6.7	6.9	3.1	5.9
Min.(m/m)	1.6	2.6	2.7	2.2	1.9
Energy dissipation factor (250 W/m^3 max.)					
max. (W/m^3)	281	448	573	304	168
min. (W/m^3)	177	63	119	75	104
Average velocity (0.37 m/s max.)					
max. (m/s)	0.71	0.84	0.94	0.30	0.52
min. (m/s)	0.14	0.15	0.32	0.14	0.25

* Data for fish passage not available at Thurlow and Upper Stokes project sites. Maximum and minimum values estimated based on range during primary migration period from February 1 to July 7.

To develop a relative scoring system to describe effectiveness of fish passage at the rock vortex weirs analyzed in this thesis, data from Table 5.1 were assigned a qualitative score. A rating scale from A to F was assumed and associated with the percent of time during the migration season the hydraulic parameter was within passage guidelines (Table 5.3). The ranges for grade percentages in Table 5.3 were assumed and are suggested as thresholds to establish methodology.

Overall, most rock vortex weirs performed favorably, earning “A” and ”B” grades for most hydraulic parameters at most rock vortex weirs, in comparison to fish passage guidelines at culverts from NMFS (2000) and WDFW (2003). However, for Lower Stokes weir 2, Thurlow weir 1, and Upper Stokes weir 1, poor grades of “F” were calculated for modeled hydraulic drop, indicating the rock vortex weirs rarely (less than 50-percent of the migration season) met fish passage guidelines (Table 5.1 and Table 5.3). Also, weir 3 at Lower Stokes

and weir 1 at Upper Stokes performed poorly for average cross section velocity at the rock vortex weir crests, when compared to fish passage guidelines for average cross section velocity at culverts, earning grades of "F" and "D", respectively (Table 5.1 and Table 5.3).

Table 5.3. Grading of effectiveness of fish passage at rock vortex weirs in comparison to culvert fish passage guidelines from NMFS (2000) and WDFW (2003). Rating scale from A to F assumed.

	Lower Stokes			Thurlow	Upper Stokes
Hydraulic parameter	Weir 1	Weir 2	Weir 3	Weir 1	Weir 1
Hydraulic drop	A	F	A	F	F
Ratio pool depth to hydraulic drop	A	A	A	A	A
Energy dissipation factor (EDF)	A	A	B	A	A
Average velocity	A	B	F	A	D

Grading scale for effectiveness (assumed):
A 90-100%
B 80-90%
C 70-80%
D 60-70%
F less than 60%

Upon closer inspection of the modeled hydraulic parameters, most rock vortex weirs were actually close to performing within culvert guidelines (Figure 5.1 to 5.16, Table 5.1, and Table 5.2, Appendix A, and Appendix G). For example, weir 2 at Lower Stokes showed a hydraulic drop that was estimated as high as 0.27 m during detected fish passage (Appendix G), only 0.03 m above the fish passage guidelines (WDFW 2003).

Such borderline cases shown in Table 5.1 may not present barriers to fish passage, in the context of hydraulic diversity at rock vortex weirs (Appendix D) and the variation of swimming and jumping abilities of juvenile fish (Lang et al. 2004). In addition, Stuart (1962) and Pearson (2005a, 2005b) indicated that juvenile salmonids could jump at least 0.26 to 0.30 m.

Also, borderline cases may be the result of uncertainties in field measurements or regression analysis. For example, for the hydraulic drop at weir 2 at Lower Stokes, the linear regression for the rating curve (Figure 3.24) varied up to $\pm$ 0.02 m from measured values, which resulted in slightly higher and slightly lower estimates of hydraulic drop above and below a discharge of 0.22 m^3/s, respectively. Because the linear regression was very close to the threshold of 0.24 m, according to NMFS (2000) and WDFW (2003) guidelines, the subsequent analysis resulted in a negative assessment of weir 2 at Lower Stokes for hydraulic drop (Figure 3.24, Table 5.1, and Table 5.3). This level of precision is comparable to uncertainties associated with visual observation of staff gages in turbulent weir pools, which were used as rating points for hydraulic drop. Additional field observations and regression analysis would strengthen the rating curve and the estimates hydraulic drop.

Leaping behavior may not be the only means that juvenile fish passed the rock vortex weirs. If the hydraulic drop exceeded the guideline, a juvenile fish could have passed by some other means, such as swim-through with burst speed. This is possible since every rock vortex weir at the three project sites had a low flow notch where a single boulder in the weir crest was lowered about 0.1 to 0.2 m (McLaughlin, personal communications, 2006). Also, by nature of their construction, rock vortex weirs create diverse hydraulic conditions that are likely more conducive to passing fish than a culvert outfall with more uniform or focused hydraulics, such as an outfall from a corrugated metal pipe (Appendix D).

5.5 Updated evaluation of effectiveness based on fish movement data

Since the rock vortex weirs have more diverse hydraulic conditions than focused hydraulics from typical culverts, modifications to evaluating effectiveness of fish passage at rock vortex weirs were suggested, in the context of culvert passage guidelines (Table 5.4). These suggested modifications to the evaluation process were developed using modeled values of hydraulic parameters during confirmed fish passage (Chapter 4), which were assumed to reflect suitable conditions for typical juvenile fish to pass the rock vortex weirs at the project

sites. The suggested modifications to the evaluations were kept within reasonable limits, established by research and guidelines by others.

For example, as shown in Table 5.4, juvenile fish passed the rock vortex weirs when the hydraulic drop was more than 0.24 m. According to Stuart (1962), Lang et al. (2004), and Pearson (2005b) juvenile fish can jump up to 0.30 m. Therefore, a suggestion is made in this thesis to re-evaluate fish passage effectiveness analysis by increasing maximum hydraulic drop from 0.24 m (WDFW 2003) to 0.30 m. Similarly, maximum allowable average cross section velocity at the weir crest could be increased to 0.60 m/s (Table 5.4), compared to the maximum of 0.37 m/s suggested by WDFW (2003). This value is in the upper range of recommended values from NMFS (2000) (Appendix A).

Table 5.4. Comments on performance of rock vortex weirs in relation to culvert guidelines from NMFS (2000) and WDFW (2003) for fish passage.

Hydraulic parameter	Culvert guideline	Findings	Comment
Hydraulic drop	0.24 m maximum WDFW (2003)	Juvenile fish passed up to 0.27 m drop	Re-evaluate performance of rock vortex weirs with increased maximum of 0.30 m (Stuart 1962, Pearson 2000b, Lang et al. 2004)
Ratio of pool depth to hydraulic drop	1.5 minimum NMFS (2000)	Always exceeded minimum	Rock vortex weirs met guideline, possibly lower to 1.25 (Pearson 2005b)
Energy dissipation factor (EDF) in pool	250 W/m^3 maximum (WDFW 2003)	Never exceeded 230 W/m^3 for juvenile fish detected moving upstream	Rock vortex weirs met guideline. Continue to collect data to confirm guideline.
Average cross section velocity at rock vortex weir crest	0.37 m/s maximum (WDFW 2003)	Juveniles passed weirs with 0.5 m/s	Re-evaluate performance of rock vortex weirs with increased maximum of 0.6 m/s max. for juvenile fish, per NMFS (2000).

Using these two suggestions from Table 5.4, namely, a maximum hydraulic drop of 0.30 m and a maximum average cross section velocity at the weir crest of 0.6 m/s, an updated assessment of effectiveness of fish passage of rock vortex weirs was performed. With the

revised criteria, the results of the updated thresholds improved performance of the rock vortex weirs with respect to hydraulic drop and average cross section velocity (Table 5.5).

Table 5.5. Updated assessment of effectiveness of fish passage at rock vortex weirs based on observations of fish movement. Allowable hydraulic drop increased to 0.30 m and allowable average velocity increased to 0.6 m/s.

	Lower Stokes			Thurlow	Upper Stokes
	Weir 1	Weir 2	Weir 3	Weir 1	Weir 1
Hydraulic drop	A	A	A	A	A
Ratio pool depth to hydraulic drop	A	A	A	A	A
EDF	A	A	B	A	A
Average velocity	A	A	A	A	A

Grading scale for effectiveness (assumed):
A 90-100%
B 80-90%
C 70-80%
D 60-70%
F less than 60%

With the suggested modifications to evaluate fish passage, the assessment of rock vortex weirs at Lower Stokes, Thurlow, and Upper Stokes improved significantly (Table 5.5). Improved assessment is mostly due to confirmed fish passage when hydraulic parameters were just beyond the guidelines from NMFS (2000) and WFW (2003). For example, weir 2 at Lower Stokes had a modeled hydraulic drop around 0.26 m. With a suggested modification of the maximum hydraulic drop to 0.30 m, based on data from Stuart (1962), Lang et al. (2004), and Pearson (2005b), weir 2 at Lower Stokes improved from an effectiveness grade of “F” to “A” (Table 5.5), reflected by increased percent from 1- to 100-percent (percent of migration season the weir met the modified guideline). Similarly, weir 1 at Upper Stokes and weir 1 at Thurlow improved from “F” to “A” for hydraulic drop (Table 5.5), reflected by changes of 16- to 99-percent and 0- to 93-percent, respectively.

In addition, with the suggested modification of average velocity to 0.6 m/s maximum (NMFS 2000), all weirs were rated as “A” grades (Table 5.5), compared to mixed evaluation

before, with low grades “F” and “D” for weir 3 at Lower Stokes and weir 1 at Upper Stokes, respectively. Specifically, Lower Stokes weir 2, Lower Stokes weir 3, and Upper Stokes weir 1, upgraded from 89- to 100-percent, 0- to 100-percent, and 69- to 100-percent, respectively (percent of migration season the weir met the modified guideline).

At this time culvert guidelines from NMFS (2000) and WDFW (2003) for EDF and the ratio of pool depth to hydraulic drop seem applicable to rock vortex weirs, based on detected fish passage and estimated ratios and EDF at these field study sites. For weir 3 at Lower Stokes, the EDF scored a “B”, likely due to observed deposition in the weir pool below the crest of weir 3 (Appendix B).

While the results from this thesis suggest that rock vortex weirs show promise for allowing fish passage, additional studies of hydraulics at rock vortex weirs and juvenile fish behavior will help refine critical parameters, thresholds, and design criteria, more representative of hydraulic complexity at rock vortex weirs. The results of the current study by the BOR will be an important next step (BOR 2007 and Holmquist-Johnson, personal communications, 2007). Consideration of rock vortex weirs with design geometry different from the weirs in this thesis should be studied as well (Table 3.2).

5.6 Suggested design process for fish passage at rock vortex weirs

Typical applications for rock vortex weirs are for grade control. For the weirs in Beaver Creek, multiple objectives were sought, namely backwater for irrigation diversion, sediment transport, and fish passage. The designer of rock vortex weirs is advised to use due diligence and apply formulas and methods (in addition to those suggested in this thesis) to estimate design parameters for rock vortex weirs, considering other aspects of design, such as hydraulic stability. This thesis is focused on fish passage at rock vortex weirs. The following is a suggested approach to illustrate integration of fish passage considerations to a typical design process of rock vortex weirs or channel grade control.

Steps and considerations to design rock vortex weirs for fish passage include the following (NMFS 2000, Thomas et al. 2000, Hegberg et al. 2001b, WDFW 2003):

1. Determine target species and life stages.
2. Calculate hydrology for high and low design flows.
3. Determine reach design slope and grade control spacing.
4. Prepare design of weir geometry in plan and section.
5. Calculate weir stage versus discharge capacity from hydrology and weir geometry.
6. Determine size of boulders for crest stones.
7. Calculate scour potential in pool.
8. Design pool geometry.
9. Check weir design for hydraulic parameters and revise design as needed to meet criteria.

5.6.1 Determine target species and life stages for site

To determine the hydraulic constraints of the site, an inventory of resident species and species of concern should be compiled. The designer should consult with NMFS, U.S. Fish and Wildlife Service, and other regional and state agencies to determine if there are endangered or threatened species of migratory fish. Adult and juvenile fish of different species require a wide range of channel hydraulics and migration periods. Natural histories of resident, non-threatened fish should also be considered. Once the target species and life stages are selected, the migration season should be determined as well as physical factors that limit swimming performance.

5.6.2 Calculate hydrology for high and low design flows

For weir design, the structure must convey the 100-yr flow (NMFS 2000, WDFW 2003). In addition, the hydraulics of the structure should comply with fish passage parameters at the flows Q_{low} and Q_{fp}, determined from flow duration analysis (Chapter 2). The low design flow, Q_{low}, is typically 95-percent exceedance, and the high design flow, Q_{fp}, could be the 10-percent or 5-percent exceedance flow, depending on target species and life stages. Juvenile fish may only require 10-percent exceedance for Q_{fp} (NMFS 2000). For small watersheds, more barriers may be present at low flow, relative to large watersheds. Therefore, Q_{fp} would need to be a lower percent (higher flow), so barriers would be more passable and fish can move upstream (Lang et al. 2004).

To develop the 100-year flow, Q_{low}, and Q_{fp}, average daily flows for multiple years of record within the migration season are required to perform the flow duration analysis and flood frequency analysis. If historical flow records are not available, alternatives, such as regional regression relationships, could be used (Hegberg et al. 2001a).

5.6.3 Determine reach design slope and grade control spacing

Depending on site conditions, the height and spacing of grade controls will vary. Thomas et al. (2000) studied natural step pools in Colorado and developed an empirical formula from natural analogs, suggesting that step pool spacing should be:

$$L = \frac{0.3113}{S_{channel}^{1.188}} \tag{5.1}$$

Where:

L = Spacing of grade controls or step pools, in m

$S_{channel}$ = Channel slope

For example, for a stream reach with a slope of 2-percent, the spacing of the weirs would be about 10 m (32 feet), according to Equation (5.1). This is a design guideline according to

Thomas et al. (2000). The rock vortex weir designer should consider site-specific considerations and other possible design spacing. The suggested spacing from Thomas et al.(2000) is included in this thesis for reference in the context of discussing fish passage at rock vortex weirs.

Alternative design methods for step pool spacing can be developed from a geomorphic analysis that determines a stable channel slope and specification of maximum height for fish passage. In all cases, the drop over a grade control should not exceed 0.30 m for adult fish and 0.24 m for juveniles (WDFW 2003). For design purposes, the hydraulic drop can be estimated by the difference in elevation from the neat line of the weir crest [2] to the elevation of the pool tailout. Maximum design slope from the weir crest to the tailout should be 5-percent (Thomas et al. 2000).

5.6.4 Design geometry of weir crest in plan and section

Design geometry of rock vortex weirs according to Rosgen (2001) could generally follow the plan and sections shown in Figure 3.2, with the crest width (W) equal to 1/3 bank full width, wing wall angles from 20 to 30 degrees, and wing wall profile slopes (S) from 2- to 7-percent (Rosgen 2001). Site constraints may require slight changes in dimensions to conform, as was done for the weirs for the Methow project studied in this thesis. The designer is advised to use available sources and current information to confirm geometry and hydraulics for a rock vortex weir design. Both NMFS (2000) and WDFW (2003) recommend that rock vortex weirs “sufficiently pass” or “maintain integrity” during a 100-year discharge.

Placement of boulders for the crest should include a low flow notch to concentrate flows and allow swim-though passage for juvenile fish. The notch also creates deeper flow areas during low flows, required for adult fish, which need a minimum depth of 0.3 m (NMFS

[2] The neat line of the weir crest is about half way between the tips of the crest boulders and the interstices in the rocks.

2000). The low flow notch could be constructed by lowering one of the center crest boulders by 0.2 m.

5.6.5 Calculate weir stage versus discharge capacity from hydrology and weir geometry

Given a base width, W, and fixed profile slopes for the weir crest, a stage discharge relationship for the weir design can be estimated by a trapezoidal model. This trapezoidal model can then be used to estimate water stage for discharges of different return intervals and flow durations. Determining the water stage for the 100-year flow is important for structure stability and compliance to design guidelines from NMFS (2000) and WDFW (2003).

A simplified trapezoidal flow model over the rock vortex weir was developed from data in this thesis (Figure 5.17). For a trapezoidal model to best simulate flow over a rock vortex weir, the base of the trapezoid should be offset about 0.1 to 0.3 m upward from the minimum crest elevation (measured low elevations at the contact points of the crest boulders), as shown in Figure 5.17. The coefficient, μ, in the Poleni equation for weir flow (Equation (3.12)) should be set to 0.5 to 0.7, with a lower value for an irregular placement of crest boulders and a higher value for crest boulders that are smoothly interfaced and interlocked. The weir width for the Poleni equation will change with stage. Calculation of weir width is based on weir length projected transverse to the channel direction. To develop projected weir length as a function of stage, Equations (5.2), (5.3), and (5.4) should be used (Figure 3.14).

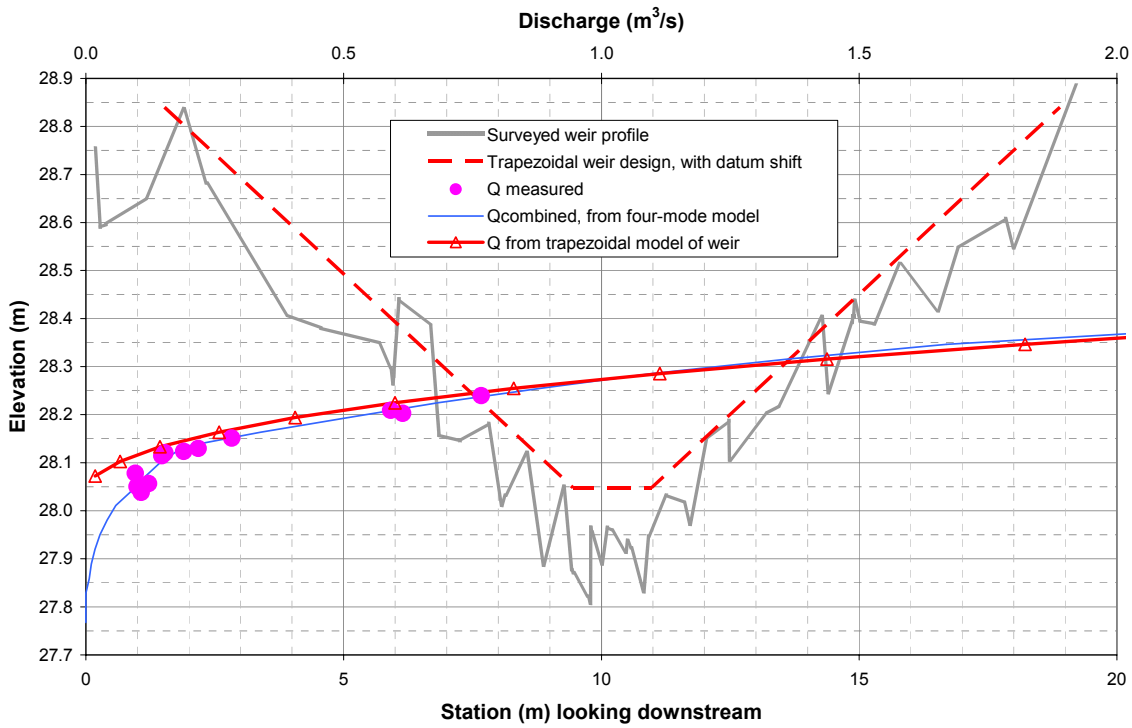


Figure 5.17. Trapezoidal model of weir showing weir cross section and datum shift. Discharge from trapezoidal model of weir and four-mode model shown.

Flow over the rock vortex weirs can be estimated with the modified Poleni Equation (3.12) (Chow 1959). The length of the trapezoidal weir, B, is calculated along the oblique alignment, based on design side slopes, S, and then contracted to a length transverse to the channel direction by a cofactor C_w, which is based on the plan angle of the wing walls. The formulations are as follows:

$$Q_{weir} = \frac{2}{3} \cdot \mu \cdot B_{weir} \cdot \sqrt{2g} \cdot H_{crest}^{1.5} \tag{3.12}$$

Where :

Q_{weir} = Discharge for weir flow, in m^3/s

μ = Weir coefficient (function of the geometry ≈ value of 0.5–0.7, suggested, with lower values for more roughness on weir crest), no units

C_w = Contraction coefficient for weir crest profile length, calibration parameter based on weir geometry, no units (Equation (3.14) and Figure 3.14)

B_{weir} = Projected weir length, function of water stage and weir geometry, in m

g = Acceleration of gravity, 9.81 m/s^2

H_{crest} = Water depth at the weir crest, in m

The projected length of the weir used in Equation (3.12) is determined by:

$$B_{weir} = C_w \cdot B \tag{5.2}$$

Oblique weir length is calculated based on design geometry (Figure 3.14):

$$B = W + 2 \cdot \frac{H_{crest}}{S} \tag{5.3}$$

Where:

B = Oblique profile length of weir, in m

W = Base width of crest, in m (Figure 3.14)

H_{crest} = Depth of flow over weir, in m

S = Profile slope of wing wall (Figure 3.14)

The contraction coefficient, which projects the oblique length of the weir crest, B, to a length perpendicular to the flow direction is calculated as:

$$C_w = \frac{W + (B - W) \cdot Sin\alpha}{B} \tag{3.14}$$

Where:

B = Total oblique length of weir profile, in m

W = Base width of trapezoidal weir crest in m

α = Angle of wing wall relative to stream bank (Figure 3.3), in degrees

According to data collected in this thesis, at the five rock vortex weirs in Beaver Creek, the simplified trapezoid flow model was calibrated over a range of flows between 0.1 and 2.0 m^3/s. A more robust model would implement the four-mode hydraulic model and provide better predictions of stage versus discharge, for rock vortex weirs, comparable to the ones in this study (Chapter 3). Application of a four-mode hydraulic model would introduce an

intermediate element of gap flow prior to weir flow (Figure 5.17 and Chapter 3). A suggested value for C_g, the contraction and loss coefficient of total weir length for gap flow, is between 0.1 and 0.2. The weir coefficient, μ, could vary between 0.5 and 0.7 in the four-mode model. To calculate gap flow and weir flow, Equations (3.10), (3.11) and (3.12) should be used.

5.6.6 Determine size of boulders for crest stones

Minimum boulder size for the crest boulders can be calculated from the following equation (COE 1991, page 3-8, and Thomas et al. 2000):

$$D_{30} = \frac{1.95 \cdot S^{0.555} \cdot q^{\frac{2}{3}}}{g^{\frac{1}{3}}} \tag{5.4}$$

Where:

S = Channel slope

q = Unit discharge, in $ft^3/s/ft$

g = Gravitational constant, 32.2 ft/s^2

Rock size may need to increase for a factor of safety. Larger rocks should be installed as foundation stones and to anchor the downstream ends of the rock vortex weirs. The designer is again advised to check current rock design criteria and is reminded that this thesis discusses rock sizing in the context of fish passage. The information included herein is not intended as a comprehensive design guide for rock vortex weirs.

5.6.7 Calculate scour potential in weir pool

From Thomas et al. (2000) the scour depth in a weir pool is:

$$D = \left(-0.018 + 1.394 \cdot \frac{H_{drop}}{W_{avg}} + 5.514 \cdot \frac{S_0 \cdot q_{25}}{\sqrt{g} \cdot W_{avg}^{\frac{3}{2}}} \right) \cdot W_{avg} \tag{5.5}$$

Where:

D = Scour depth, in ft

H_{drop} = Hydraulic drop over weir, in ft

S_0 = Channel bed slope

q_{25} = Unit discharge for 25-year flow, in $ft^3/s/ft$

W_{avg} = Average channel width, in ft

Crest rocks should be installed below the level of estimated scour depth. Additional sources and methodologies for scour protection should be checked and considered by the designer. The guideline in Equation (5.5) for scour is provided as a reference in the context of evaluating fish passage and does not represent a robust design method for structural concerns.

5.6.8 Design pool geometry

The plan geometry of the weir pool is recommended by Thomas et al. (2000). The maximum width of the weir pool, about half-way down the length should be 1.2* W_{avg} . The width of the control section downstream, or tailout should be 0.92 * W_{avg}. Pool depth is recommended as a minimum of 0.61 m per NMFS (2000). Specification of pool depth should also consider the recommended ratio of 1.25 to 1 (Stuart 1962) of pool depth to hydraulic drop. When designing the contours of the pool, the designer should also keep in mind that fish have been observed using the upwelling effect from flow, reflecting off the bottom of the weir pool, to assist their jumps over the weirs (Pearson 2005b).

5.6.9 Check weir design for hydraulic parameters and revise design to meet criteria

Prior to construction, the rock vortex weir design should be checked with estimated hydraulic parameters from fish passage guidelines (NMFS 2000 and WDFW 2003). The

design will likely be driven by geomorphic constraints and the required hydraulic drop, which should not exceed 0.24 m, according to guidelines from NMFS (2000) and WDFW (2003). Findings in this thesis indicate that fish passage could occur with a hydraulic drop up to 0.3 m (Lang et al. 2004 and Pearson 2005b).

Four hydraulic parameters are suggested as criteria for weir design: hydraulic drop, ratio of pool depth to hydraulic drop, energy dissipation factor (EDF), and average cross section velocity. These four hydraulic parameters, suggested as design criteria, do not preclude additional factors that must be considered for regional variation of regulations and target species.

Design hydraulic parameters for upstream fish passage are driven by the low flow and high flows for fish passage (Q_{low} and Q_{fp}) (NMFS 2000 and WDFW 2003). For Q_{low}, hydraulic drop, the ratio of pool depth to hydraulic drop, and EDF will need to be checked against fish passage guidelines from NMFS (2000) and WDFW (2003). Also, minimum depth on the weir should be checked for Q_{low}. A low flow notch in the weir crest will focus flows and provide deeper water and possible swim-through conditions. During high flows, near Q_{fp}, EDF and average cross section velocity should be examined more closely with regard to fish regulations and guidelines.

To determine the ratio of pool depth to hydraulic drop and EDF, hydraulic drop needs to be estimated from water stage downstream and upstream of the rock vortex weir crest. Water stage downstream can be estimated assuming subcritical flow and downstream control. Two possible methods could be used: 1) normal flow depth from the Manning Equation (3.13) or 2) a calibrated hydrodynamic model for the downstream channel. Each method would be used to determine stage versus discharge relationships in the weir pool, assuming that the tailwater does not impose downstream control on critical flow over the weir crest. Water stage at the weir crest can be estimated using the Poleni Equation (3.12) for a simplified trapezoidal model of the weir or a four-mode hydraulic model (Chapter 3).

Alternatively, the ratio of pool depth to hydraulic drop can be estimated by comparing estimated scour depth from Equation (5.5) to modeled hydraulic drop.

Energy dissipation factor can be estimated from Equation (3.15). The EDF is a function of hydraulic drop, discharge, and pool volume within 3 m of the weir crest. The design of the pool and crest width should consider the relationships between discharge, hydraulic drop, and pool volume. Discharge and hydraulic drop can be related using the simplified trapezoidal model of the weir crest and estimated gap flow, discussed above. Weir pool volume estimates can be calculated from the scour depth in Equation (5.6) and weir pool geometry. Given discharge, hydraulic drop, and pool volume, a rating curve for EDF can be estimated. The value of EDF should not exceed 250 W/m^3 for a rock vortex weir (WDFW 2003), as calculated with Equation (3.15).

$$EDF = \gamma \cdot \frac{Q \cdot D_s}{V_p} \tag{3.15}$$

Where:

EDF = Energy dissipation factor, suggested to be less than a value of 250 W/m^3

γ = Unit weight of water

Q = Discharge for a range of flows between high and low fish passage design flows Q_{low} and Q_{fp} (Chapter 2), in m^3/s

D_s = Differential hydraulic drop at weir estimated or observed, in m

V_p = Volume of pool, function of water stage in pool, determined from pool volume rating curves developed from design or topographic survey, in m^3

If the EDF is high, pool volume can be increased by lengthening weir crest laterally or flattening the plan angles of the wing walls. If the EDF is low, there is less concern for fish passage, but extremely low values should be investigated to be sure the weir is creating attraction flows for jumping fish.

The third hydraulic parameter to check is average velocity of flow over the rock vortex weir crest, which should not exceed 0.37 m/s (WDFW 2003). Average velocity can be calculated using the simplified trapezoidal weir (described above) and the Poleni equation (or a four

mode hydraulic model) to predict the stage versus discharge relation. For these data, average velocity can be calculated from discharge divided by flow area. For low flows, below 0.1 to 0.2 m^3/s, a more robust four-mode hydraulic model could provide better estimates of the stage versus discharge relation (Chapter 3). If velocities are high, the roughness of the rock crest can be increased, reducing velocity for a given discharge. Also, the width of the weir crest can be increased, as long as the flow depth is at least 0.30 m for adults and 0.15 m for juvenile fish.

5.7 Discussion

Rock vortex weirs are likely more passable than prefabricated fishways or culverts, which have more focused or uniform hydraulic conditions. Juvenile salmonids seek hydraulic niches, and they work their way through boulder weirs better than uniform, streaming flow from a structure like a rectangular weir (Lang et al. 2004). Also, the presence of a pool upstream assists fish in passing the structure, so they do not have to sustain costly burst swimming speeds for more than a few seconds, allowing them to reach calm waters immediately after jumping the obstruction (Stuart 1962, Pearson 2005b). For a culvert, the fish typically have to jump up and then continue to swim quickly through fast water for the length of the culvert. Therefore fish passage guidelines for culverts from NMFS (2000) and WDFW (2003) may need to be more stringent than those required for rock vortex weirs.

Possible future studies could pursue a multivariate analysis of hydraulic parameters for fish passage as some factors may have more influence that others, and some factors may be linked, such as velocity and jump height. An index similar to specific energy in channel flow could be used to model abilities of fish to pass the weir. A given fish may have a certain propensity to jump and swim for successful passage. Velocity head for jumping, as represented by Equation (1.1) from Bell (1991) and velocity at the weir crest, as modeled by a four-mode hydraulic model, could be used as two factors to work towards understanding why some fish succeed at jumping and others do not. Turbulent effects, as quantified by

EDF, and pool dynamics need to be considered as well (NMFS 2000, WDFW 2003, and Appendix A).

5.8 Conclusions

This thesis study addressed the effectiveness of rock vortex weirs for fish passage in a field setting. The primary findings include the following:

1. Watershed-scale data collection of geomorphic, hydraulic, and temperature properties were useful to determine locations of index reaches for fish surveys and potential restoration sites (Chapter 2).
2. The rock vortex weirs demonstrated favorable performance, based on comparison of estimated hydraulic parameters to fish passage guidelines for culverts (NMFS 2000 and WDFW 2003) and detected fish movement. According to observations of fish movement and estimated hydraulic parameters during the movement (Appendix G, end values for hydraulic parameters), juvenile and adult fish moved upstream, past the rock vortex weirs, when hydraulic drops varied from 0.11 to 0.27 m, compared to the fish passage guideline of 0.24 m, maximum. The ratio of pool depth to hydraulic drop ranged from 1.6 to 6.1, compared to guideline value of 1.5, minimum. Energy dissipation factors in the weir pools varied from 66 to 450 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 0.65 m/s, compared to a guideline of 0.37 m/s, maximum (Chapter 5).
3. Based on comparison of estimated hydraulic parameters during upstream fish movement to culvert passage guidelines from NMFS (2000) and WDFW (2003), fish passed the rock vortex weirs when estimated hydraulic parameters slightly exceeded the guidelines. These data suggest that rock vortex weirs have more hydraulic diversity when compared to culvert structures and therefore, more opportunity for juvenile and adult salmonids to move upstream, past the rock vortex weirs for a given discharge (Chapter 5, Appendix D).

4. A calibrated, four-mode hydraulic model for flow over a rock vortex weir effectively simulated stage versus discharge for rock vortex weirs with geometry according to the study sites (Table 3.2), as designed by the BOR per Rosgen (2001). The first two modes, orifice flow and gap flow, are useful estimators of stage versus discharge for low flows (less than 0.1 m^3/s), reflecting higher friction losses for low flows from boundary effects. The third flow mode, weir flow, effectively modeled measured discharge at a stage approximately 0.2 to 0.4 m above the rock vortex weir crest, when augmented with orifice flow and gap flows. Calibration of the coefficient, μ, for weir flow was between 0.5 and 0.8 (Poleni equation, Chow 1959). Contraction and friction loss coefficients for gap flow (C_g) and weir flow (C_w) varied from 0.10 to 0.45 and 0.42 to 1.00, respectively (Figure 3.14). These data could be used to reproduce stage discharge relationships at other rock vortex weirs by applying the first three modes of the four-mode model. The fourth flow mode, rough boundary flow, was determined to initiate at a discharge beyond fish passage design flows (NMFS 2000 and WDFW 2003), and was not considered important to fish passage effectiveness evaluation (Chapter 3).
5. The combination of PIT-tag technology, continuous stage recorders, and models for hydraulic parameters at rock vortex weirs were effective in evaluating upstream fish passage. Time series of fish movement and hydraulic parameters can be compared to fish passage guidelines for evaluation and monitoring. Quantification of fish passage effectiveness was informative using a grading scale from A to F, according to the proportion of the migration period when estimated hydraulic parameters met guidelines from NMFS (2000) and WDFW (2003) (Chapter 5).
6. Design and monitoring of rock vortex weirs can be enhanced for upstream fish passage by incorporating hydraulic models that estimate hydraulic parameters from NMFS (2000) and WDFW (2003). The target species and life stages at each project site need to be determined to select guidelines for swimming and leaping performance and compare hydraulic parameters for effective evaluation. Also, additional hydraulic parameters, such as temperature, may need to be evaluated depending on target species and life stages (Chapter 5).

7. Flow over rock vortex weirs could be modeled using a simplified 2-dimensional trapezoid model of the weir geometry (Chapter 3). A vertical datum shift of the base of the trapezoid from 0.1 to 0.3 m above the minimum crest elevation, and a weir coefficient, μ, of 0.5 to 0.8 could be used to estimate stage versus discharge at the vortex weirs for flows equal to and greater than 0.1 m^3/s. Rock vortex weirs with more irregularity would have smaller values of μ and larger values for the datum shift. Additional studies are needed to develop these estimated coefficients further and determine how well they represent rock vortex weirs at other sites.

REFERENCES

Aarestrup, K. and M. C. Lucas. 2003. Efficiency of a nature-like bypass channel for sea trout (Salmo truttu) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish 12:160-168.

Aaserude, R. G. 1984. New concepts in fishway design. M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University.

Andonaegui, C. 2000. Salmon, steelhead, and bull trout habitat limiting factors, Water Resource Inventory Area 48. Washington State Conservation Commission.

Bain, M. B. and N. J. Stevenson, editors. 1999. Aquatic habitat assessment: common methods. American Fisheries Society. Bethesda, Maryland.

Bell, M. 1991. Fisheries Handbook of Engineering Requirements and Biological Criteria, Third Edition, U.S. Army Corps of Engineers, Fish Passage Development and Evaluation Program, Portland, Oregon.

Baxter, C. and F. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences. 57:1470-1481.

Chapman, D., C. Peven, A. Giorgi, T. Hillman, and F. Utter. 1995. Status of spring Chinook salmon in the mid-Columbia region. Don Chapman Consultants, Inc. Boise, Idaho.

Chow, V. 1959. Open Channel Hydraulics. McGraw Hill. Boston, Massachusetts.

Connolly, P. J., I. G. Jezorek and E. F. Prentice. 2005. Development and use of in-stream PIT-tag detection systems to assess movement behavior of fish in tributaries of the Columbia River Basin, USA. Proceedings of the Measuring Behavior 2005 Conference, Paper FP 1.2. Noldus Information Technology, Wageningen, Netherlands, September 2005.

Connolly, P. 2006. Personal communications, Lead Research Fish Biologist, USGS-Western Fisheries Research Center, Columbia River Research Laboratory. Cook, Washington. April 5, 2006.

Cross, D. 2005. Personal communications, Fisheries Biologist, Methow Ranger District, USDA Forest Service, Winthrop, Washington. May 12, 2005.

DHI Water and Environment. 2003. Mike 11: A modeling system for Rivers and Channels, Reference Manual. Hersholm, Denmark.

Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK). 1996. Fischaufstiegsanlagen - Bemessung, Gestaltung, Funktionskontrolle, Merkblätter zur Wasserwirtschaft. Report 232/1996. Bonn, Germany.

Ead, S. A., N. Rajaratnam, and C. Katopodis. 2002. Generalized study of hydraulics of culvert fishways. Journal of Hydraulic Engineering 128:1018-1022.

Ely, M. 2001. Use of a precipitation-runoff model to simulate natural streamflow conditions in the Methow River basin, Washington. U.S. Geological Survey . Water-Resources Investigations Report 01-4198. Tacoma, Washington.

Ely, M. 2003. Precipitation-runoff simulations of current and natural streamflow conditions in the Methow River basin, Washington, U.S. Geological Survey. Water-Resources Investigations Report 03-4246. Tacoma, Washington.

Gibbons, J. W. and K. M. Andrews. May 2004. PIT Tagging: Simple technology at its best. Bioscience 54:447-454.

Guiny, E. and J. D. Armstrong. 2003. Preferences of mature male brown trout and Atlantic salmon parr for orifice and weir fish pass entrances matched for peak velocities and turbulence. Ecology of Freshwater Fish 12:190-195.

Grade Control Task Committee. 1998. Siting, monitoring, and maintenance for the design of grade control structures, Draft report July 14, 1998. Hydraulic Structures Committee, ASCE.

Hegberg, C., P. A. Schlindwein, S. Cohen, and S. Jacobs. 2001a. Natural fish passage structures in urban streams (Part 1: Hydrologic and resource issues), John Muir Institute, Road Ecology Center (University of California Davis).

Hegberg, C., P. A. Schlindwein, S. Cohen, and S. Jacobs. 2001b. Natural fish passage structures in urban streams (Part 2: Hydrologic design and analysis), John Muir Institute, Road Ecology Center (University of California Davis).

Hillman, T. and A. Georgi. 2002. Monitoring Protocols: Effectiveness monitoring of physical/environmental indicators in tributary habitats. Bonneville Power Administration, Portland, Oregon.

Holmquist-Johnson, C. Personal communications, Hydraulic Engineer, Sedimentation and River Hydraulics Group, U.S. Bureau of Reclamation. Denver, Colorado. January 16, 2007.

Holthe, E., E. Lund, B. Finstad, E. B.Thorstad, and R. S. Mckinley. 2005. A fish selective obstacle to prevent dispersion of an unwanted fish species, based on leaping capabilities. Fisheries Management and Ecology 12:143-147.

Kalher, T. H. and T. P. Quinn. 1998. Juvenile and resident salmonids movement and passage through culverts. Final research report from the School of Fisheries, University of Washington, Seattle, Washington to the Washington Department of Transportation.

Katopodis, C. 1992. Introduction to Fishway Design. Canadian Department of Fisheries and Oceans, Freshwater Institute Central and Arctic Region. Winnepeg, Manitoba.

Katopodis, C., N. Rajaratnam, S. Wu, and D. Tovell. 1997. Denil fishways of varying geometry. Journal of Hydraulic Engineering 123:624-631.

Katopodis, C. 2005. Developing a toolkit for fish passage, ecological flow management, and fish habitat works. Journal of Hydraulic Research 43:451-467.

Klavas, P. 2006. Personal communications, Hydraulic Engineer, Habitat Program – Environmental Engineering, Washington Department of Fish and Wildlife (WDFW), Olympia, Washington. July 5, 2006.

Lang, M., M. Love, and W. Trush. 2004. Improving stream crossings for fish passage, final report. National Marine Fisheries Service. Contract No.50ABNF800082.

Lauritzen, D. V. 2002. Preferences, behaviors, and biomechanics of pacific salmon jumping at waterfalls and fish ladders. Dissertation, University of California, Los Angeles.

Love, M., S. Firor, M. Furniss, T. Dunklin and B. Gubernick. 1999. Fish Xing 2: Software and learning systems for fish passage through culverts. USDA Forest Service, San Dimas Technology and Development Center. San Dimas, California.

Mantua, N., S. Hare, Y. Zhang, J.Wallace, and R. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

McLaughlin, J. 2006. Personal communications, Design engineer, U.S. Bureau of Reclamation (BOR), Boise, Idaho. June 15, 2006.

Meehan, W.R. 1991. Influences of forest and rangeland management on salmonids fishes and their habitats. USDA Forest Service. American Fisheries Society Special Publication 19. Bethesda, Maryland.

Montgomery, D. and J. Buffington. 1997. Channel-reach morphology in mountain drainage basins. GSA Bulletin. 109:596-611.

Mullian, J., K. Williams, G. Rhodus, T. Hillman, and J. McIntyre. 1989. Production and habitat of salmonids in mid-Columbia river tributary streams.

Musseter, R. 1989. Dynamics of mountain streams. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

National Marine Fisheries Service (NMFS). 2000. Guidelines for salmonid passage at stream crossings, Final Draft. NOAA, Department of Commerce. Southwest Region.

National Marine Fisheries Service (NMFS). 2004. Detection of PIT-Tagged juvenile salmonids in the Columbia River Estuary using a pair-trawl, 2000 and 2001. NOAA, Department of Commerce, Fish Ecology Division, Northwest Fisheries Science Center. Seattle, Washington.

National Oceanic Atmospheric Agency, National Marine Fisheries Service (FCRPS BiOp). 2000. Federal Columbia River Power System Biological Opinion.

Nikora, V. I., J. Aberle, B. J. F. Biggs, I. G. Jowett, and J. R. E. Sykes. 2003. Effects of fish size, time-to-fatigue, and turbulence on swimming performance: a case study of Galaxias maculates; Journal of Fish Biology 63:1365-1382.

Nolan, K.M., C. Frey, and J. Jacobson. 2001. Surface-water field techniques training class (Version 1.0). Water Resources Investigations Report 98-4252. USGS Training Class-SW 4230. US Geological Survey.

Northwest Power and Conservation Council. 2004. Methow Subbasin Plan. KWA Ecological Sciences, Inc., Okanogan County, Washington Department of Fish and Wildlife, and Colville Tribes.

Odeh, M. 2000. Advances in fish passage technology: Engineering design and biological evaluation. American Fisheries Society, Bethesda, Maryland.

Ojanguen, A. F. and F. Brana. 2003. Effects of size and morphology on swimming performance in juvenile brown trout. Ecology of Freshwater Fish 12:241-246.

Oregon State University. 2005. Streamflow evaluations for watershed restoration planning and design. <http://water.oregonstate.edu/streamflow/>, Accessed 2006 April 24.

Pearson, W. H. 2005a. Protocols for evaluation of upstream passage of juvenile salmon in an experimental culvert test bed. Washington Department of Transportation, Battelle Pacific Northwest Division. Report WA-RD 614.1. Richland, Washington.

Pearson, W. H. 2005b. Evaluation of juvenile salmon leaping ability and behavior at an experimental culvert test bed. Washington Department of Transportation, Battelle Pacific Northwest Division. Report WA-RD 614.1. Richland, Washington.

Powers, P. D., and J. F. Orsborn. 1985. Analysis of barriers to upstream fish migration: An investigation of the physical and biological conditions affecting fish passage success at culverts and waterfalls. Bonneville Power Administration report.

Reynolds, F. L., R. L.Reavis, and J. Schuler. 1990. Sacramento and San Joaquin River Chinook salmon and steelhead restoration and enhancement plan. Draft. Inland Fisheries Division, California Department of Fish and Game. Sacramento, California.

Rosgen, D. L. 1996. Applied river morphology. Wildland Hydrology. Pagosa Springs, Colorado.

Rosgen, D. L. 2001. The cross-vane, W-weir, and J-hook vane structures...Their description, design, and application for stream stabilization and river restoration, ASCE conference Reno, Nevada 2001.

Sauer, V.B., and R.W. Meyer. 1992. Determination of error in individual discharge measurements. U.S. Geological Survey. Open file report 92-144. Norcross, Georgia.

Scarnecchia, D. L., and B. B. Roper. 2000. Large-scale, differential summer habitat use of three anandromous salmonids in a large river basin in Oregon, USA. Fisheries Management and Ecology 7:197-209.

Schmetterling, D. 2000. Seasonal movements of fluvial westslope cutthroat trout in the Blackfoot River drainage, Montana. North American Journal of Fisheries Management. 21:507-520.

Steel, E., A, Feist, D.W. Jensen, G.R. Pess, M.B. Sheer, J.B. Brauner, and R.E. Bilby. 2004. Landscape models to understand steelhead (Oncorhynchus mykiss) distribution and help prioritize barrier removals in the Willamette basin Oregon, USA. Canadian Journal of Fisheries and Aquatic Science 61:999-1011.

Stuart, T. A. 1962. The leaping behaviour of salmon and trout at falls and obstructions, Department of Agriculture and Fisheries for Scotland, Freshwaters Fisheries Laboratory, Edinburgh, Scotland.

Symons, P. E. K. 1978. Leaping behavior of juvenile Coho and Atlantic salmon. Journal of the Fisheries Research Board of Canada 35:907-909.

Taylor, R. and M. Love . 2003. California salmonid stream habitat restoration manual, Part IX, Fish passage evaluation at stream crossings. California Department of Fish and Game.

Thomas, D. B., S. R. Abt, R. A. Mussetter, and M. D. Harvey. 2000. A design procedure for sizing step-pool structures. Water Resources proceedings, ASCE.

U.S. Army Corps of Engineers (COE). 1991. Hydraulic design of flood control channels. EM 1110-2-1601.

U.S. Army Corps of Engineers (COE). 2002. HEC RAS River Analysis System, Users manual, version 3.1. Report CPD-68. Institute for Water Resources, Hydrologic Engineering Center. Davis, California.

U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and Bonneville Power Administration (UPA). 2004. Final updated proposed action for the FCRPS biological opinion remand.

U.S. Bureau of Reclamation (BOR). 2004a. Completion report: Lower Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Pacific Northwest Region, PN-3400/Design group. Boise, Idaho.

U.S. Bureau of Reclamation (BOR). 2004b. Completion report: Upper Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Pacific Northwest Region, PN-3400/Design group. Boise, Idaho.

U.S. Bureau of Reclamation (BOR). 2004c. Completion report: Thurlow Transfer Ditch fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Pacific Northwest Region, PN-3400/Design group. Boise, Idaho.

U.S. Bureau of Reclamation (BOR). 2007. River restoration structures research. Sedimentation and River Hydraulics Group. Denver, Colorado. <http://www.usbr.gov/pmts/sediment/projects/>. Accessed 2007 February 1.

U.S. Department of Agriculture, Forest Service (USFS). 1992. Beaver Creek Basin, stream survey report by Troy R. Harmon. Okanogan National Forest, Winthrop, Washington.

U.S. Department of Agriculture, Forest Service (USFS). 1997. Gold Creek, stream survey report. Okanogan National Forest, Winthrop, Washington.

U.S. Department of Agriculture, Forest Service (USFS). 1999. Libby Creek, stream survey report. Okanogan National Forest, Winthrop, Washington.

U.S. Department of Agriculture, Forest Service (USFS). 2004. Stream inventory handbook, Level 1 & 2. Pacific Northwest Region, Region 6.

U.S. Geological Survey (USGS). 1981. Guidelines for determining flood flow frequency. Bulletin 17B. Interagency Advisory Committee on Water Data, Office of Water Data Coordination, Reston, Virginia.

U.S. Geological Survey, StreamStats. 2006. StreamStats statistics report, output reports 18310, 21636, and 21638. <http://streamstats.usgs.gov>. Accessed 2006 March 30.

Washington Department of Fish and Wildlife (WDFW), Yakama Indian Nation, and the Colville Confederated Tribes. 1990. Methow and Okanogan Rivers Subbasin, Salmon

and Steelhead Production Plan. Columbia Basin System Planning, Northwest Power Planning Council, Portland, Oregon.

Washington Department of Fish and Wildlife (WDFW). 2003. Principal author Bates, K. Design of road culverts for fish passage. Olympia, Washington.

Washington Department of Fish and Wildlife (WDFW). 2004. Stream habitat restoration guidelines: Final draft 2004. Olympia, Washington.

GLOSSARY

ADV: Acoustic doppler velocimeter, a sonar-based instrument used for calculating velocities in water column. Typically mounted on top-setting wading rod and connected to data recorder that calculates stream discharge based on velocity and depth measurements.

Bull trout (*Salvelinus confluentus*)

Burst swim speed: Swim speed that can be maintained by a fish for 5 to 10 seconds. Utilized for predation, escape, and jumping.

Cruising swim speed: Swim speed use for movement or migration that can be sustained for many hours.

DEM: Digital elevation model of equidistant, orthogonal points with x, y, and z coordinates. Data developed for USGS quad sheets on resolution scale 10 m and lower.

DTM: Digital terrain model developed from TIN. Utilized for surface sampling, rendering, and volumetric calculations.

EDF: Energy dissipation factor, a hydraulic parameter defined by WDFW

Flow duration analysis: Hydrologic analysis used to determine the duration of time a particular flow is exceeded in percent. Higher percentages are associated with lower flows that are exceeded more frequently.

Flood frequency analysis: Hydrologic analysis that calculates flows associated with annual return periods. Analysis typically determines flows for 2-, 5-, 10-, 25-,50-, 100-, and 500-yr flows. Longer time frames equate to higher flows.

Freshet: High flow occurring in the spring in conjunction with snowmelt and/or rainfall.

Hydrodynamic model: One dimensional model of a stream that calculates water surface elevations, based on conservation of energy.

Hyporheic flow: Subsurface flow through gravels in fluvial system

Log Pearson III distribution: Statistical distribution used to estimate discharges for flood frequencies based on historical flow record. Facilitates calculation of all recurrence flows (USGS 1981).

Niche: Specific feeding strategy within a habitat for a particular species, allows species to cohabitate and feed in the same space (resource partitioning).

Piscivorous: Feeding strategy that includes eating fish.

PIT-tag: Passive integrated transponder tag, electronic microchip inserted into the body cavity of fish with a unique alphanumeric code. When a fish with an implanted PIT-tag passes an antenna, the unique numerical code is registered in a data logger. Data from a network of antennas provides spatial and temporal tracking of fish movement.

Redband rainbow trout (*Oncorhynchus mykiss gairdnei):* resident form of steelhead.

Redd: Bowl-shaped depression in gravel bed created by salmonids for laying eggs

Rock vortex weir: Instream structure constructed of boulders in a 'V' shape that facilitates grade control and backwater for irrigation diversion, while maintaining sediment transport and fish passage.

Spring Chinook (*Oncorhynchus tshawytscha*)

Summer steelhead (*Oncorhynchus mykiss*)

Sustained swim speed: Fish swim speed that can be maintained for minutes, usually used for passing difficult areas.

TIN: Triangular irregular network that serves as a basis for a DTM.

TYP: Typical, indicates that description for entity represents descriptions for similar entities also shown in graphic or sequences graphics, eliminating the need to identify all occurrences of graphic feature.

Weir crest profile: Measured profile along centerline of boulders forming weir crest, following a trapezoidal alignment for a rock vortex weir

Westslope cutthroat trout (*Oncorhynchus clarkii lewisi*)

APPENDIX A. Fish passage guidelines from NMFS and WDFW

The National Marine Fisheries Service (NMFS) and Washington Department and Fish and Wildlife (WDFW) have developed design guidelines for anandromous fish passage at culverts (NMFS 2000, WDFW 2003). Since no guidelines were identified specifically addressing fish passage at rock vortex weirs, culvert-based guidelines were used to set the hydraulic criteria and evaluate the effectiveness of rock weir structures for upstream fish passage for this thesis. The key performance criteria include limits on high stream velocities, large hydraulic drops, and other factors that restrict fish passage. A summary of fish passage guidelines from NMFS (2000) and WDFW (2003) is shown in Table A.1.

Table A.1 Summary of fish passage guidelines from NMFS (2000) and WDFW (2003).

Criteria	NMFS (2000)		WDFW (2003)			
	Juvenile salmonids	Adult salmonids	Juvenile salmonids	Trout >6in.	Pink, chum salmon	Chinook, Coho, sockeye, steelhead
Max. hydraulic drop (m)	0.15	0.30	Not specified	0.24	0.24	0.30
Max. velocity (m/s)	0.30 to 0.61 *	1.83	0.37 *	1.22	1.52	1.83
Min. water depth (m)	0.15	0.30	Not specified	0.24	0.24	0.30
Min. pool depth (m)	0.61 m		0.91 m			
Min. ratio pool depth to hydraulic drop	1.5		Not specified			
Max. energy dissipation factor	Not specified		250 W/m^3 for hydraulic design (5 ft-lb/ft^3/s) (Klavas, personal communications, 2006)			
Low design flow	95% exceedance	50% exceedance	95% exceedance **			
High design flow	10% exceedance	1% exceedance	10% exceedance or 2-yr flood			

* Velocities are averaged over cross section area.

** Exceedance flows only include flows during migration season for target species and life stages. An exceedance flow is a discharge that is equaled or exceeded a specified percent of time. Higher values of percent exceedance correspond to lower flows.

Four hydraulic parameter guidelines established by NMFS (2000) and WDFW (2003) used in this thesis to evaluate fish passage at rock vortex weirs include the following (Figure A.1):

1) Hydraulic drop
2) Average velocity over weir
3) Ratio of pool depth to hydraulic drop
4) Energy dissipation factor

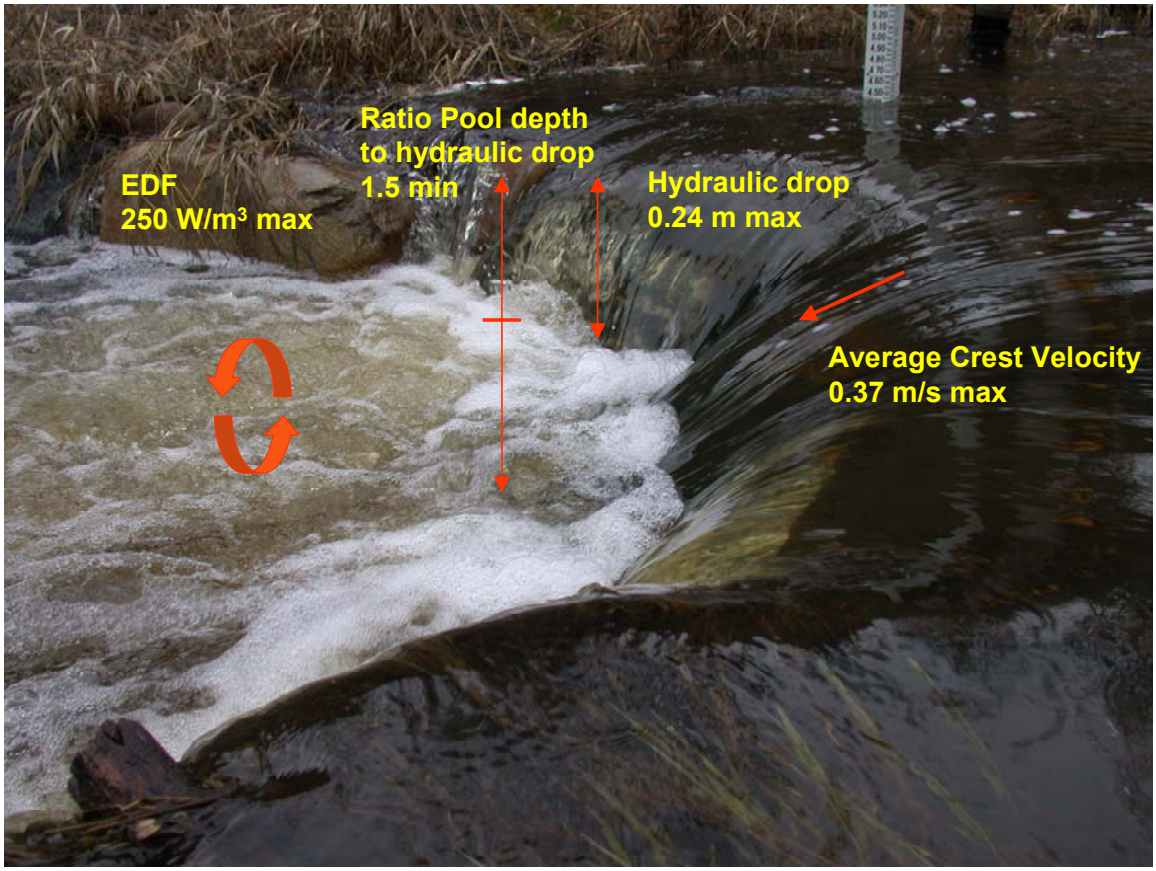


Figure A.1 Photo of rock vortex weir with hydraulic parameters for fish passage.

Threshold values for these four hydraulic parameters were distilled from Table A-1 into a composite set of criteria as shown in Table A-2. The values for the thresholds were based on a review of NMFS (2000) and WDFW (2003) and personal communications with Pat Klavas of WDFW (2006), to clarify appropriate guidelines for passing juvenile and adult salmonids, as shown in WDFW (2003). The effectiveness of upstream fish passage at the rock vortex

weirs was evaluated based on the threshold values in Table A.2 for the four hydraulic parameters. A high design flow value of 5-percent exceedance, rather than 10-percent, was used to capture 90-percent of the flows for juvenile and adult fish passage, as suggested by WDFW (2003). This range of design flows concurs with the NMFS Northwest region criteria (Lang et al. 2004).

Table A.2 Hydraulic parameters used in this thesis to evaluate fish passage effectiveness rock vortex weirs.

Criteria	Value
Max. hydraulic drop (m)	0.24
Max. average velocity (m/s)	0.37
Min. ratio pool depth to hydraulic drop	1.5
Max. energy dissipation factor (W/m^3)	250
Low design flow	95% exceedance
High design flow	5% exceedance

<u>Additional NMFS (2000) guidelines</u>

- Hydraulic design should provide an acceptable range of flows, based on monthly periods when salmonids migrate. It is recommended to consult with local NMFS biologists.
- Unimpeded passage of water, sediment, and debris over a wide range of flows is necessary to maintain channel processes, hydraulic and geologic stability in the vicinity of the structure, and habitat values over a stream reach.
- For high passage design flows, in the absence of hydrologic data, high passage discharge flow should be based on the discharge occupied by the cross sectional area of the active channel.
- Structures must sufficiently pass the 100-year storm.
- Structures should be aligned with the stream, with no abrupt changes in flow direction.

- Livestock fences should be avoided in streambeds, otherwise there should be a minimum of 0.24 m between pickets and timely clearing of debris must be provided.
- Construction disturbance should be minimized and should not impact fish migration or spawning.

Additional WDFW (2003) guidelines

- Structures should provide fish passage for 90% of flows during the passage season.
- Structure should provide mitigation for future design flows and land use changes.
- A minimum of two rows of rock should be placed to form a crest and provide scour protection. For small streams, a minimum rock diameter should be 0.6 m, and for larger streams rock diameter should be 1.2 to 1.8 m. In general, crest and foundation rocks should be sized according design discharge and stream slope. Large rocks should be carefully placed to withstand hydraulic loads, maintain multiple points of contact with adjacent rocks, and reduce gaps.
- Structure should maintain integrity in a 100-year peak flow.
- General criteria for fishways are provided in WDFW policy POL-M5001.
- Flow condition at weirs for non-leaping fish shall be optimized to allow swim-though conditions at notch (lowered boulder in middle of rock vortex weir) by creating streaming, rather than plunging flow, and a velocity appropriate for the species requiring passage.
- Fishway pools and corners shall be designed to minimize unnecessary turbulence.
- Pool volume for energy dissipation needs to be within 3.0 m of the plunge.
- Areas impacted during construction shall be revegetated.

Appendix B. Surveyed topographic data for Lower Stokes, Thurlow and Upper Stokes project sites

Each of the three project sites (Lower Stokes, Upper Stokes, and Thurlow) required multiple instrument set ups for survey equipment and local arbitrary vertical and horizontal control, since official georeferenced control points were not available near the project sites. Initial ground survey established the control network to tie in all cross sections, profiles, and pre-existing monuments established by others. The initial total station set up was chosen for line of sight on major benchmarks with arbitrary coordinates for northing, easting, and elevation. Additional instrument set ups were required to shoot survey points in heavy vegetation. Horizontal and vertical controls were maintained throughout the ground survey. About 1,000 points were surveyed at each project site in 2004 and 2005.

Approximately 18–19 cross sections were measured at each project site, including cross sections at the pressure transducer instrument sites. In addition, topography near the rock weirs and longitudinal profiles of top of bank, edge of water, and thalweg were also measured. Cross sections described positions and shapes of structures as well as the channel dimensions upstream, between, and downstream of structures. Cross section endpoints were marked with 0.5 meter long, 15 mm diameter (18-inch long, 1/2-inch) rebar driven flush to the ground. Each rebar was covered with an orange plastic caps scribed with cross section number to provide repeated measures for future ground surveys. The cross section surveys extended from about 10 to 15 channel widths upstream of structures to about 10 to 15 channel widths downstream of the structures to facilitate boundary conditions for rough boundary flow modeling. Locations of the cross sections for Lower Stokes, Upper Stokes, and Thurlow project sites are shown in Figures B.1, B.2, and B.3, respectively.

In addition to cross sections, staff gages, topographic details of the structures, and channel features were surveyed. Staff gage data were surveyed to correlate visual readings on the staff gages to a common vertical datum that included topographic survey and pressure transducer sensor elevation. The surveyed topographic details included outlines of the weir crests, pool spot elevations and other bathymetric points to facilitate generation of a digital terrain model (DTM). Surveyed channel features included channel thalweg, stream banks, slope breaks and water surface profiles. These survey details were used to construct a DTM of a triangular irregular network (TIN) in AutoCAD

2003 (Autodesk, San Rafael, California). Base on the TIN, contours were generated for the weirs at 0.10 meter intervals. Figures showing the contours at each for the three project sites are given below.

For survey points at the staff gages and water surfaces, the date, time, and pressure transducer staff readings were noted to correlate discharge to water surface elevations. These data were used to calibrate and validate the hydrodynamic model for rough boundary flow.

Surveyed data included the following:

- Weir topography
- Weir pool volume estimates
- Cross sections
- Longitudinal profiles

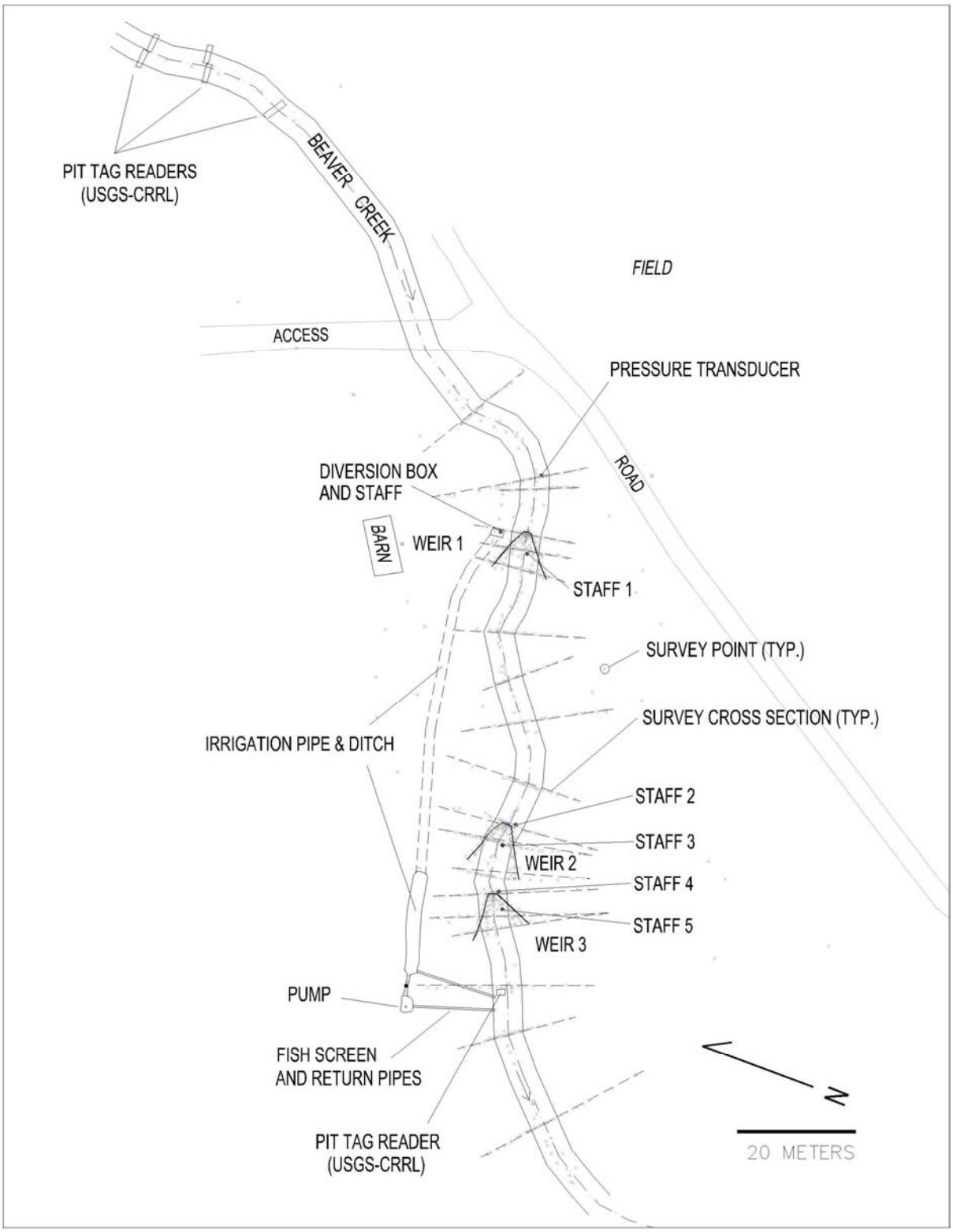


Figure B.1 Site layout at Lower Stokes project.

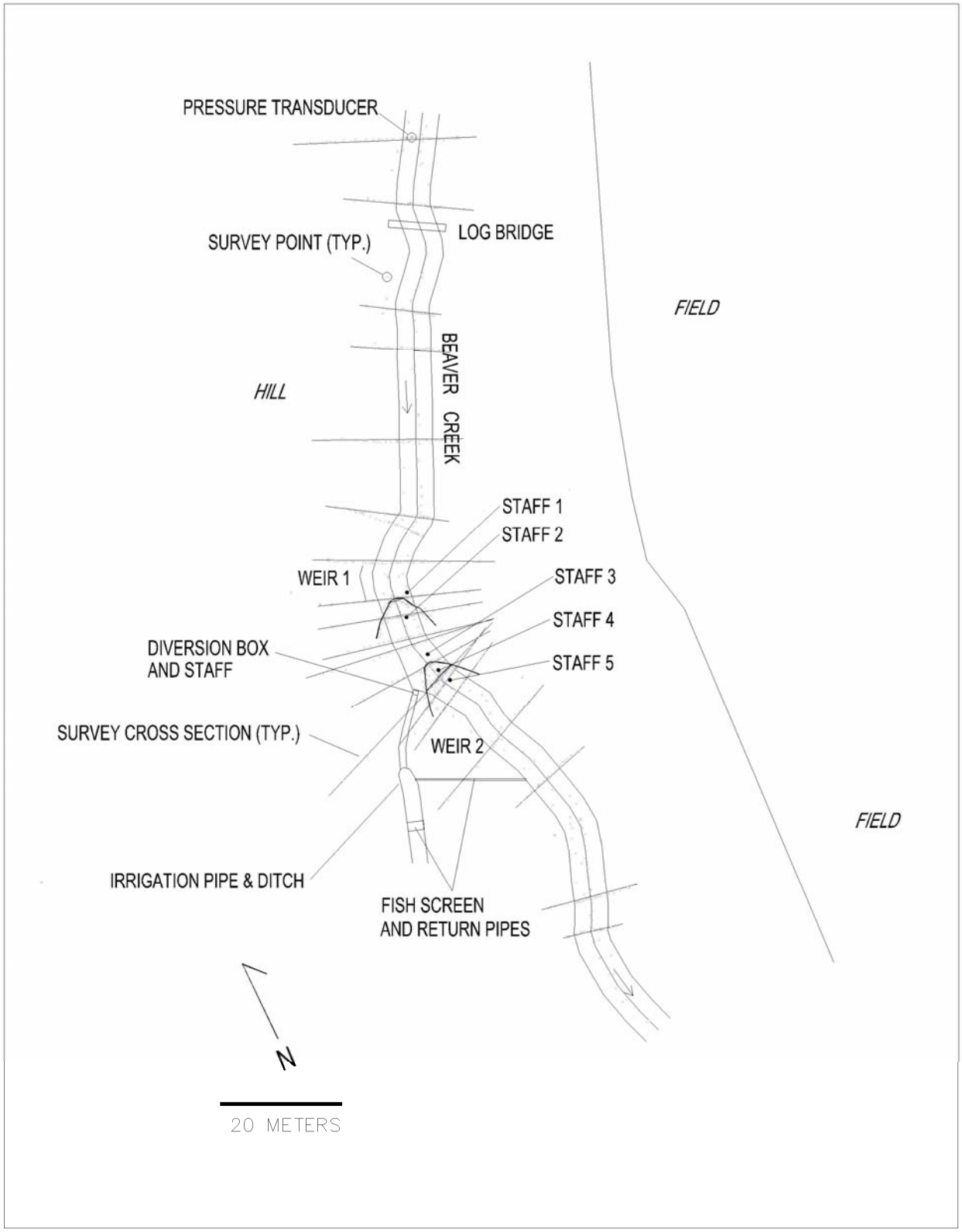


Figure B.2 Site layout at Upper Stokes project.

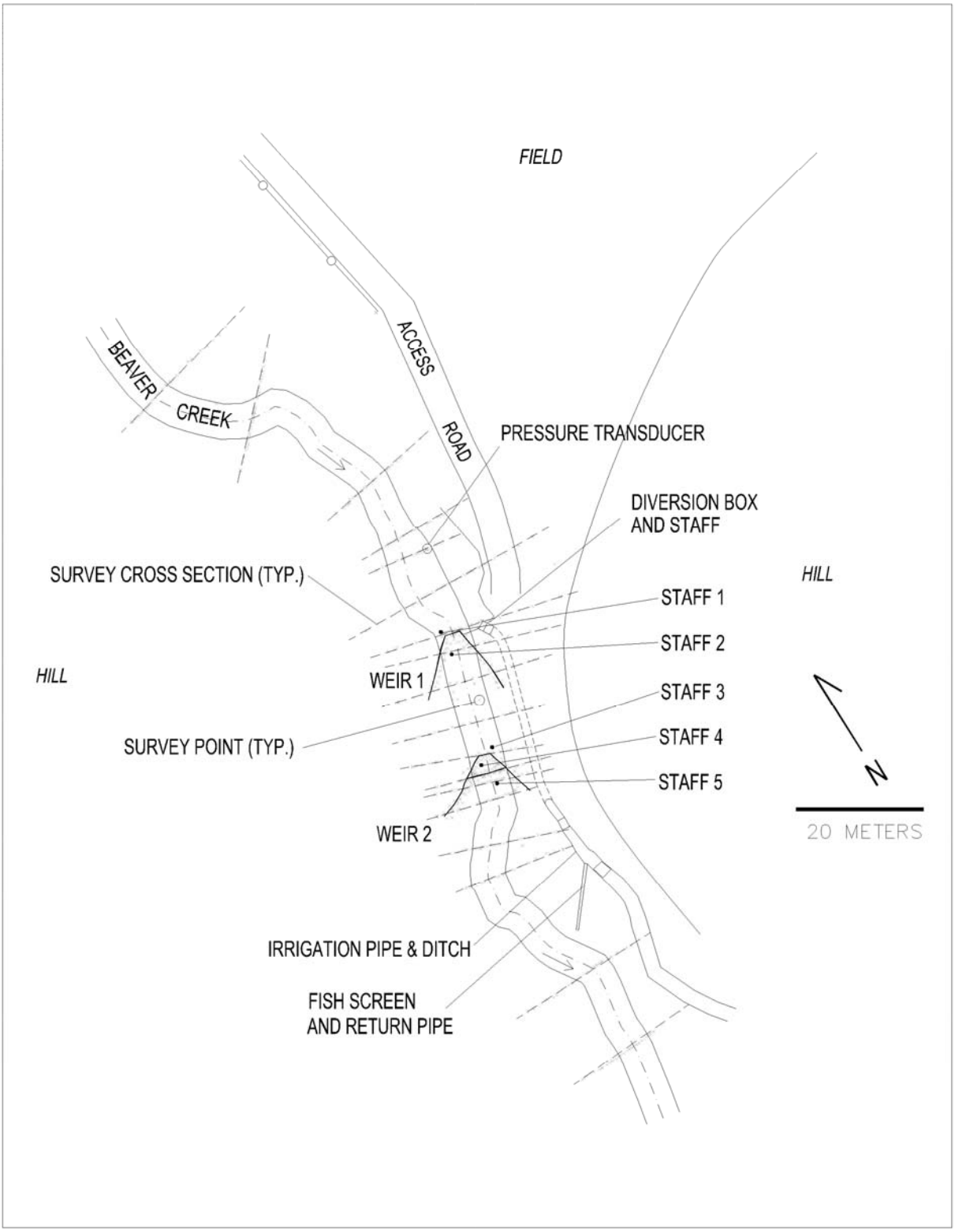


Figure B.3 Site layout at Thurlow project.

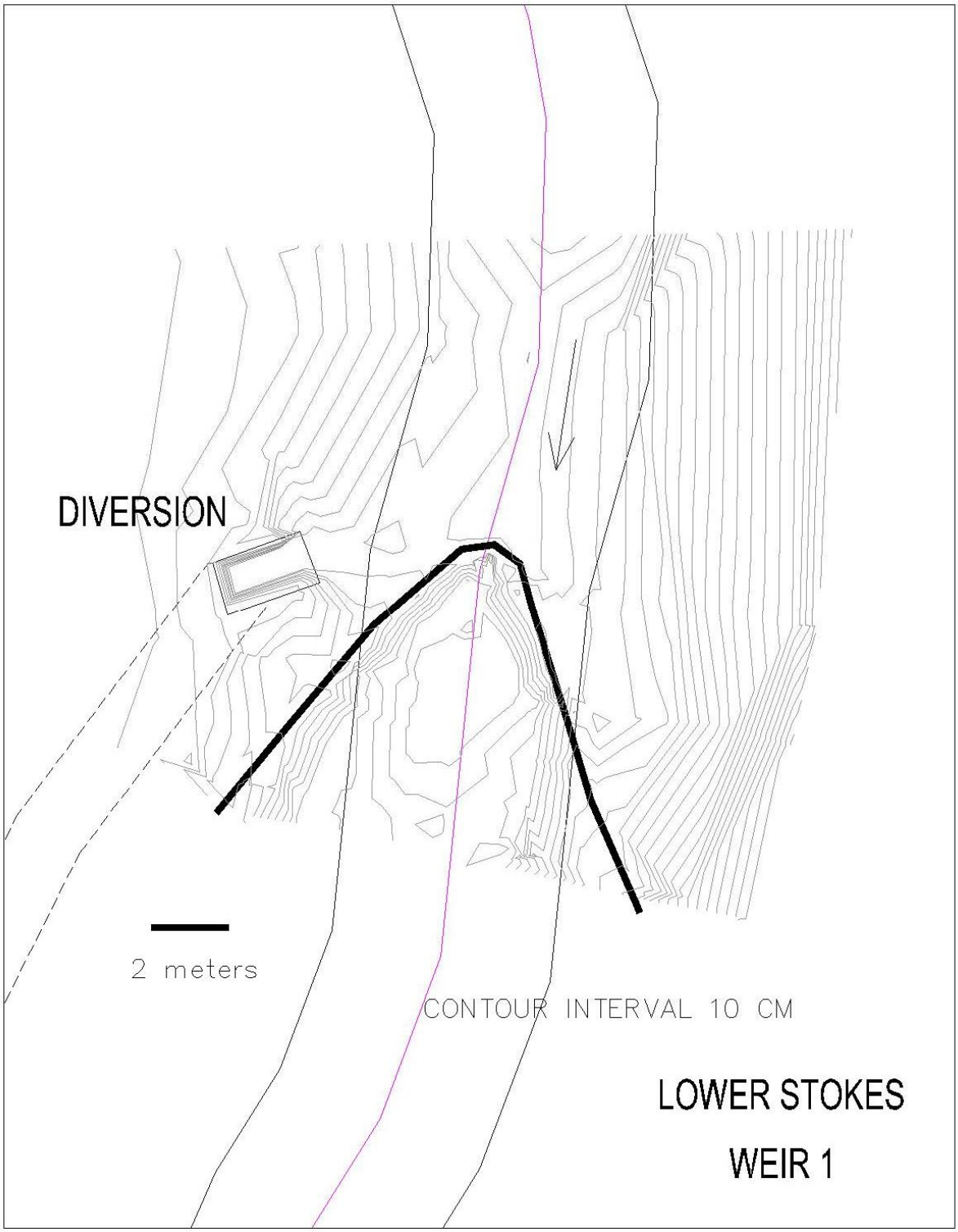


Figure B.4 Topography at Lower Stokes, Weir 1.

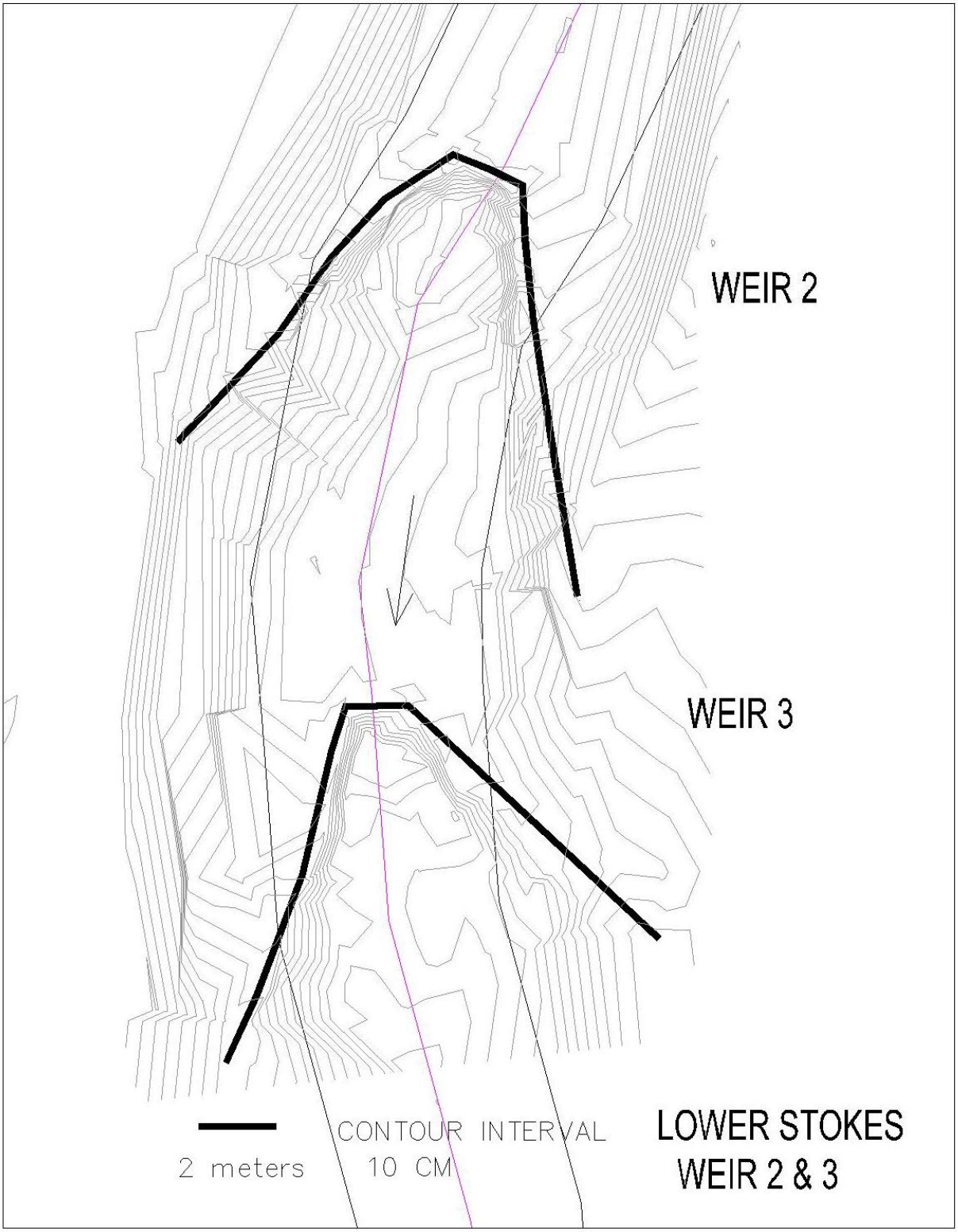


Figure B.5 Topography at Lower Stokes, Weirs 2 and 3.

Figure B.6 Topography at Thurlow, Weirs 1, 2 and 3.

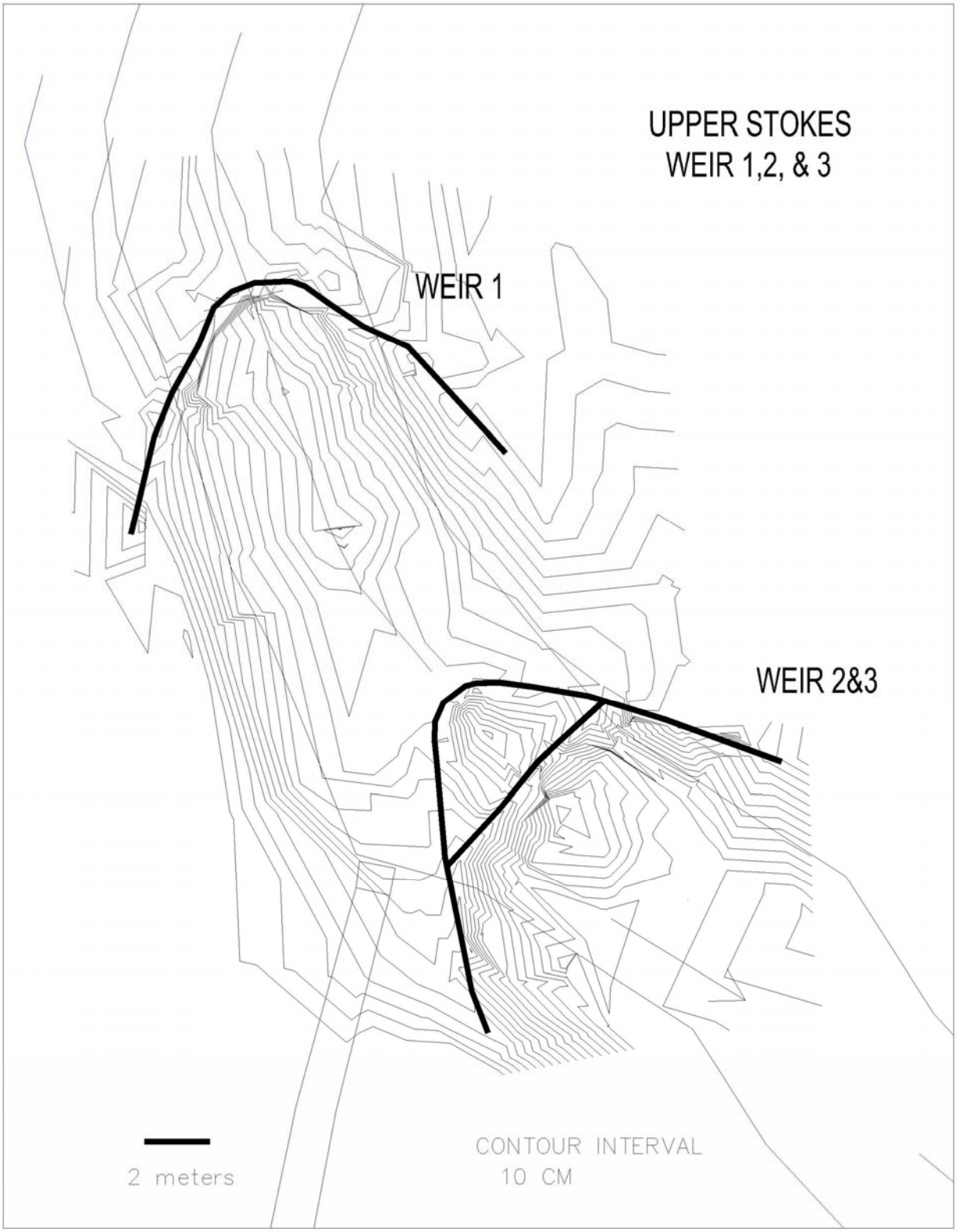


Figure B.7 Topography at Upper Stokes, Weirs 1, 2, and 3.

Table B.1 Weir pool volumes at Lower Stokes.

LOWER
STOKES
Pool volume estimates from DTMs of weirs 1, 2, 3

Pool volume calculation includes volume within 3 m (10 feet) downstream of weir crest.

Weir 1 pool volume estimate

source	el (m)	depth (m)	CAD area (m^2)	inc vol m^3	cum vol m^3
dtm	28.2	0.0	0.0	0.0	0.0
ctr	28.3	0.1	1.9	0.1	0.1
ctr	28.5	0.3	4.5	0.5	0.6
ctr	28.7	0.4	5.9	0.8	1.4
ctr	28.8	0.6	7.6	1.0	2.4
ctr	29.0	0.7	9.9	1.3	3.7
top weir	29.1	0.9	9.9	1.5	5.2
	29.3	1.0	9.9	1.5	6.7
	29.4	1.2	9.9	1.5	8.3
	29.6	1.3	9.9	1.5	9.8

no change in area at top of weir

Weir 2 pool volume estimate

source	el (m)	dep (m)	area m^2	inc vol m^3	cum vol m^3
dtm	27.1	0.0	0.0	0.0	0.0
ctr	27.3	0.2	3.2	0.2	0.2
ctr	27.4	0.3	5.2	0.6	0.9
ctr	27.6	0.5	6.6	0.9	1.8
ctr	27.7	0.6	7.4	1.1	2.8
ctr	27.9	0.8	8.2	1.2	4.0
ctr	28.0	0.9	9.2	1.3	5.4
top weir	28.2	1.1	10.6	1.5	6.9
	28.3	1.2	10.6	1.6	8.5
	28.5	1.4	10.6	1.6	10.1

Weir 3 pool volume estimate

source	el (m)	depth (m)	area m^2	inc vol m^3	cum vol m^3
dtm	27.0	0.0	0.0	0.0	0.0
ctr	27.1	0.2	1.4	0.1	0.1
ctr	27.3	0.3	3.9	0.4	0.5
ctr	27.4	0.5	5.5	0.7	1.2
ctr	27.6	0.6	6.2	0.9	2.1
ctr	27.7	0.8	7.4	1.0	3.2
top weir	27.9	0.9	9.7	1.3	4.5
	28.0	1.1	9.7	1.5	5.9
	28.2	1.2	9.7	1.5	7.4
	28.3	1.4	9.7	1.5	8.9

Table B.2 Weir pool volumes at Thurlow and Upper Stokes.

THURLOW

Pool volume estimates from DTM of weir 1

Pool volume calculation includes volume within 3 m (10 feet) downstream of weir crest.

Weir 1 pool volume estimate

source	el (m)	depth (m)	CAD area m^2	inc vol m^3	cum vol m^3
dtm	26.7	0.0	0.0	0.0	0.0
ctr	26.8	0.1	0.9	0.0	0.0
ctr	27.0	0.2	4.7	0.4	0.5
ctr	27.1	0.4	6.7	0.9	1.3
ctr	27.3	0.5	8.0	1.1	2.5
ctr	27.4	0.7	9.4	1.3	3.8
top weir	27.6	0.9	12.6	1.7	5.5
	27.7	1.0	12.6	1.9	7.4
	27.9	1.2	12.6	1.9	9.3
	28.0	1.3	12.6	1.9	11.2

no change in area at top of weir

UPPER STOKES

Pool volume estimates from DTM of weir 1

Weir 1 pool volume estimate

source	el (m)	depth (m)	CAD area m^2	inc vol m^3	cum vol m^3
dtm	27.9	0.0	0.0	0.0	0.0
ctr	28.0	0.2	1.8	0.1	0.1
ctr	28.2	0.3	4.8	0.5	0.6
ctr	28.3	0.5	7.3	0.9	1.6
ctr	28.5	0.6	9.0	1.2	2.8
ctr	28.7	0.8	10.0	1.4	4.3
top weir	28.8	0.9	12.0	1.7	5.9
	29.0	1.1	13.5	1.9	7.9
	29.1	1.2	14.8	2.2	10.0
max area	29.3	1.4	16.0	2.3	12.4

no change in area at top of weir

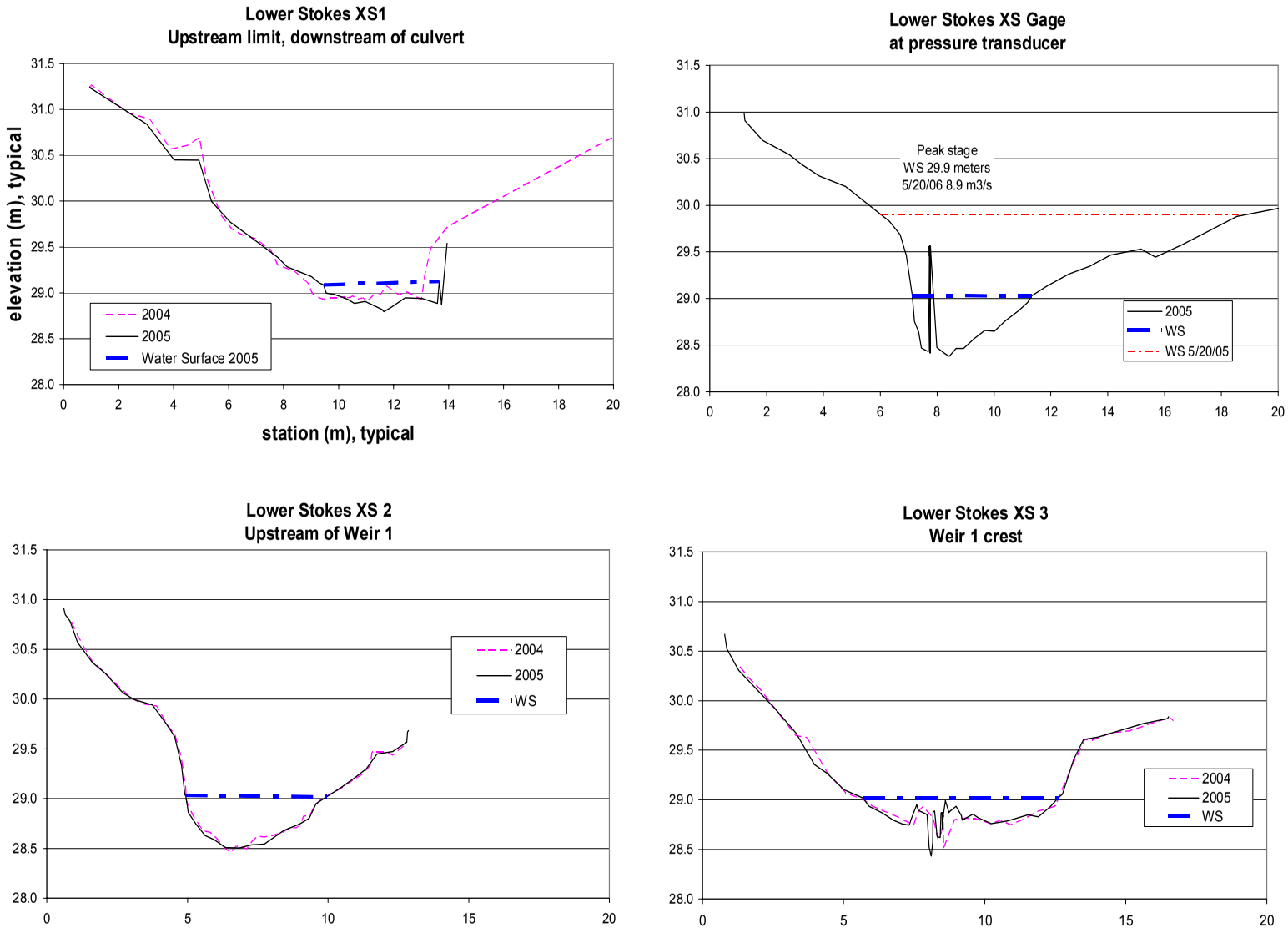


Figure B.8 Cross sections at Lower Stokes.

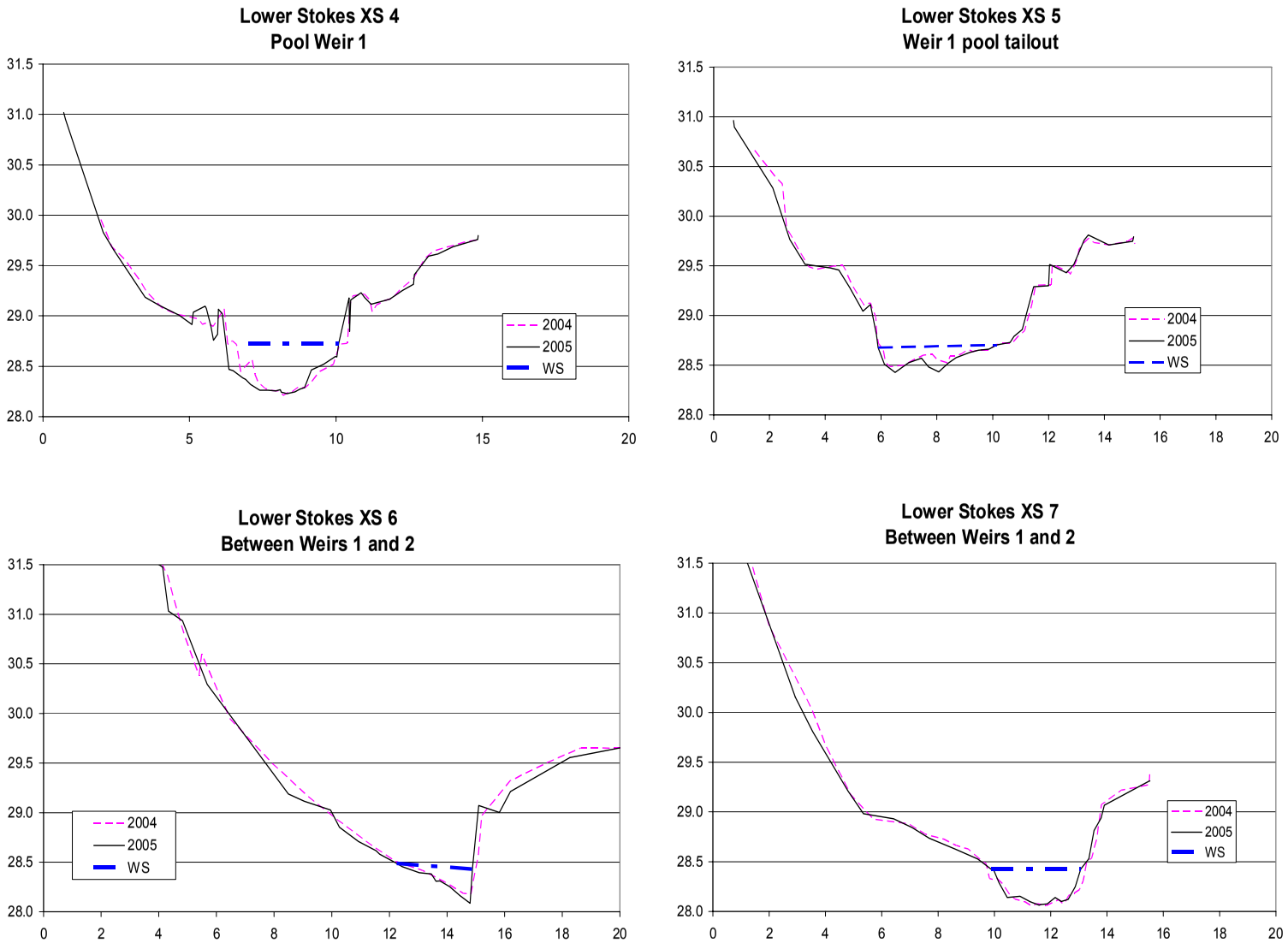


Figure B.8 (continued) Cross sections at Lower Stokes.

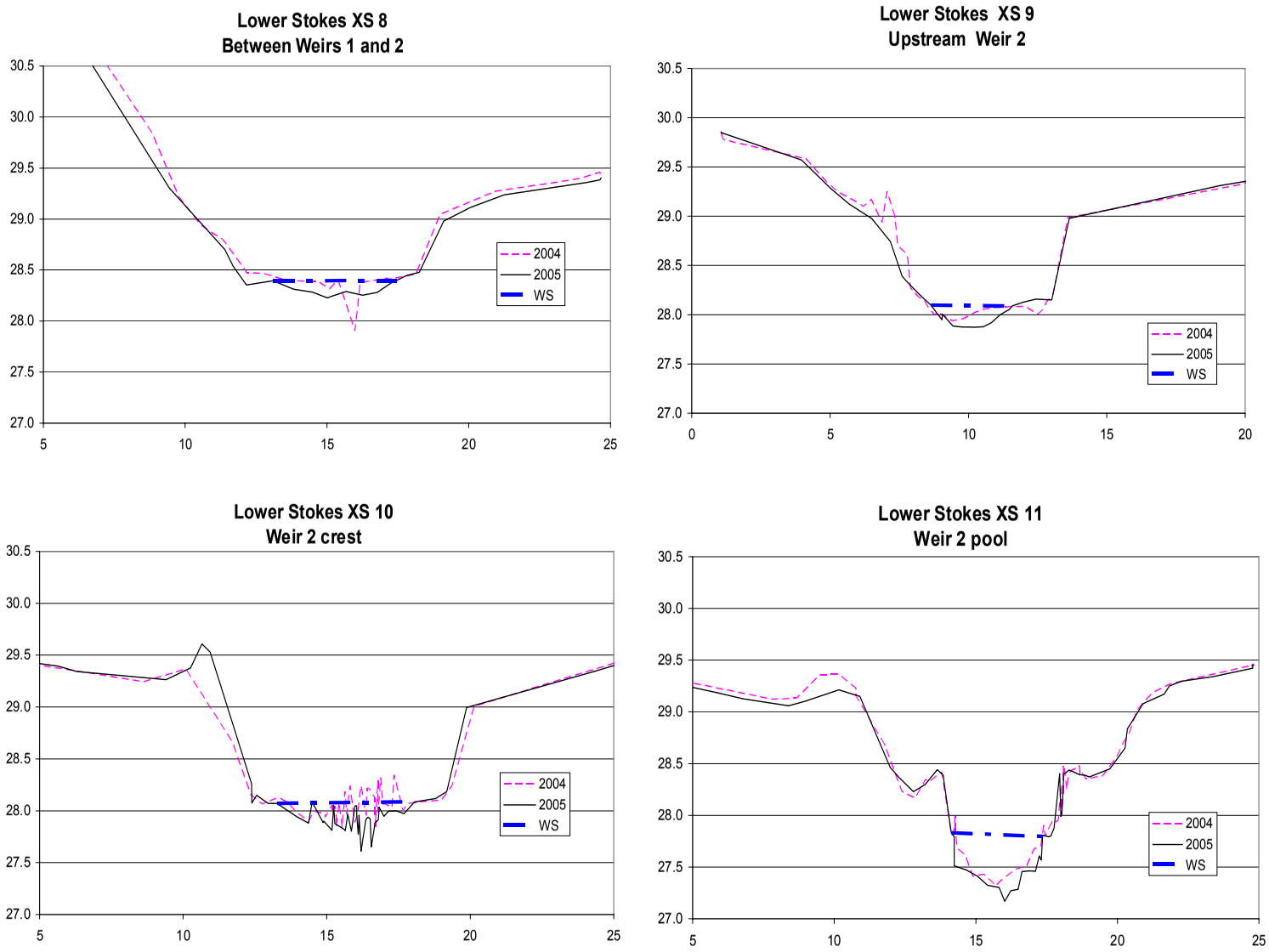
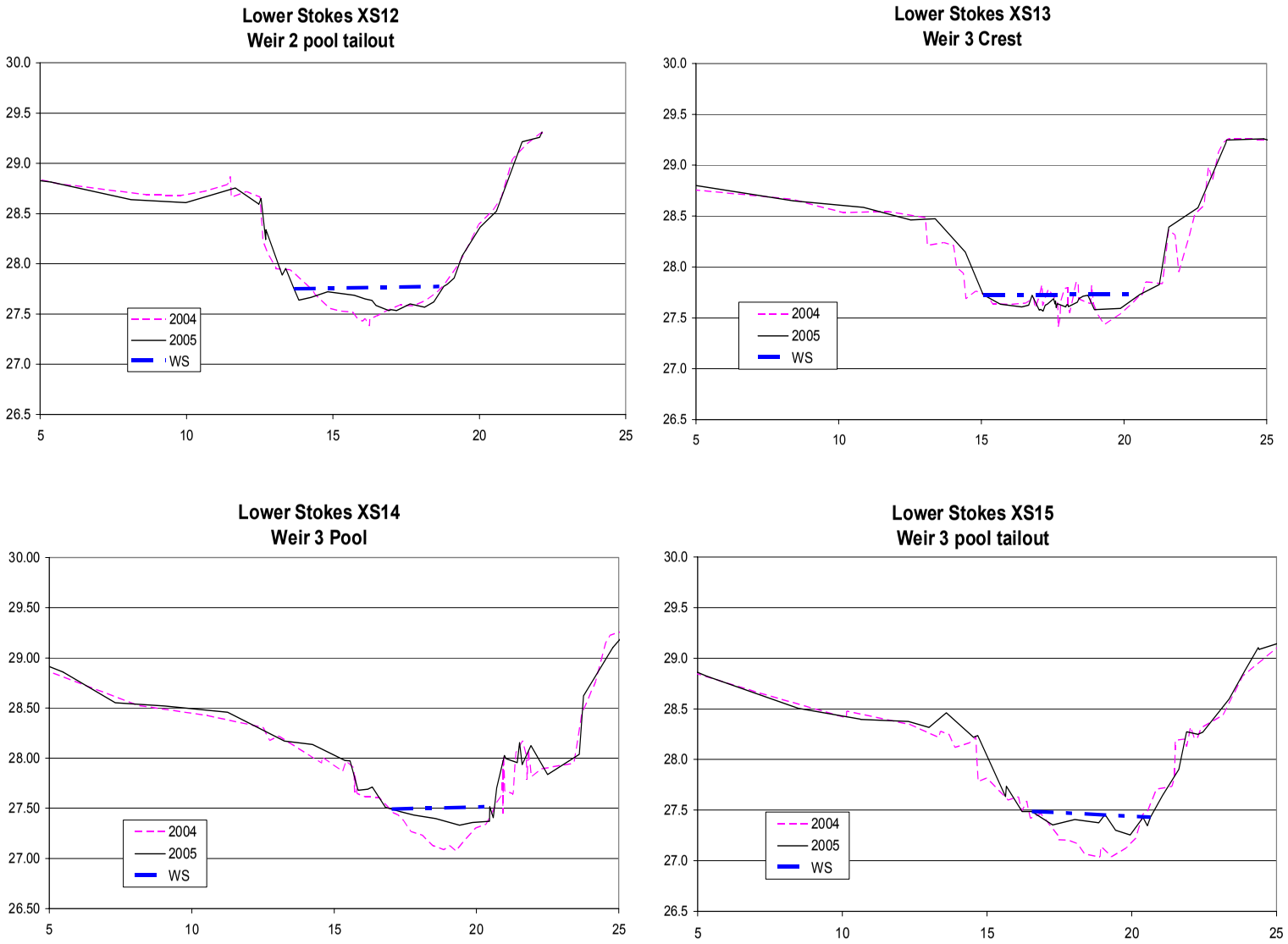


Figure B.8 (continued) Cross sections at Lower Stokes.



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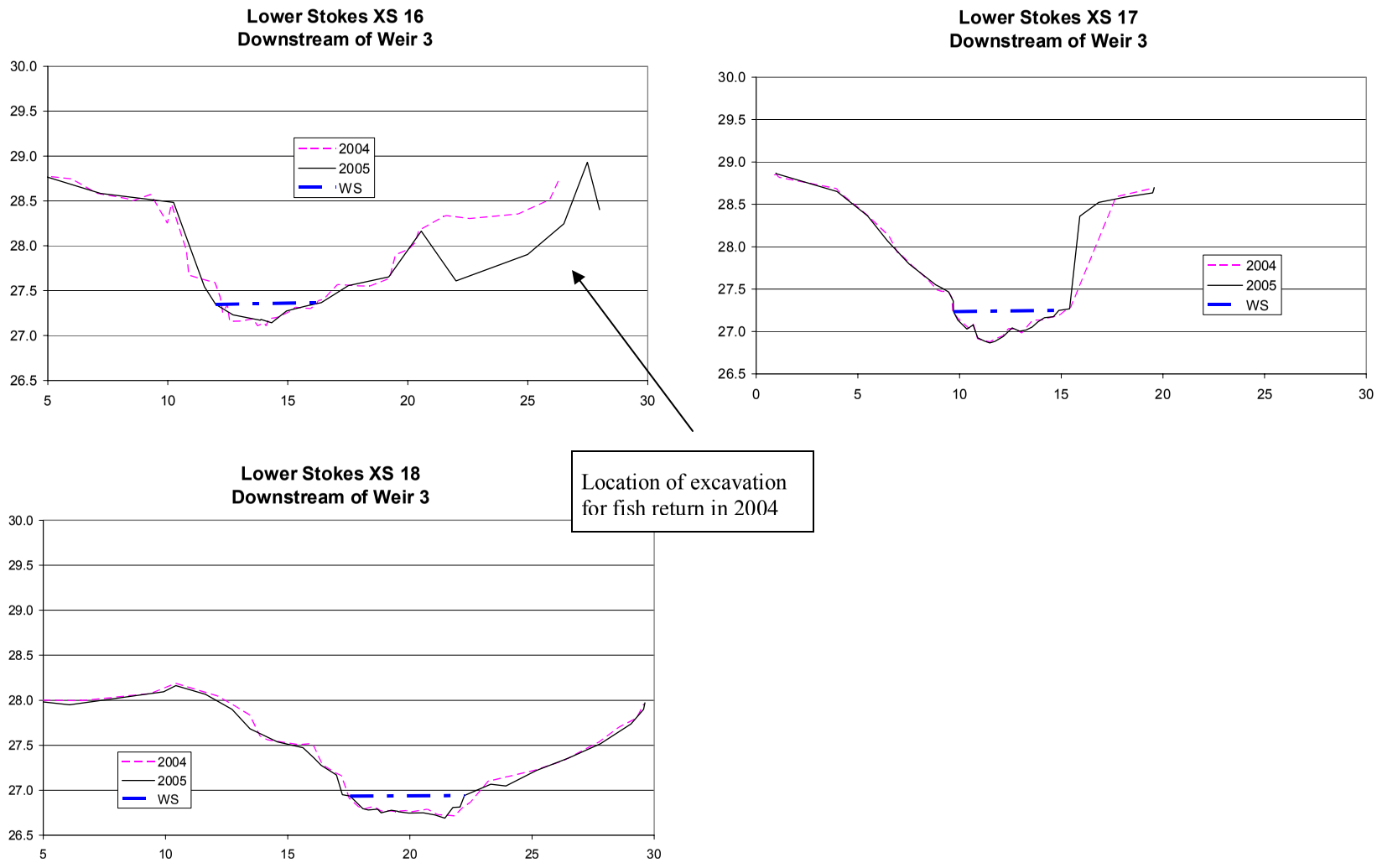

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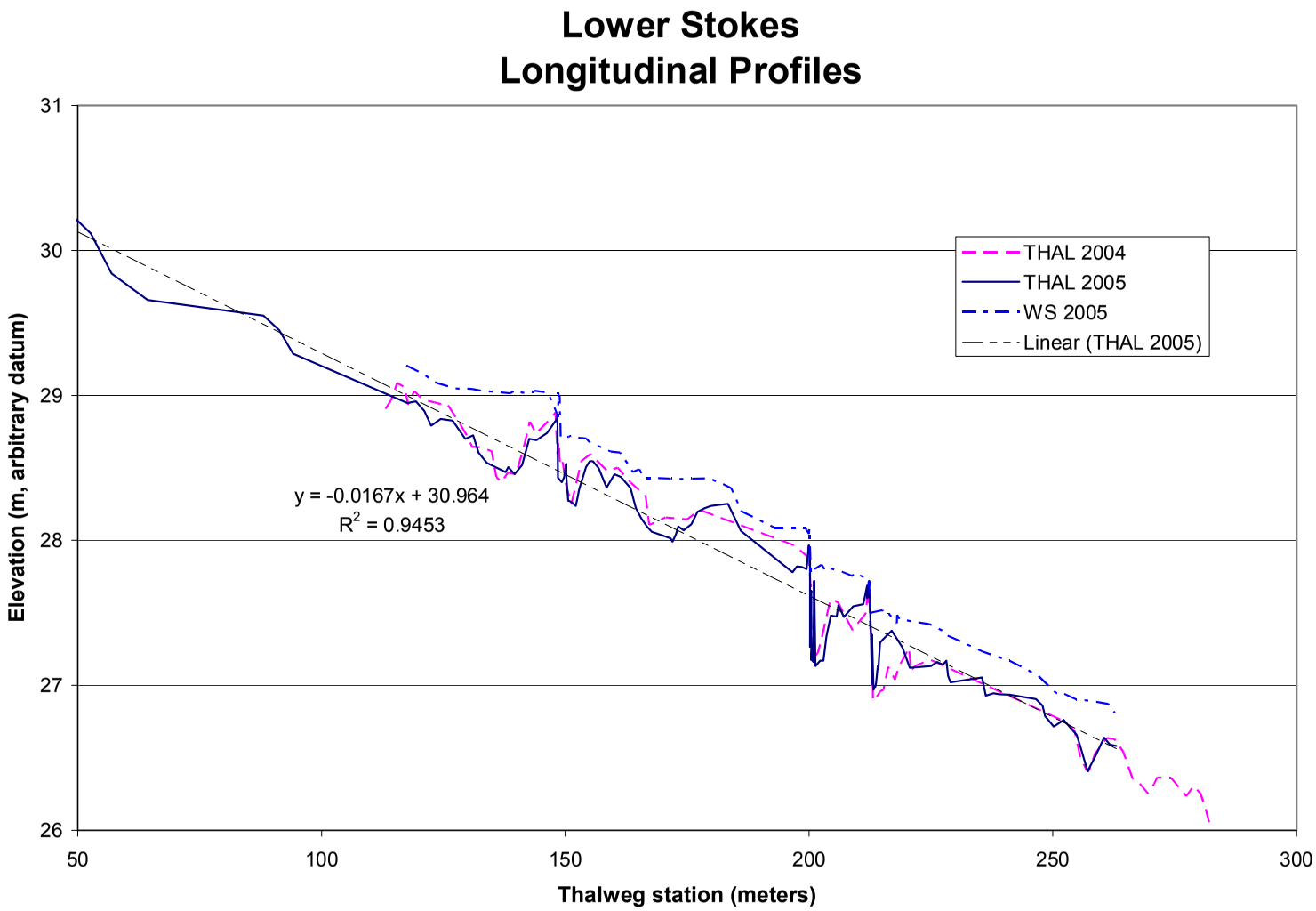


Figure B.9 Surveyed profiles at Lower Stokes.

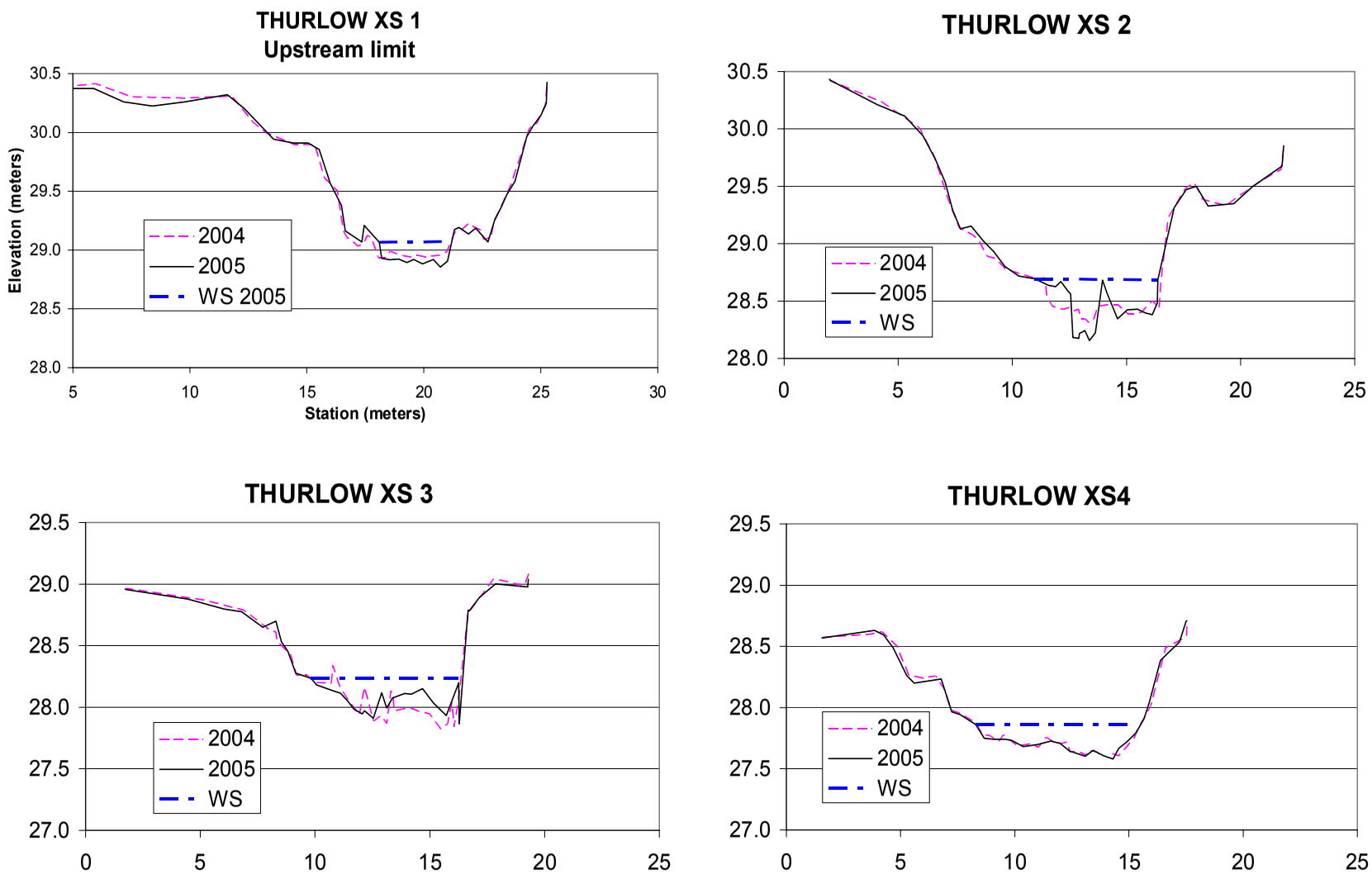


Figure B.10 Cross sections at Thurlow.

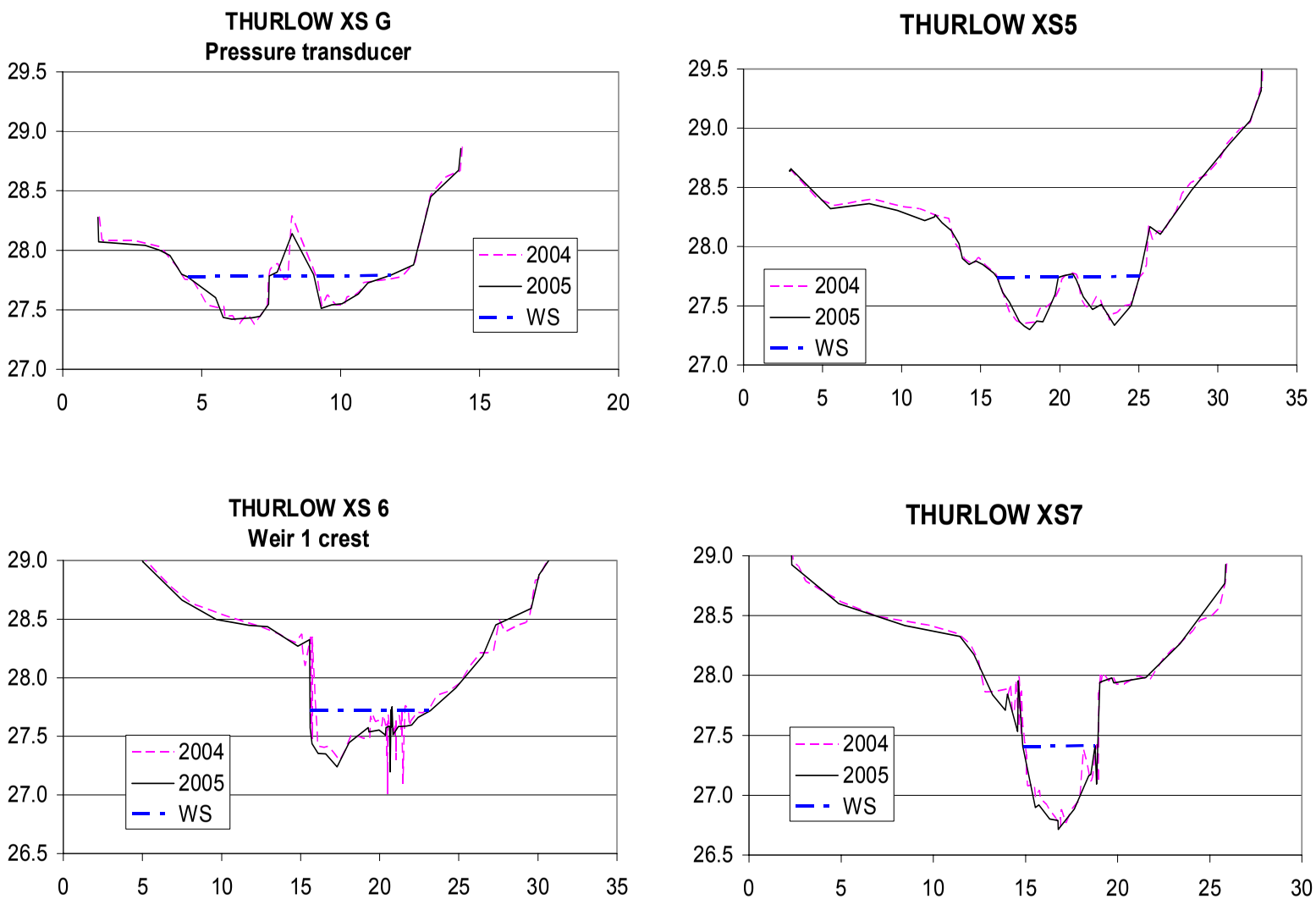
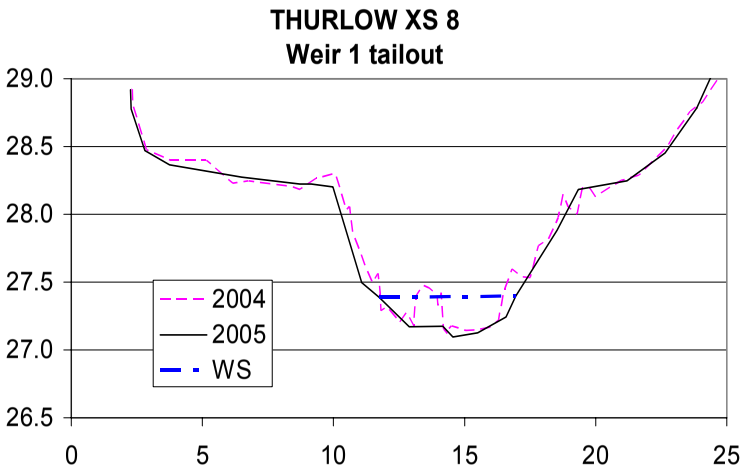
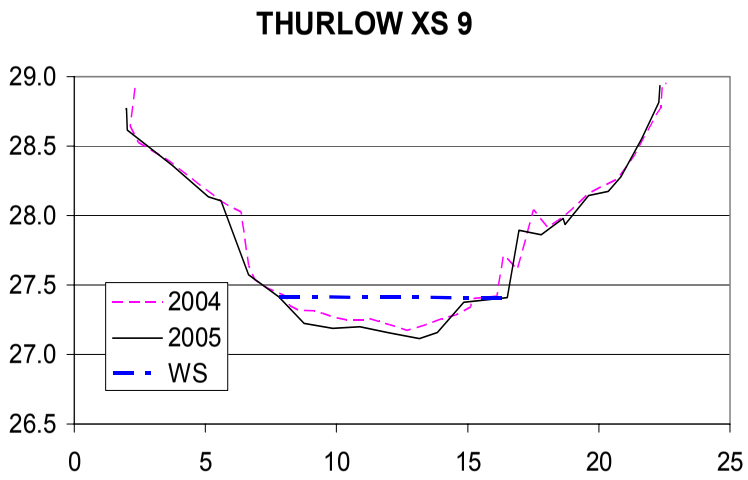
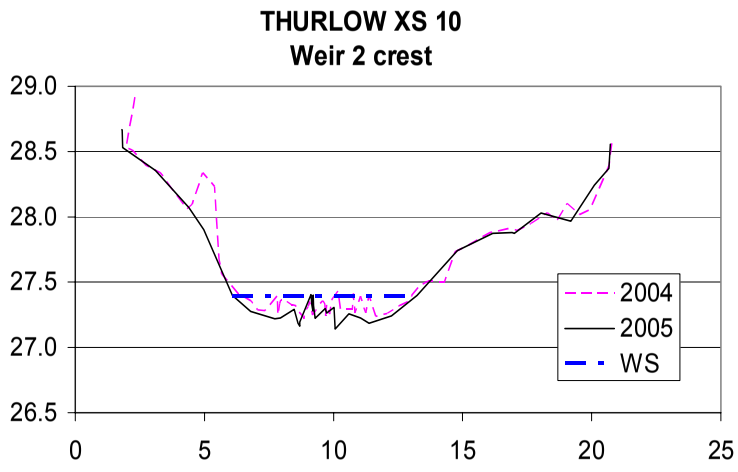


Figure B.10 (continued) Cross sections at Thurlow.







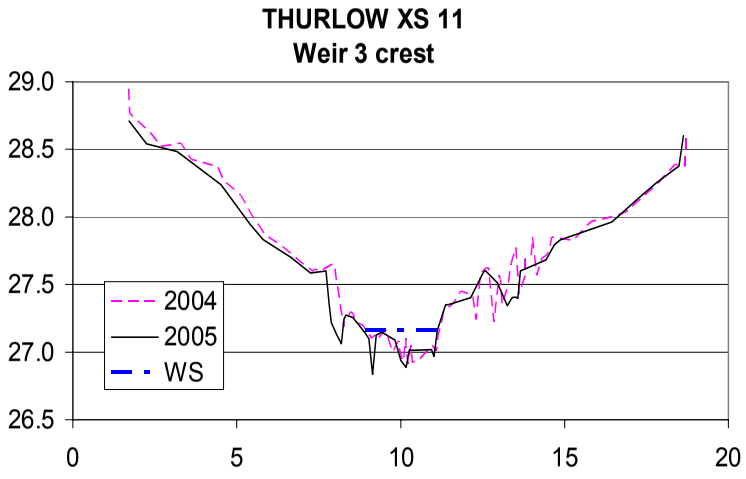


Figure B.10 (continued) Cross sections at Thurlow.

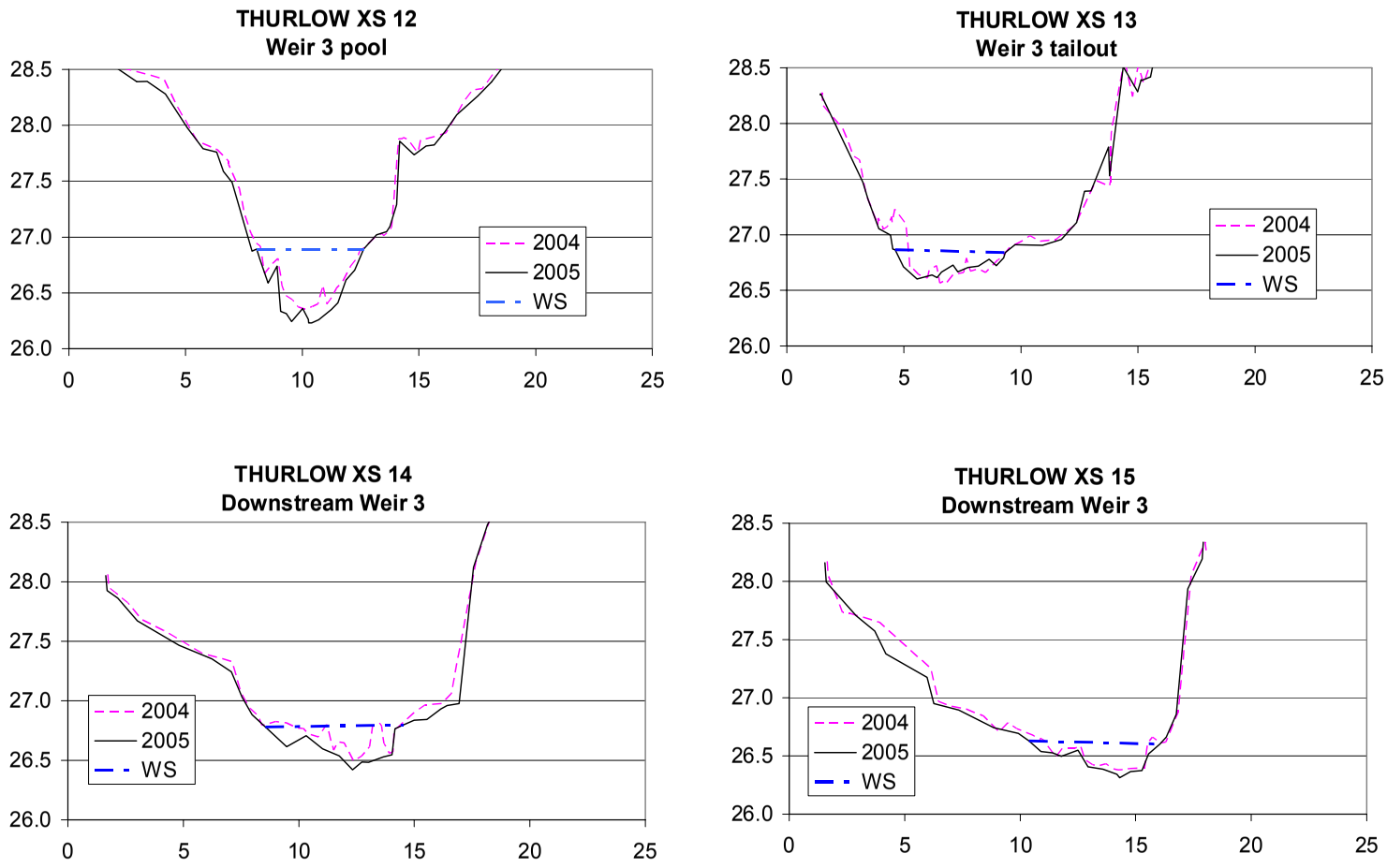
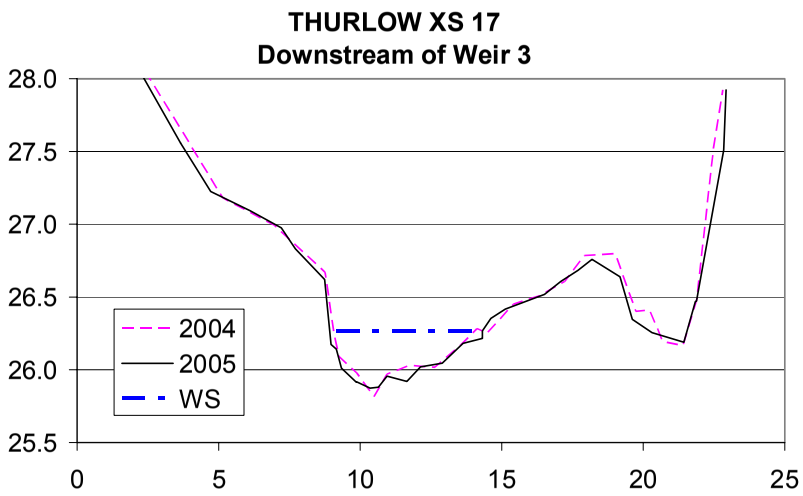


Figure B.10 (continued) Cross sections at Thurlow.



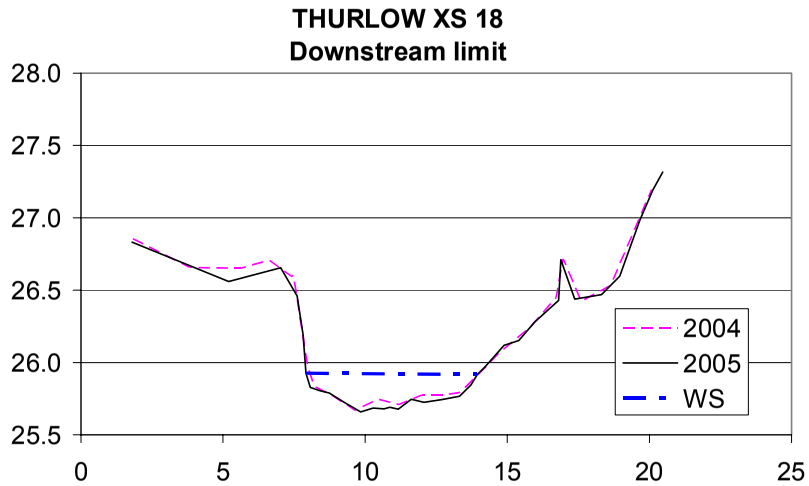


Figure B.10 (continued) Cross sections at Thurlow.

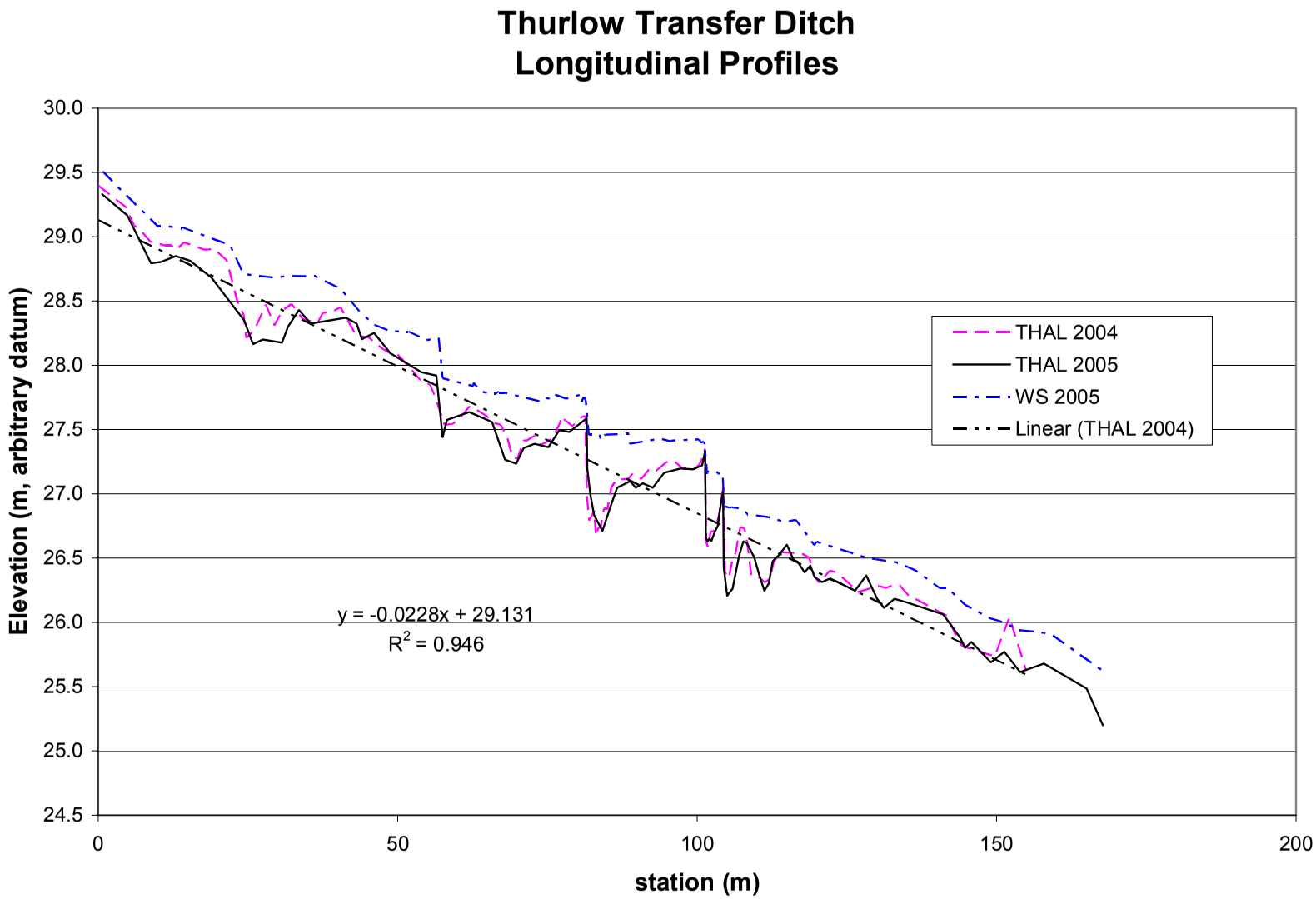


Figure B.11 Surveyed profiles at Thurlow.

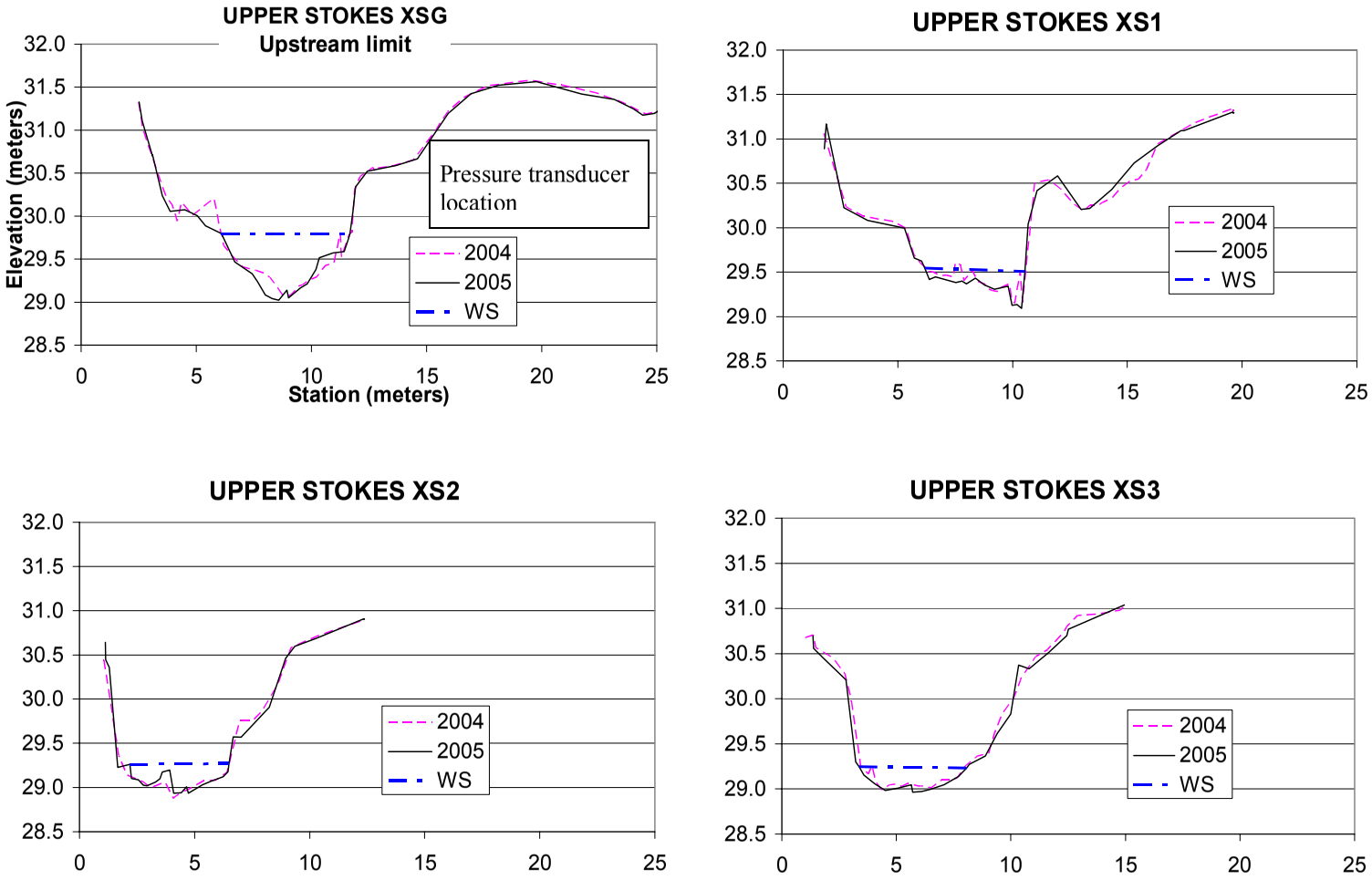


Figure B.12 Cross sections at Upper Stokes.

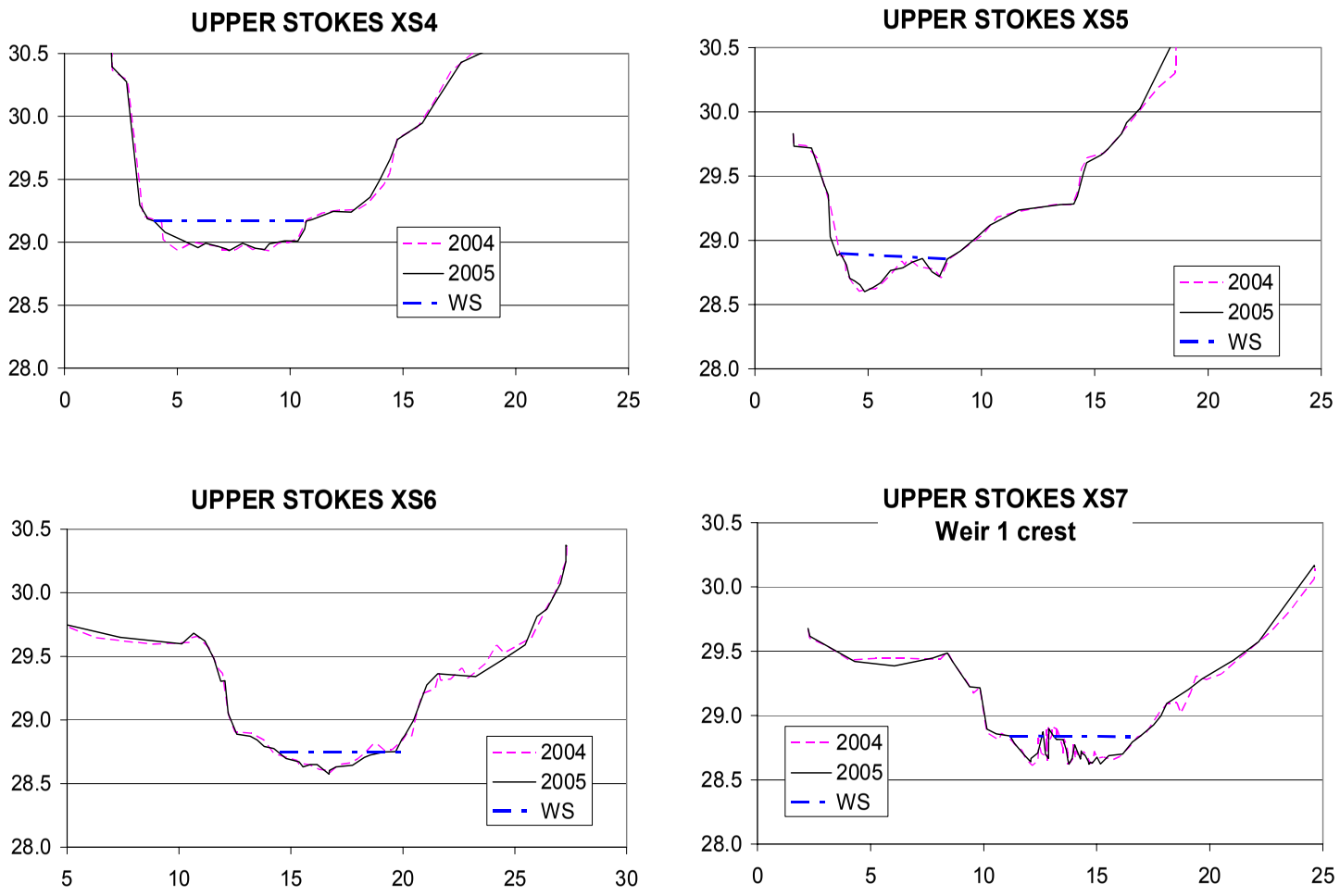


Figure B.12 (continued) Cross Sections at Upper Stokes.

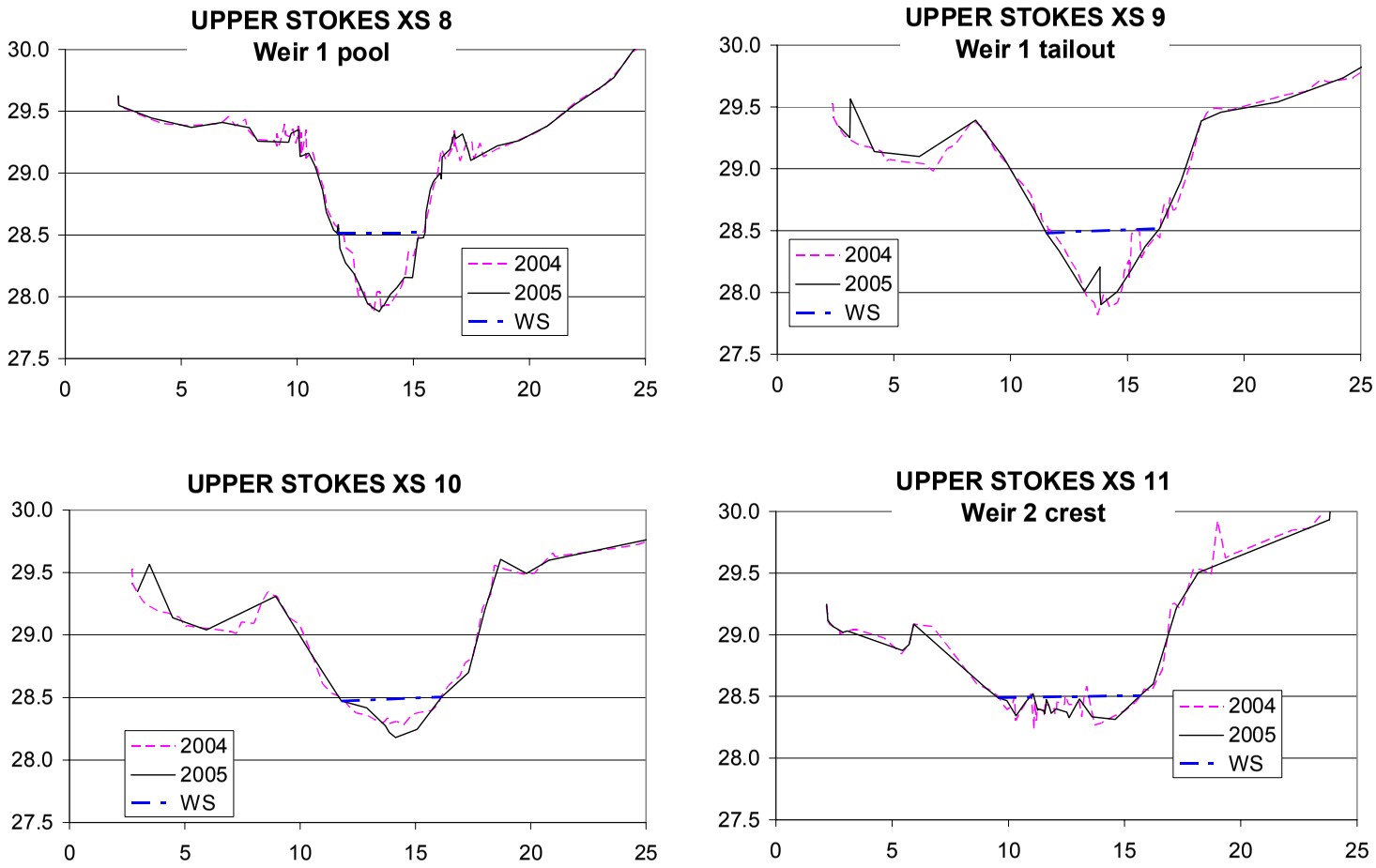
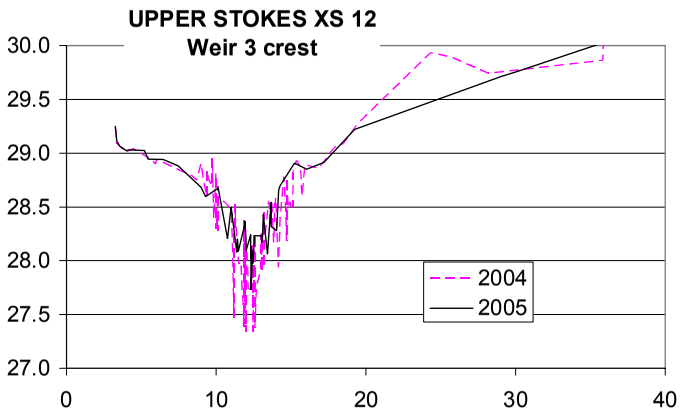
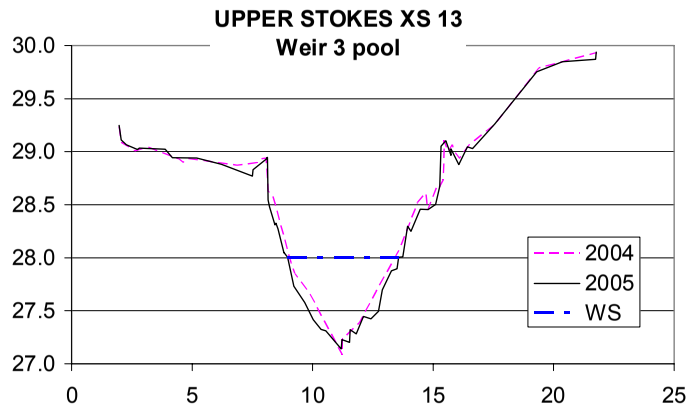
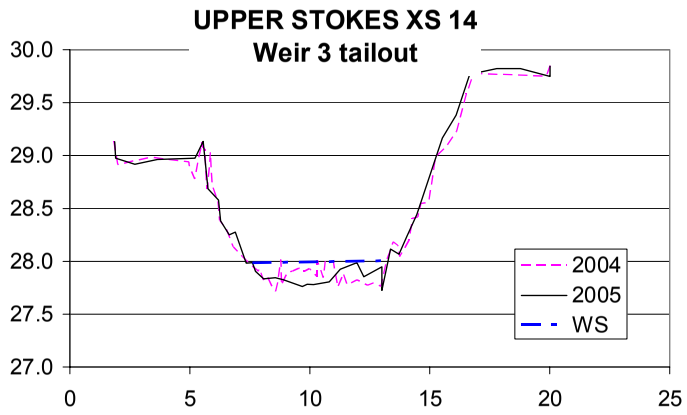


Figure B.12 (continued) Cross Sections at Upper Stokes.







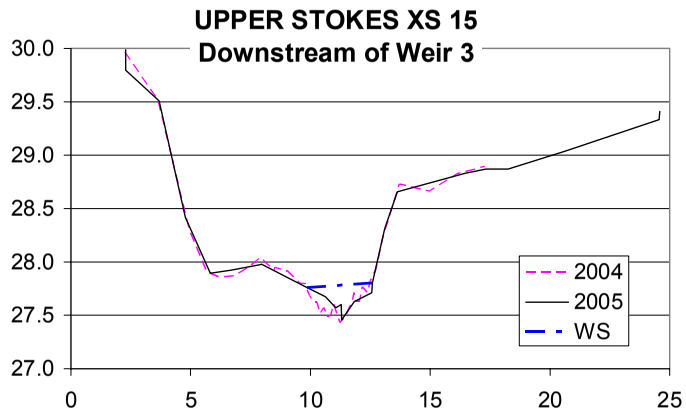
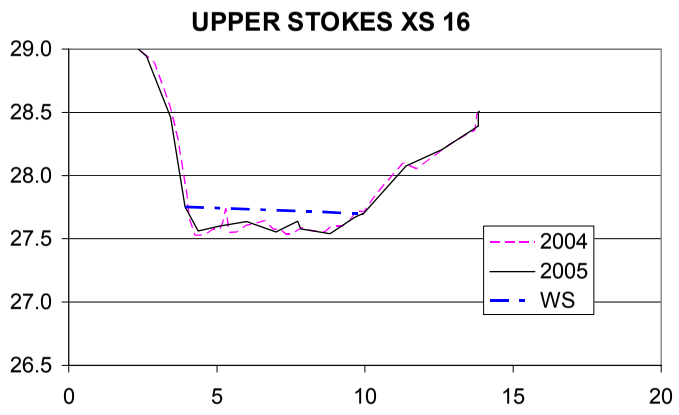
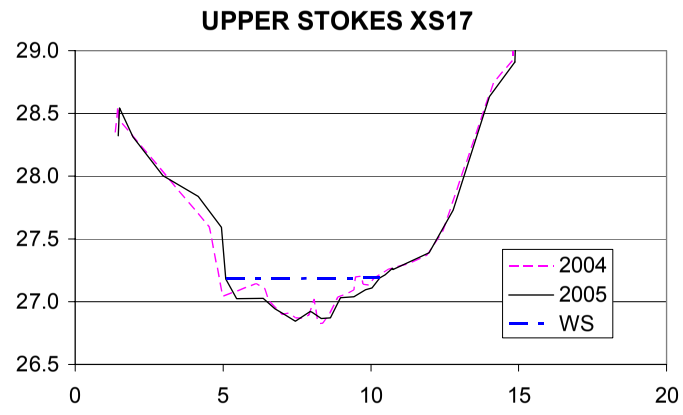


Figure B.12 (continued) Cross Sections at Upper Stokes.





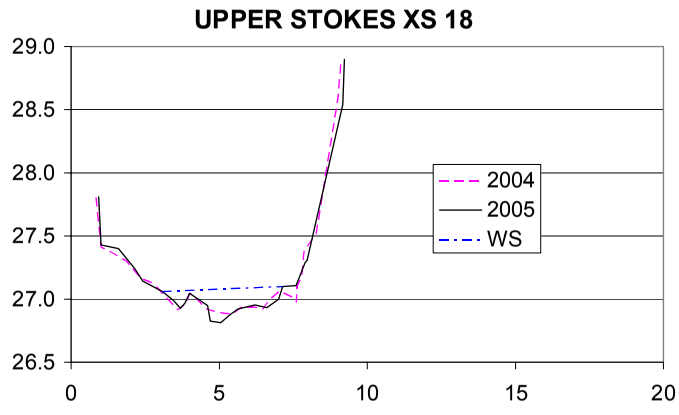


Figure B.12 (continued) Cross Sections at Upper Stokes.

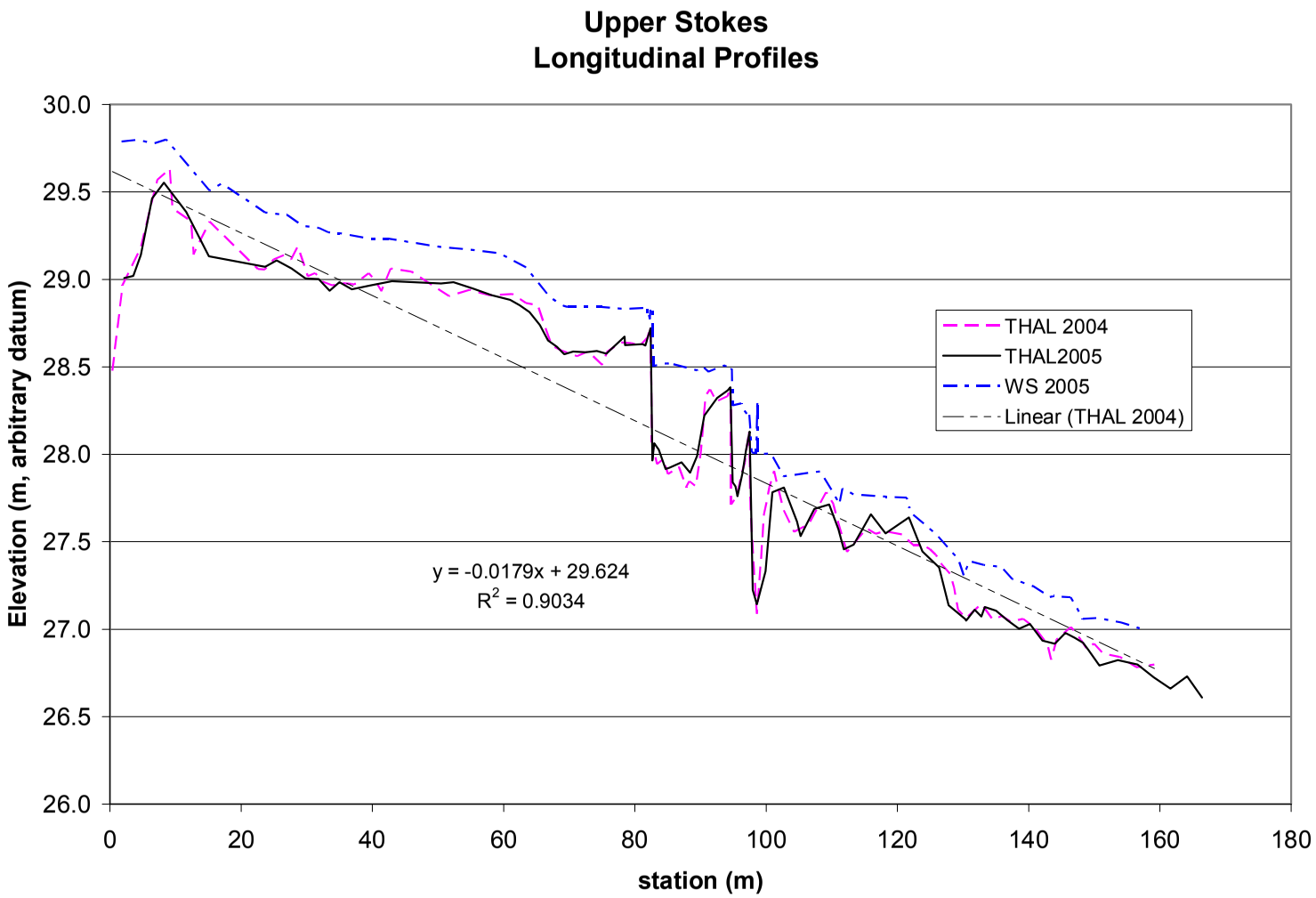


Figure B.13 Surveyed profiles at Upper Stokes.

APPENDIX C. Staff gage readings and hydraulic drops at rock vortex weirs at Lower Stokes, Thurlow, and Upper Stokes project sites

Table C.1 Staff gage readings at Lower Stokes rock vortex weirs. Visual observation of staff gages performed by UI-CER and USGS-CRRL personnel and converted to stage elevations based on ground survey of staff gages.

METRIC UNITS		Stage calculation ~ based on ground survey and staff gage readings							Calculated drops at weirs		
	flow	DIV Box	staff 1	staff 2	staff 3	staff 4	staff 5		WDFW (2003): Max = 0.24 m (0.8 feet)		
date	Qweir	US W1	POOL W1	US W2	POOL W2	US W3	POOL W3	UI PT	W1 drop	W2 drop	W3 drop
	m^3/s	m	M	m	m	m	m	m	m	m	m
26-Oct-05	0.10	28.99	28.72	28.08	27.81	27.73	27.53	29.01	0.27	0.26	0.20
11-Oct-05	0.10	28.96	28.70	28.05	27.77	27.70	27.49	28.97	0.27	0.28	0.20
5-Oct-05	0.11	28.98	28.68	28.04	27.76	27.69	27.49	28.99	0.30	0.27	0.20
23-Sep-05	0.12	29.01	28.70	28.06	27.78	27.71	27.50	29.00	0.31	0.28	0.21
17-Nov-05	0.15	29.01	28.76	28.11	27.84	27.75	27.55	29.03	0.25	0.27	0.20
11-Mar-06	0.15	29.01	28.81	28.12	27.88	27.76	27.58	29.04	0.20	0.24	0.18
2-Feb-06	0.19	29.02	28.81	28.12	27.86	27.76	27.57	29.05	0.21	0.26	0.20
22-Mar-06	0.22	29.02	28.84	28.13	27.89	27.77	27.59	29.05	0.19	0.24	0.18
10-Jan-06	0.23	29.03	28.82	28.21	27.88	27.77	27.50	29.05	0.21	0.33	0.27
30-Mar-06	0.28	29.04	28.85	28.15	27.91	27.77	27.60	29.05	0.19	0.24	0.17
10-Apr-06	0.59	29.10	28.95	28.21	27.97	27.87	27.67	29.12	0.15	0.23	0.20
17-Apr-06	0.61	29.09	28.96	28.20	27.96	27.88	27.68	29.13	0.13	0.24	0.20
14-Apr-06	0.77	29.11	29.00	28.24	27.99	27.90	27.71	29.16	0.11	0.25	0.19
MIN	0.10	28.96	28.68	28.04	27.76	27.69	27.49	28.97	**0.11**	0.23	0.17
MAX	0.77	29.11	29.00	28.24	27.99	27.90	27.71	29.16	0.31	**0.33**	0.27
AVG	0.28	29.03	28.82	28.13	27.87	27.77	27.57	29.05	0.21	0.26	0.20

ENGLISH UNITS		Stage calculation ~ based on ground survey and staff readings							Calculated drops at weirs		
	flow	DIV Box	staff 1	staff 2	staff 3	staff 4	staff 5				
date / time	Qweir	US W1	POOL W1	US W2	POOL W2	US W3	POOL W3	UI PT	W1 drop	W2 drop	W3 drop
	cfs	ft	ft	ft	ft	ft	ft	ft	ft	ft	ft
26-Oct-05	3.4	95.12	94.24	92.12	91.25	90.99	90.32	95.17	0.884	0.869	0.672
11-Oct-05	3.5	95.02	94.15	92.03	91.12	90.87	90.20	95.06	0.874	0.909	0.672
05-Oct-05	3.8	95.09	94.10	91.99	91.09	90.84	90.19	95.10	0.989	0.899	0.652
23-Sep-05	4.3	95.17	94.15	92.05	91.14	90.91	90.22	95.14	1.024	0.909	0.692
17-Nov-05	5.2	95.17	94.36	92.24	91.35	91.04	90.39	95.23	0.814	0.889	0.652
11-Mar-06	5.4	95.19	94.54	92.26	91.46	91.07	90.48	95.26	0.654	0.799	0.592
02-Feb-06	6.7	95.21	94.52	92.27	91.42	91.08	90.44	95.30	0.694	0.849	0.642
22-Mar-06	7.7	95.22	94.61	92.29	91.51	91.11	90.51	95.30	0.614	0.779	0.602
10-Jan-06	8.1	95.25	94.57	92.55	91.46	91.10	90.23	95.32	0.684	1.089	0.872
30-Mar-06	10.0	95.27	94.66	92.36	91.57	91.12	90.56	95.32	0.614	0.789	0.562
10-Apr-06	20.9	95.47	94.99	92.55	91.78	91.45	90.78	95.54	0.484	0.769	0.672
17-Apr-06	21.7	95.43	95.01	92.53	91.74	91.47	90.82	95.56	0.424	0.789	0.652
14-Apr-06	27.1	95.51	95.16	92.65	91.82	91.53	90.92	95.66	0.354	0.829	0.612
MIN	3.39	95.02	94.10	91.99	91.09	90.84	90.19	95.06	**0.35**	0.77	0.56
MAX	27.09	95.51	95.16	92.65	91.82	91.53	90.92	95.66	1.02	**1.09**	0.87
AVG	9.83	95.24	94.54	92.30	91.44	91.12	90.46	95.30	0.70	0.86	0.66

APPENDIX D. Velocity measurements at Lower Stokes, Thurlow and Upper Stokes project sites

Velocity profiles were measured near the rock vortex weirs to characterize velocity distributions upstream of the weir, at the weir crest, within the weir pool, and downstream of the weir. Each velocity profile consisted of sampling three velocities at 0.2, 0.6, and 0.8 total depth. Velocities were measured using a Sontek Handheld Flowtracker ADV flow meter and saved to a data recorder that logs velocity in three orthogonal directions (i.e., V_x, V_y, V_z). Upstream of each rock vortex weir, one velocity profile was sampled at the center of the channel, followed by a velocity profile at the weir crest, five velocity profiles across the center of the pool, and one downstream of the pool.

Data were processed in MathCAD to generate contours for longitudinal velocities and vectors to represent lateral and vertical velocities. Not all data sets had V_x, V_y, and V_z components measured.

VELOCITY PROFILE PLOTS FOR WEIR POOL CROSS SECTIONS
METHOW RIVER PROJECT
BEAVER CREEK PROJECT SITES

Vx , Vy , Vz are components of the velocity vector measured in the x, y, and z directions, respectively. Measurements were made by ADV.

V_x is parallel to the stream direction, V_y is transverse to the stream, and Vz is vertical

V_x shown by contours, V_y and V_z represented by vectors

All data are reported in centimeters/second and plotted in MathCAD by Mathsoft. Matrices for velocity plots rotated 90 degrees clockwise for MathCAD (Mathsoft, Inc) plotting.

Upper Stokes
Weir 1 Pool XS
July 19, 2004
0.126 m3/s

bottom pool -----> Water surface

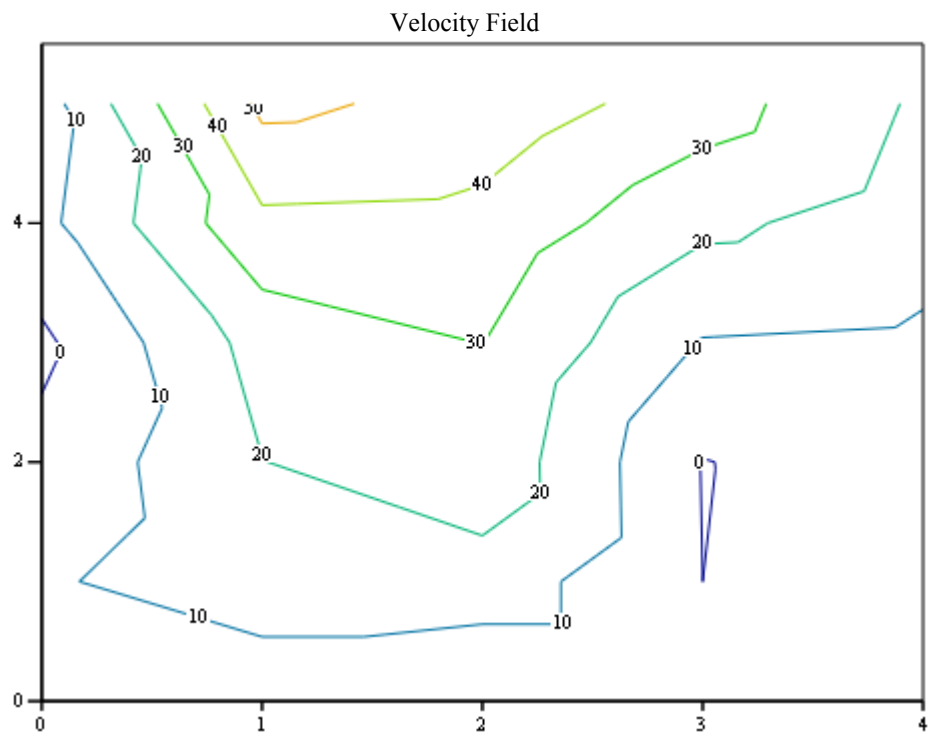
$$Vx := \begin{pmatrix} 0 & 8.23 & 2.44 & -1.83 & 7.32 & 5.18 \\ 0 & 18.59 & 19.81 & 23.77 & 37.80 & 52.43 \\ 0 & 15.54 & 27.13 & 30.18 & 36.88 & 46.63 \\ 0.00 & 0.00 & -0.30 & 9.45 & 22.25 & 34.75 \\ 0 & 4.88 & 5.18 & 8.23 & 14.63 & 18.29 \end{pmatrix}$$

Left Bank

Center

Right Bank

No V_y or V_z for this data set



Vx

Plots are not to scale

Figure D.1 Velocity profile at Upper Stokes at 0.126 m^3/s.

Upper Stokes
Weir 1 Pool XS
July 21, 2004
0.134 m3/s

$$Vx := \begin{pmatrix} 0 & 0.00 & 7.01 & 17.98 & 21.34 & 26.21 \\ 0 & -1.22 & 4.57 & 8.84 & 9.75 & 25.60 \\ 0 & 5.18 & 11.28 & 14.33 & 20.73 & 29.87 \\ 0 & -1.83 & 1.22 & 3.66 & 13.72 & 39.93 \\ 0 & -8.23 & -3.96 & 3.05 & 7.92 & 26.21 \end{pmatrix}$$

No Vy or Vz for this data set

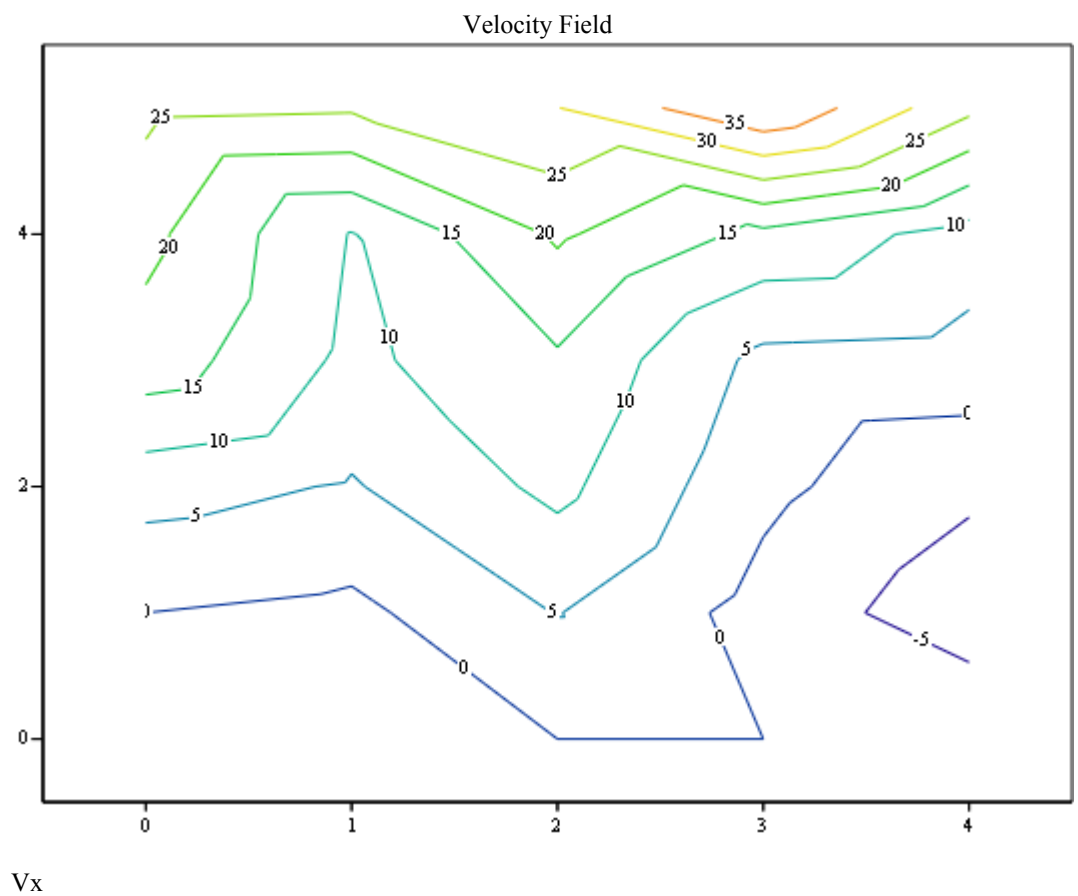


Figure D.2 Velocity profile at Upper Stokes at 0.134 m^3/s.

Upper Stokes
Weir 1 Pool XS
July 22, 2005
0.125 m3/s

$$Vx := \begin{pmatrix} 0.00 & 7.53 & 20.42 & 15.94 \\ 0.00 & 1.19 & 3.66 & 26.58 \\ 0.00 & 0.06 & 28.71 & 27.25 \\ 0.00 & 2.23 & 20.30 & 30.36 \\ 0.00 & 2.90 & 3.51 & 3.17 \end{pmatrix} \quad Vy := \begin{pmatrix} 0.00 & 2.62 & -2.23 & -2.01 \\ 0.00 & -3.63 & 3.66 & 11.89 \\ 0.00 & -0.03 & 12.53 & 10.39 \\ 0.00 & 4.11 & 4.91 & 3.54 \\ 0.00 & 4.05 & 0.55 & -6.46 \end{pmatrix} \quad Vz := \begin{pmatrix} 0.00 & 0.43 & -4.72 & -10.09 \\ 0.00 & 2.23 & 3.29 & 2.59 \\ 0.00 & -0.21 & 4.48 & 1.58 \\ 0.00 & 2.71 & 1.37 & -2.50 \\ 0.00 & 0.70 & -0.06 & -21.09 \end{pmatrix}$$

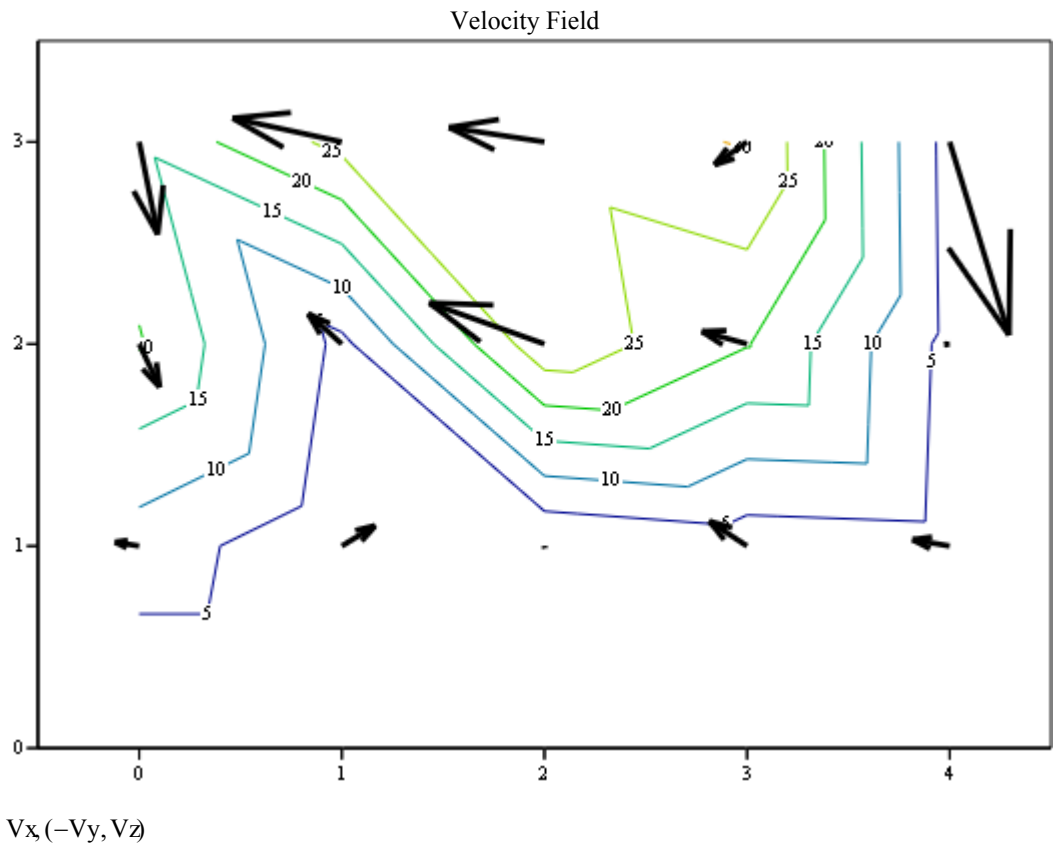


Figure D.3 Velocity profile at Upper Stokes at 0.125 m^3/s.

Upper Stokes
Weir 1 Pool XS
April 15,2006
0.564 m3/s

$$Vx := \begin{pmatrix} 0.0 & -8.1 & -2.7 & 13.0 \\ 0.0 & 13.8 & 31.1 & 47.3 \\ 0.0 & 44.7 & 78.0 & 104.1 \\ 0.0 & 13.5 & 64.3 & 73.4 \\ 0.0 & -3.2 & -1.0 & 35.3 \end{pmatrix} \quad Vy := \begin{pmatrix} 0 & -2.72 & -2.87 & 0.13 \\ 0 & -6.55 & -8.12 & 11.94 \\ 0 & -16.29 & 16.79 & 28.2 \\ 0 & -1.47 & 13.16 & 9.97 \\ 0 & 2.81 & -0.08 & -9.26 \end{pmatrix} \quad Vz := \begin{pmatrix} 0 & 0.6 & 2.62 & -2.95 \\ 0 & -2.7 & 5.16 & 0.38 \\ 0 & -18.14 & -1.79 & 0.03 \\ 0 & 4.55 & -2.16 & 6.82 \\ 0 & 1.75 & 1.79 & 0.99 \end{pmatrix}$$

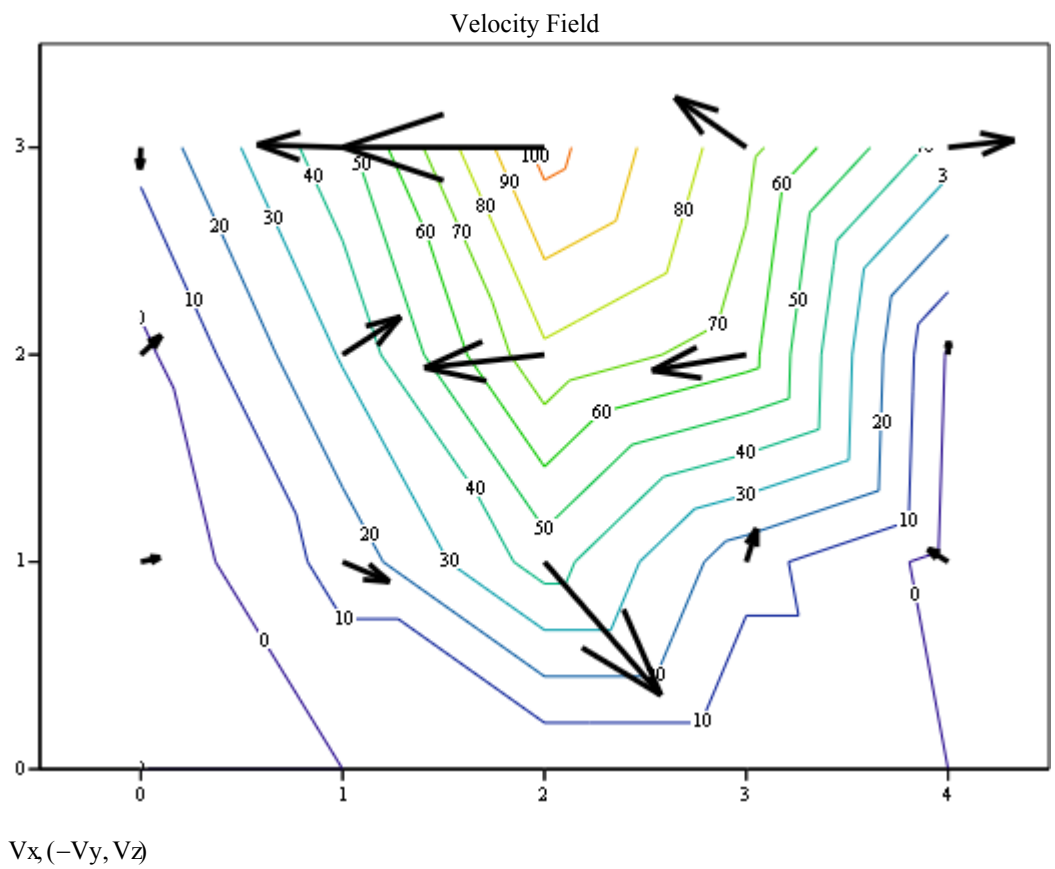


Figure D.4 Velocity profile at Upper Stokes at 0.564 m^3/s.

Thurlow
Weir 1 Pool XS
July 22, 2005
0.161 m3/s

$$Vx := \begin{pmatrix} 0.00 & -7.07 & -3.78 & 6.04 \\ 0.00 & 0.37 & -0.46 & 9.45 \\ 0.00 & 12.68 & 17.74 & 21.03 \\ 0.00 & 2.47 & 27.71 & 46.45 \\ 0.00 & 1.83 & 6.77 & 25.24 \end{pmatrix} \quad Vy := \begin{pmatrix} 0.00 & -4.08 & 0.12 & -2.07 \\ 0.00 & -3.02 & -0.82 & -1.31 \\ 0.00 & -1.86 & -1.83 & -4.27 \\ 0.00 & 8.17 & -1.46 & -9.27 \\ 0.00 & 2.53 & 8.84 & 0.64 \end{pmatrix} \quad Vz := \begin{pmatrix} 0.00 & 0.91 & 2.26 & 2.16 \\ 0.00 & 0.79 & 0.91 & 3.57 \\ 0.00 & 0.21 & 6.16 & 0.09 \\ 0.00 & 4.05 & 5.49 & 16.09 \\ 0.00 & -1.10 & -7.19 & -2.62 \end{pmatrix}$$

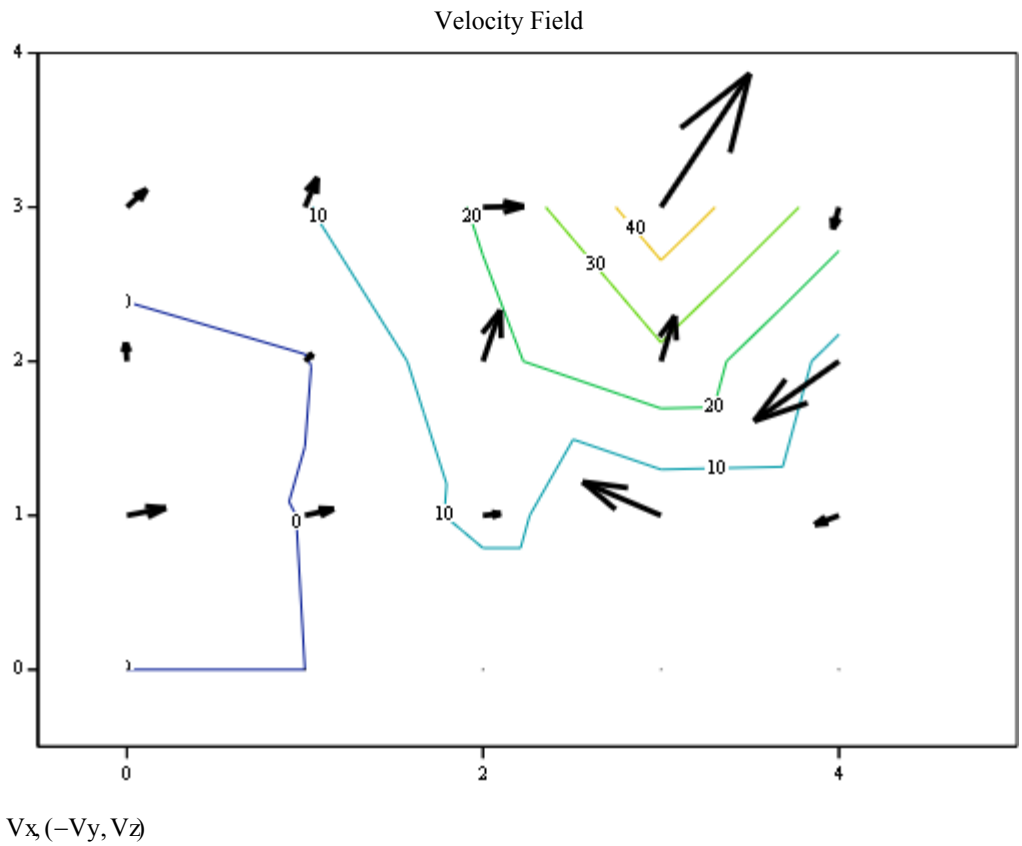


Figure D.5 Velocity profile at Thurlow at 0.161 m^3/s.

Lower Stokes
Weir 3 Pool XS
July 14, 2004
0.058 m3/s

$$Vx := \begin{pmatrix} 0 & 0.00 & -6.71 & -8.53 & -11.58 & -2.13 \\ 0 & -3.66 & -7.92 & -4.88 & 3.66 & 11.89 \\ 0 & 0.00 & 8.23 & 15.54 & 28.65 & 64.92 \\ 0 & 9.75 & 28.35 & 34.75 & 42.67 & 57.91 \\ 0 & 11.28 & 11.89 & 15.85 & 19.81 & 23.47 \end{pmatrix}$$

No Vy or Vz for this data set

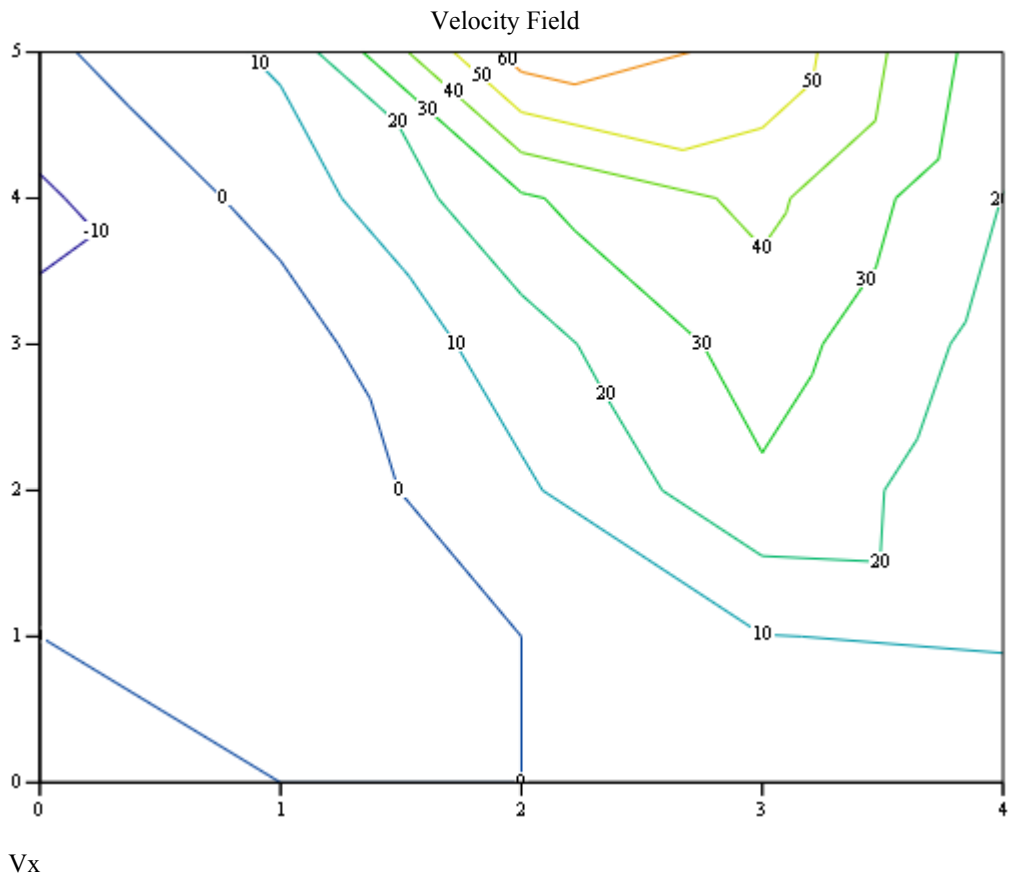


Figure D.6 Velocity profile at Lower Stokes at 0.058 m^3/s.

Lower Stokes
Weir 1 Pool XS
July 22, 2005
0.103 m3/s

$$Vx := \begin{pmatrix} 0.00 & -1.37 & 4.51 & -20.42 \\ 0.00 & -0.03 & 9.69 & -1.58 \\ 0.00 & -4.57 & 34.93 & 41.97 \\ 0.00 & 11.09 & 14.33 & 14.20 \\ 0.00 & 89.18 & 59.38 & 25.97 \end{pmatrix} \quad Vy := \begin{pmatrix} 0.00 & -4.69 & -3.47 & -0.12 \\ 0.00 & -0.15 & -14.17 & -4.36 \\ 0.00 & -8.99 & -24.48 & -2.35 \\ 0.00 & -4.48 & 0.64 & 13.32 \\ 0.00 & 0.82 & 11.03 & 21.92 \end{pmatrix} \quad Vz := \begin{pmatrix} 0.00 & -17.68 & -4.21 & 4.57 \\ 0.00 & -0.34 & -3.23 & 3.66 \\ 0.00 & 8.53 & -8.90 & 28.83 \\ 0.00 & -1.58 & 2.83 & 6.34 \\ 0.00 & -24.87 & 2.93 & 23.26 \end{pmatrix}$$

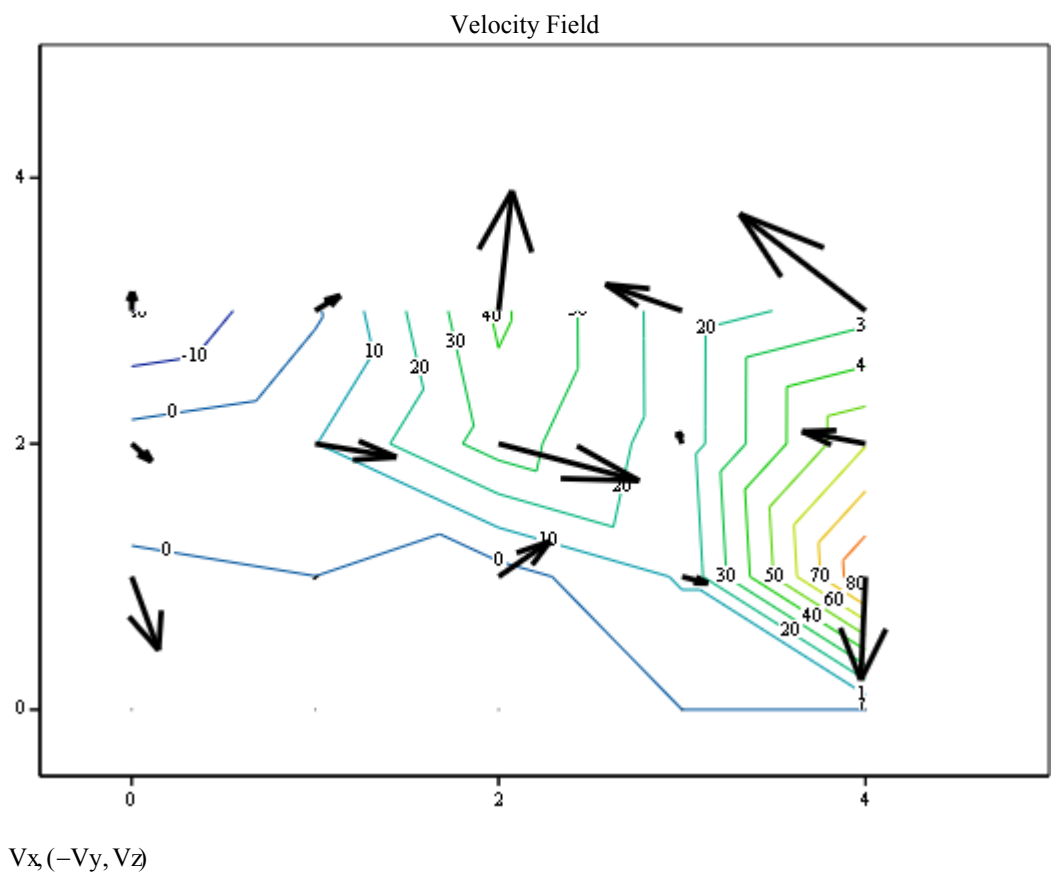


Figure D.7 Velocity profile at Lower Stokes at 0.103 m^3/s.

APPENDIX E. Wolman Pebble Counts and particle size distributions at Lower Stokes, Thurlow, and Upper Stokes project sites

Results from Wolman Pebble counts are shown in Table E.1 and plotted in Figure E.1 to E.3. For all pebble counts, the coarsest material was approximately 400 mm. Also, the Wolman Pebble Counts completed just upstream of the weirs show a higher proportion of fine material, compared to sites further upstream and downstream of the rock vortex weirs. This pattern is expected, since the weirs impound water and slow stream velocities, creating conditions for finer material to drop out of suspension and collect on the channel bed. In addition, substrate appeared to be slightly finer between 2004 and 2005 (Figure E.1 to E.3, and Table E.1).

While not quantified with a Wolman Pebble count, prior to construction, silt and sand material much finer than the sizes shown in Figure E.1 to E.3, and Table E.1 were distributed across the full channel width and extended upstream to the end of the impoundments created by the original diversion structures.

Table E.1. Particle size distributions from Wolman Pebble Counts.

	2004			**2005**		
	upstream	*near weir*	*downstream*	*upstream*	*near weir*	*downstream*
Lower Stokes						
D16 (mm)		16		2	2	2
D50 (mm)		47		25	45	2
D84 (mm)		91		75	150	280
Sample size		103		103	107	103
Thurlow						
D16 (mm)	2	2	2	2	1	2
D50 (mm)	38	2	60	25	2	53
D84 (mm)	84	33	183	80	29	220
Sample size	100	102	104	101	102	104
Upper Stokes						
D16 (mm)	2	2	2	2	2	2
D50 (mm)	10	20	48	20	30	55
D84 (mm)	111	106	138	136	90	154
Sample size	104	111	104	106	105	105

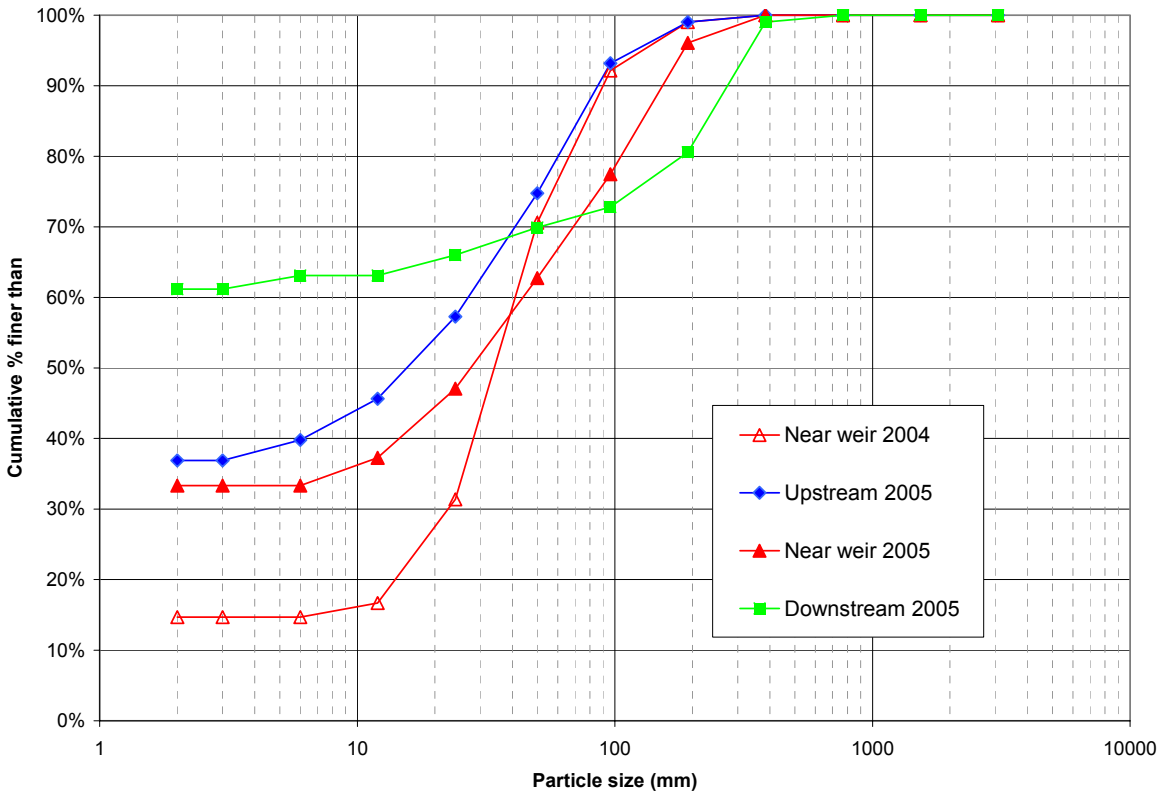


Figure E.1. Particle size distributions at Lower Stokes.

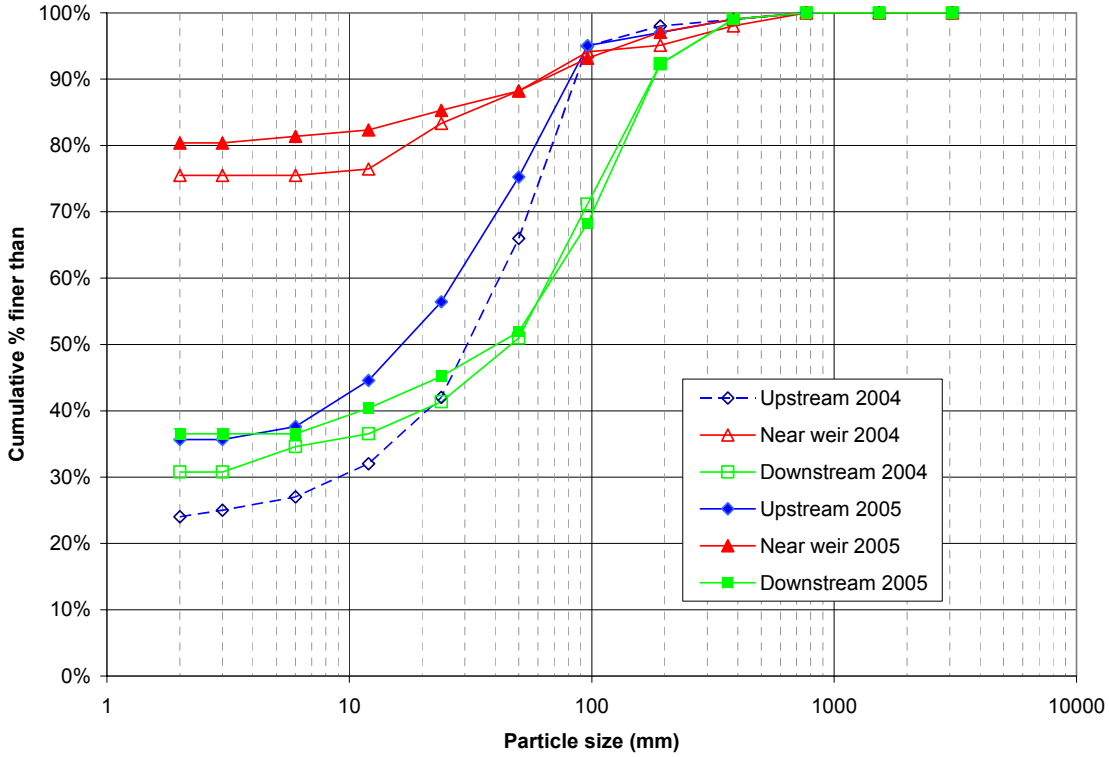


Figure E.2 Particle size distributions at Thurlow.

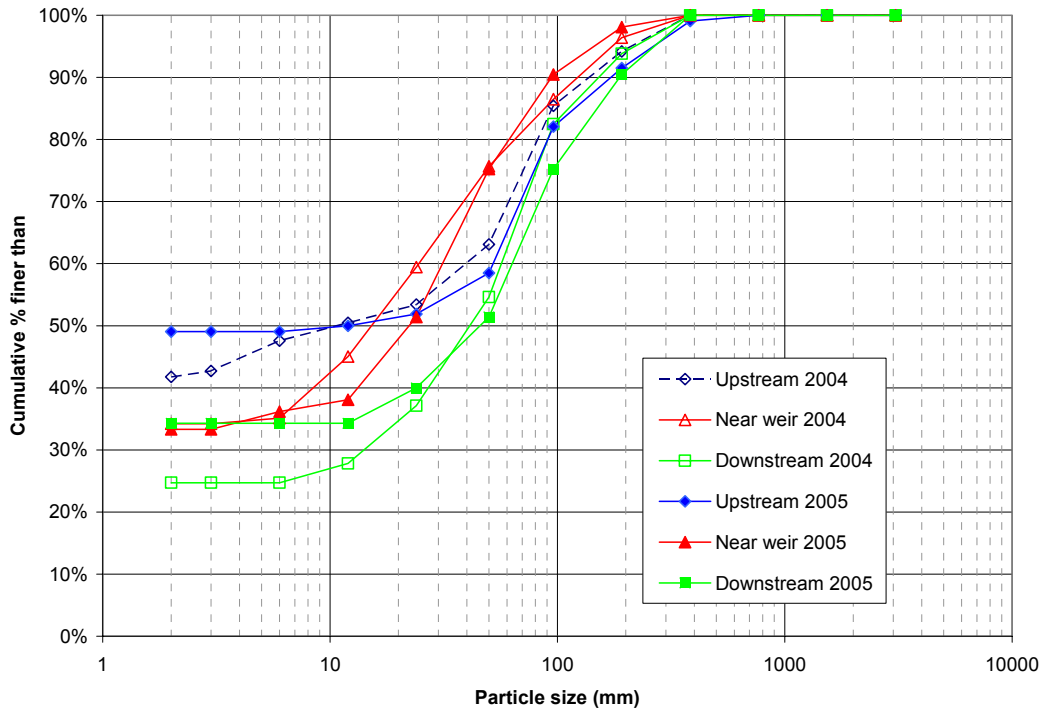


Figure E.3 Particle size distributions at Upper Stokes.

APPENDIX F. Hydraulic models for rock vortex weirs at Lower Stokes, Thurlow, and Upper Stokes project sites

Table F.1. Results of spreadsheet-based hydraulic model at Lower Stokes, weir 1.

Measured flows		Modeled flows					
Stage meters	flow m^3/s	stage meters	$Q_{orifice}$ m^3/s	Q_{gap} m^3/s	Q_{weir} m^3/s	$Q_{combined}$ m^3/s	Flow type *
28.99	0.096	28.65	0.000			0.00	sub flow
28.96	0.099	28.68	0.000			0.00	sub flow
28.98	0.108	28.71	0.000			0.00	sub flow
29.01	0.122	28.74	0.000			0.00	sub flow
29.01	0.147	28.77	0.000			0.00	O + G
29.01	0.154	28.80	0.001	0.000		0.00	O + G
29.02	0.190	28.83	0.002	0.002		0.00	O + G
29.02	0.218	28.86	0.002	0.006		0.01	O + G
29.03	0.229	28.90	0.003	0.016		0.02	O + G
29.04	0.283	28.93	0.005	0.033		0.04	O + G
29.10	0.591	28.96	0.008	0.063		0.07	O + G
29.09	0.614	28.99	0.013	0.091		0.10	O + G
29.11	0.767	29.00	0.012	0.111		0.12	O + G
		29.02	0.012	0.142	0.000	0.15	O + G + W
		29.05	0.011	0.217	0.055	0.28	O + G + W
		29.08	0.010	0.262	0.169	0.44	O + G + W
		29.11	0.008	0.293	0.330	0.63	O + G + W
		29.14	0.007	0.364	0.523	0.89	O + G + W
		29.17		0.429	0.755	1.18	O + G + W
		29.20		0.508	1.073	1.58	O + G + W
		29.23		0.584	1.458	2.04	O + G + W
		29.26		0.658	1.917	2.57	O + G + W
		29.29		0.724	2.437	3.16	O + G + W
		29.32		0.790	3.036	3.83	O + G + W
		29.35		0.834	3.620	4.45	O + G + W
		29.38		0.870	4.223	5.09	O + G + W
		29.41		0.981	4.762	5.74	O + G + W
		29.44		0.990	5.442	6.37	O + G + W
		29.47		1.006	6.493	7.50	O + G + W
		29.50		1.043	7.345	8.39	O + G + W
		29.54		1.064	8.121	9.19	O + G + W
		29.57		1.085	8.922	10.01	O + G + W

* Flow types are orifice (O), gap (G), and weir (W)

Table F.2. Results of spreadsheet-based hydraulic model at Lower Stokes, weir 2.

Measured flows		Modeled flows					
Stage meters	flow m^3/s	stage meters	$Q_{orifice}$ m^3/s	Q_{gap} m^3/s	Q_{weir} m^3/s	$Q_{combined}$ m^3/s	Flow type *
27.73	0.10	27.57	0.000				
28.05	0.099	27.80	0.000			0.00	O + G
28.04	0.108	27.83	0.000	0.000		0.00	O + G
28.06	0.122	27.86	0.006	0.000		0.01	O + G
28.11	0.147	27.89	0.008	0.002		0.01	O + G
28.12	0.154	27.92	0.010	0.007		0.02	O + G
28.12	0.190	27.95	0.010	0.017		0.03	O + G
28.13	0.218	27.98	0.010	0.031		0.04	O + G
28.15	0.283	28.01	0.010	0.048		0.06	O + G
28.21	0.591	28.04	0.010	0.079		0.09	O + G
28.20	0.614	28.07	0.010	0.106		0.12	O + G
28.24	0.767	28.10	0.010	0.136	0.000	0.15	O + G + W
		28.13	0.010	0.147	0.033	0.19	O + G + W
		28.16	0.010	0.218	0.112	0.34	O + G + W
		28.19	0.010	0.272	0.229	0.51	O + G + W
		28.22	0.010	0.308	0.366	0.68	O + G + W
		28.25	0.010	0.343	0.529	0.88	O + G + W
		28.29	0.010	0.373	0.715	1.10	O + G + W
		28.32	0.009	0.408	0.944	1.36	O + G + W
		28.35	0.009	0.445	1.214	1.67	O + G + W
		28.38	0.009	0.510	1.638	2.16	O + G + W
		28.41	0.009	0.584	2.208	2.80	O + G + W
		28.44	0.009	0.624	2.745	3.38	O + G + W
		28.47	0.009	0.649	3.276	3.93	O + G + W
		28.50	0.009	0.672	3.851	4.53	O + G + W
		28.53	0.009	0.689	4.433	5.13	O + G + W
		28.56	0.008	0.707	5.069	5.79	O + G + W
		28.59	0.008	0.741	5.883	6.63	O + G + W
		28.62	0.008	0.783	6.863	7.65	O + G + W
		28.65	0.008	0.807	7.777	8.59	O + G + W
		28.68	0.008	0.821	8.640	9.47	O + G + W
		28.71	0.008	0.831	9.500	10.34	O + G + W
		28.74	0.008	0.841	10.387	11.24	O + G + W
		28.77	0.007	0.854	11.353	12.21	O + G + W
		28.80	0.007	0.865	12.325	13.20	O + G + W
		28.83	0.007	0.922	13.137	14.07	O + G + W
		28.86	0.007	0.980	13.967	14.95	O + G + W

Table F.3. Results of spreadsheet-based hydraulic model at Lower Stokes, weir 3.

Measured flows		Modeled flows					
Stage meters	flow m^3/s	stage meters	$Q_{orifice}$ m^3/s	Q_{gap} m^3/s	Q_{weir} m^3/s	$Q_{combined}$ m^3/s	Flow type *
27.73	0.10	27.57	0.000				
27.70	0.10	27.58	0.006	0.000		0.01	O + G
27.69	0.11	27.61	0.009	0.006		0.01	O + G
27.71	0.12	27.65	0.009	0.029		0.04	O + G
27.75	0.15	27.68	0.009	0.050		0.06	O + G
27.76	0.15	27.71	0.009	0.080		0.09	O + G
27.76	0.19	27.74	0.009	0.138		0.15	O + G
27.77	0.22	27.77	0.009	0.188	0.000	0.20	O + G + W
27.77	0.23	27.80	0.009	0.201	0.046	0.26	O + G + W
27.77	0.28	27.83	0.009	0.213	0.149	0.37	O + G + W
27.87	0.59	27.86	0.009	0.225	0.295	0.53	O + G + W
27.88	0.61	27.89	0.009	0.236	0.463	0.71	O + G + W
27.90	0.77	27.92	0.009	0.246	0.651	0.91	O + G + W
		27.95	0.009	0.270	1.006	1.29	O + G + W
		27.98	0.009	0.304	1.371	1.68	O + G + W
		28.01	0.009	0.340	1.827	2.18	O + G + W
		28.04	0.009	0.352	2.198	2.56	O + G + W
		28.07	0.009	0.365	2.603	2.98	O + G + W
		28.10	0.009	0.376	3.019	3.40	O + G + W
		28.13	0.008	0.404	3.618	4.03	O + G + W
		28.16	0.008	0.423	4.201	4.63	O + G + W
		28.19	0.008	0.441	4.820	5.27	O + G + W
		28.22	0.008	0.465	5.569	6.04	O + G + W
		28.25	0.008	0.486	6.355	6.85	O + G + W
		28.29	0.008	0.510	7.245	7.76	O + G + W
		28.32	0.008	0.524	8.059	8.59	O + G + W
		28.35	0.008	0.539	8.937	9.48	O + G + W
		28.38	0.008	0.553	9.845	10.41	O + G + W
		28.41	0.008	0.572	10.912	11.49	O + G + W
		28.44	0.008	0.592	12.066	12.67	O + G + W
		28.47	0.008	0.618	13.436	14.06	O + G + W
		28.50	0.008	0.642	14.875	15.53	O + G + W
		28.53	0.008	0.666	16.422	17.10	O + G + W
		28.56	0.008	0.689	18.043	18.74	O + G + W
		28.59	0.008	0.755	19.775	20.54	O + G + W

Table F.4. Results of spreadsheet-based hydraulic model at Thurlow, weir 1.

Measured flows		Modeled flows					
Stage meters	flow m^3/s	stage meters	$Q_{orifice}$ m^3/s	Q_{gap} m^3/s	Q_{weir} m^3/s	$Q_{combined}$ m^3/s	Flow type *
27.71	0.031	27.52	0.001	0.000		0.00	O + G
27.68	0.032	27.55	0.001	0.001		0.00	O + G
27.72	0.061	27.58	0.001	0.004		0.00	O + G
27.74	0.104	27.61	0.002	0.010		0.01	O + G
27.73	0.109	27.65	0.003	0.018		0.02	O + G
27.76	0.161	27.68	0.004	0.028		0.03	O + G
27.76	0.171	27.71	0.007	0.041	0.000	0.05	O + G
27.87	0.504	27.74	0.007	0.059	0.026	0.09	O + G + W
27.89	0.631	27.77	0.007	0.124	0.077	0.21	O + G + W
		27.80	0.007	0.154	0.152	0.31	O + G + W
		27.83	0.007	0.180	0.248	0.44	O + G + W
		27.86	0.007	0.202	0.363	0.57	O + G + W
		27.89	0.007	0.223	0.499	0.73	O + G + W
		27.92		0.240	0.648	0.89	O + G + W
		27.95		0.266	0.858	1.12	O + G + W
		27.98		0.308	1.188	1.50	O + G + W
		28.01		0.326	1.476	1.80	O + G + W
		28.04		0.355	1.874	2.23	O + G + W
		28.07		0.373	2.276	2.65	O + G + W
		28.10		0.375	2.607	2.98	O + G + W
		28.13		0.378	2.949	3.33	O + G + W
		28.16		0.389	3.374	3.76	O + G + W
		28.19		0.402	3.862	4.26	O + G + W
		28.22		0.453	4.839	5.29	O + G + W
		28.25		0.469	5.546	6.02	O + G + W
		28.29		0.483	6.294	6.78	O + G + W
		28.32		0.489	6.976	7.47	O + G + W
		28.35		0.495	7.687	8.18	O + G + W
		28.38		0.507	8.543	9.05	O + G + W
		28.41		0.517	9.411	9.93	O + G + W
		28.44		0.526	10.328	10.85	O + G + W
		28.47		0.536	11.296	11.83	O + G + W
		28.50		0.546	12.315	12.86	O + G + W
		28.53		0.556	13.386	13.94	O + G + W
		28.56		0.566	14.511	15.08	O + G + W
		28.59		0.576	15.689	16.26	O + G + W
		28.62		0.586	16.922	17.51	O + G + W
		28.65		0.596	18.211	18.81	O + G + W

Table F.5. Results of spreadsheet-based hydraulic model at Upper Stokes, weir 1.

Measured Stage meters	flow m3/s	Modeled stage meters	Qor m3/s	Qgap m3/s	Qweir m3/s	Qtotal m3/s	type
28.82	0.10	28.62	0.000	0.000		0.00	O + G
28.83	0.13	28.65	0.000	0.001		0.00	O + G
28.85	0.14	28.68	0.000	0.003		0.00	O + G
28.84	0.14	28.71	0.000	0.010		0.02	O + G
28.83	0.15	28.74	0.000	0.023		0.03	O + G
28.84	0.16	28.77	0.000	0.038		0.05	O + G
28.94	0.56	28.80	0.000	0.055	0.000	0.07	O + G + W
		28.83	0.000	0.087	0.030	0.13	O + G + W
		28.86	0.010	0.126	0.095	0.23	O + G + W
		28.90	0.010	0.162	0.199	0.37	O + G + W
		28.93	0.009	0.187	0.324	0.52	O + G + W
		28.96	0.007	0.203	0.452	0.66	O + G + W
		28.99	0.000	0.219	0.602	0.82	O + G + W
		29.02	0.000	0.260	0.871	1.13	O + G + W
		29.05	0.000	0.276	1.095	1.37	O + G + W
		29.08	0.000	0.296	1.364	1.66	O + G + W
		29.11	0.000	0.314	1.666	1.98	O + G + W
		29.14	0.000	0.324	1.943	2.27	O + G + W
		29.17	0.000	0.340	2.279	2.62	O + G + W
		29.20		0.364	2.715	3.08	O + G + W
		29.23		0.381	3.147	3.53	O + G + W
		29.26		0.406	3.693	4.10	O + G + W
		29.29		0.433	4.331	4.76	O + G + W
		29.32		0.458	5.016	5.47	O + G + W
		29.35		0.484	5.791	6.27	O + G + W
		29.38		0.497	6.476	6.97	O + G + W
		29.41		0.509	7.185	7.69	O + G + W
		29.44		0.523	7.972	8.50	O + G + W
		29.47		0.530	8.690	9.22	O + G + W
		29.50		0.536	9.400	9.94	O + G + W
		29.54		0.562	10.542	11.10	O + G + W
		29.57		0.586	11.749	12.33	O + G + W
		29.60		0.610	13.050	13.66	O + G + W
		29.63		0.632	14.417	15.05	O + G + W
		29.66		0.654	15.883	16.54	O + G + W
		29.69		0.674	17.419	18.09	O + G + W
		29.72		0.694	19.056	19.75	O + G + W
		29.75		0.713	20.766	21.48	O + G + W
		29.78		0.732	22.581	23.31	O + G + W
		29.81		0.749	24.471	25.22	O + G + W
		29.84		0.767	26.470	27.24	O + G + W

APPENDIX G. Fish movement data from USGS-CRRL and estimated hydraulic parameters at Lower Stokes project site during fish movement

Table G.1. Summary fish movements from USGS-CRRL and travel times.

Fish ID	min date & time	max date & time	Duration (days)	Movement *
Juvenile Steelhead/ rainbow trout				
1	6/27/05 18:48	6/30/05 13:04	2.8	BD
2		6/13/05 4:58	N/A	XD
3	4/19/05 0:00	7/6/05 7:06	78.3	AD
4	4/13/05 0:00	5/7/05 20:53	24.9	AD
5	5/29/05 1:39	6/25/05 22:34	27.9	BD
6	6/16/05 3:30	7/5/05 21:08	19.7	BD
7	6/27/05 19:32	7/1/05 21:03	4.1	BD
8	6/26/05 0:00	6/30/05 3:31	4.1	AD
9	6/21/05 20:33	7/2/05 20:01	11.0	BD
11	6/21/05 0:00	7/2/05 22:23	11.9	AD
12	6/4/05 20:40	6/21/05 4:23	16.3	BD
13	6/3/05 20:06	7/2/05 4:36	28.4	BD
14	6/20/05 0:00	6/25/05 20:55	5.9	AD
15	6/21/05 20:31	7/1/05 21:25	10.0	BD
16	6/27/05 13:24	11/21/05 7:58	146.8	BD
17	6/18/05 0:00	6/30/05 21:39	12.9	AD
18	6/20/05 14:11	6/29/05 0:32	8.4	BD
19	6/26/05 0:00	7/2/05 14:10	6.6	AD
Juvenile brook trout				
B1	5/3/05 23:04	6/1/05 22:04	29.0	BD
B3	3/25/05 0:00	5/28/05 2:33	64.1	AD
B4	5/30/05 15:09	6/22/05 21:22	23.3	BD
adult steelhead				
AS1	4/7/05 20:33	4/25/05 9:10	17.5	BD
AS2	4/17/05 20:25	4/25/05 18:18	7.9	BD
AS3	4/23/2005	4/25/2005	2.1	BD
AS4	4/25/2005	4/26/2005	1.2	BD

* USGS-CRRL detection sites:

A: Fish weir (downstream)

B: Approximately 50 meters upstream of fish weir

C: Approximately 3 km upstream, below rock vortex weirs at Lower Stokes

D: Approximately 100 meters upstream of rock vortex weirs at Lower Stokes

X: Detected or tagged beyond mouth of Beaver Creek, within Columbia River Basin

Table G.2. Summary of hydraulic parameters during fish passage.

JUVENILE STEELHEAD / RAINBOW TROUT

Fish ID	Weir 1 drop				Weir 1 Ratio				Weir 1 EDF				W1 Velocity			
	max drop	min drop	avg drop	end drop	max ratio	min ratio	avg ratio	end ratio	max W/m^3	min W/m^3	avg W/m^3	end W/m^3	max m/s	min m/s	avg m/s	end m/s
Fish ID	m	m	m	m												
1	0.24	0.19	0.22	0.24	3.9	2.5	3.1	2.5	190	182	185	182	0.32	0.23	0.27	0.23
2	0.23	0.23	0.23	0.23	2.7	2.7	2.7	2.7	183	183	183	183	0.25	0.25	0.25	0.25
3	0.28	0.00	0.21	0.26	20.4	1.6	3.4	1.8	281	177	187	178	0.71	0.15	0.28	0.17
4	0.27	0.05	0.23	0.24	8.1	1.5	2.6	2.5	213	177	183	182	0.47	0.14	0.23	0.23
5	0.26	0.17	0.23	0.26	4.7	1.9	2.8	1.9	194	178	184	179	0.35	0.18	0.25	0.18
6	0.27	0.19	0.24	0.27	3.9	1.6	2.4	1.6	190	177	181	177	0.32	0.15	0.22	0.15
7	0.25	0.19	0.23	0.25	3.9	2.1	2.9	2.2	190	180	184	180	0.32	0.21	0.26	0.21
8	0.26	0.19	0.23	0.24	3.9	1.8	2.7	2.5	190	178	183	182	0.32	0.17	0.24	0.24
9	0.26	0.19	0.24	0.25	3.9	1.8	2.4	2.1	190	178	181	180	0.32	0.17	0.22	0.20
11	0.26	0.19	0.24	0.25	3.9	1.8	2.4	2.1	190	178	181	180	0.32	0.17	0.22	0.20
12	0.25	0.17	0.22	0.25	4.6	2.0	2.9	2.2	193	179	184	181	0.35	0.19	0.26	0.21
13	0.26	0.17	0.23	0.24	4.6	1.8	2.7	2.3	193	178	183	181	0.35	0.17	0.24	0.22
14	0.26	0.23	0.25	0.26	2.8	1.9	2.2	1.9	184	178	180	179	0.26	0.18	0.21	0.18
15	0.26	0.19	0.24	0.25	3.9	1.8	2.4	2.2	190	178	182	180	0.32	0.17	0.22	0.21
16	0.27	0.19	0.24	0.27	3.9	1.5	2.3	1.6	190	177	181	177	0.32	0.14	0.21	0.14
17	0.26	0.19	0.24	0.24	3.9	1.8	2.5	2.4	190	178	182	181	0.32	0.17	0.23	0.22
18	0.26	0.19	0.24	0.22	3.9	1.8	2.4	3.1	190	178	181	185	0.32	0.17	0.22	0.28
19	0.26	0.19	0.23	0.25	3.9	1.8	2.6	2.2	190	178	182	180	0.32	0.17	0.24	0.21
	Weir 2 drop				Weir 2 Ratio				Weir 2 EDF				W2 Velocity			
1	0.26	0.25	0.26	0.26	3.1	2.8	2.9	2.8	205	119	155	119	0.36	0.26	0.31	0.26
2	0.26	0.26	0.26	0.26	2.8	2.8	2.8	2.8	133	133	133	133	0.28	0.28	0.28	0.28
3	0.26	0.16	0.25	0.26	6.7	2.6	3.0	2.6	1161	66	173	78	0.84	0.16	0.32	0.19
4	0.27	0.23	0.26	0.26	4.0	2.6	2.8	2.8	448	63	129	118	0.54	0.15	0.26	0.26
5	0.26	0.25	0.26	0.26	3.2	2.6	2.8	2.6	247	83	138	84	0.40	0.20	0.29	0.21
6	0.26	0.25	0.26	0.26	3.1	2.6	2.7	2.6	205	69	112	70	0.36	0.17	0.25	0.17
7	0.26	0.25	0.26	0.26	3.1	2.7	2.8	2.7	205	100	141	101	0.36	0.23	0.29	0.24
8	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.8	205	79	132	123	0.36	0.20	0.28	0.27
9	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.7	205	79	115	97	0.36	0.20	0.25	0.23
11	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.7	205	79	115	97	0.36	0.20	0.25	0.23
12	0.26	0.25	0.26	0.26	3.2	2.7	2.9	2.7	240	90	142	105	0.40	0.22	0.29	0.24
13	0.26	0.25	0.26	0.26	3.2	2.6	2.8	2.7	240	79	131	108	0.40	0.20	0.28	0.25
14	0.26	0.26	0.26	0.26	2.8	2.6	2.7	2.6	139	83	105	85	0.29	0.20	0.24	0.21
15	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.7	205	79	116	103	0.36	0.20	0.26	0.24
16	0.27	0.25	0.26	0.27	3.1	2.6	2.7	2.6	205	65	107	66	0.36	0.16	0.24	0.16
17	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.7	205	79	119	113	0.36	0.20	0.26	0.26
18	0.26	0.25	0.26	0.26	3.1	2.6	2.7	2.9	205	79	113	157	0.36	0.20	0.25	0.31
19	0.26	0.25	0.26	0.26	3.1	2.6	2.8	2.7	205	79	125	102	0.36	0.20	0.27	0.24

Table G.2 . (continued) Summary of hydraulic parameters during fish passage.

JUVENILE STEELHEAD / RAINBOW TROUT

	Weir 3 drop				Weir 3 Ratio				Weir 3 EDF				W3 Velocity			
Fish ID	max drop m	min drop m	avg drop m	end drop m	max ratio	min ratio	avg ratio	end ratio	max W/m^3	min W/m^3	avg W/m^3	end W/m^3	max m/s	min m/s	avg m/s	end m/s
1	0.20	0.19	0.20	0.20	3.3	3.0	3.1	3.0	286	184	227	184	0.55	0.45	0.50	0.45
2	0.20	0.20	0.20	0.20	3.0	3.0	3.0	3.0	201	201	201	201	0.47	0.47	0.47	0.47
3	0.20	0.18	0.19	0.20	6.9	2.8	3.2	2.8	1415	123	249	136	0.94	0.33	0.50	0.36
4	0.20	0.19	0.20	0.20	4.2	2.7	3.0	3.0	573	119	197	184	0.71	0.32	0.44	0.45
5	0.20	0.19	0.20	0.20	3.4	2.8	3.0	2.8	336	142	207	144	0.59	0.38	0.47	0.38
6	0.20	0.19	0.20	0.20	3.3	2.8	2.9	2.8	286	126	177	127	0.55	0.34	0.43	0.34
7	0.20	0.19	0.20	0.20	3.3	2.9	3.0	2.9	286	162	211	163	0.55	0.42	0.48	0.42
8	0.20	0.19	0.20	0.20	3.3	2.8	3.0	3.0	286	138	200	189	0.55	0.37	0.46	0.46
9	0.20	0.19	0.20	0.20	3.3	2.8	2.9	2.9	286	138	180	159	0.55	0.37	0.44	0.41
11	0.20	0.19	0.20	0.20	3.3	2.8	2.9	2.9	286	138	180	159	0.55	0.37	0.44	0.41
12	0.20	0.19	0.20	0.20	3.4	2.8	3.0	2.9	328	150	212	168	0.58	0.39	0.48	0.42
13	0.20	0.19	0.20	0.20	3.4	2.8	3.0	2.9	328	138	199	172	0.58	0.37	0.46	0.43
14	0.20	0.20	0.20	0.20	3.0	2.8	2.9	2.8	209	142	168	144	0.48	0.38	0.42	0.38
15	0.20	0.19	0.20	0.20	3.3	2.8	2.9	2.9	286	138	181	166	0.55	0.37	0.44	0.42
16	0.20	0.19	0.20	0.20	3.3	2.8	2.9	2.8	286	121	170	122	0.55	0.32	0.42	0.33
17	0.20	0.19	0.20	0.20	3.3	2.8	3.0	2.9	286	138	185	178	0.55	0.37	0.44	0.44
18	0.20	0.19	0.20	0.20	3.3	2.8	2.9	3.1	286	138	178	230	0.55	0.37	0.43	0.50
19	0.20	0.19	0.20	0.20	3.3	2.8	3.0	2.9	286	138	192	165	0.55	0.37	0.45	0.42

Table G.2 . (continued) Summary of hydraulic parameters during fish passage.

Fish ID	max drop m	min drop m	avg drop m	end drop m	max ratio	min ratio	avg ratio	end ratio	EDF max W/m^3	EDF min W/m^3	EDF avg W/m^3	EDF end W/m^3	Velocity max m/s	Velocity min m/s	Velocity avg m/s	Velocity end m/s
JUVENILE BROOK TROUT																
	Weir 1 drop				**Weir 1 Ratio**				**Weir 1 EDF**				**W1 Velocity**			
B1	0.25	0.00	0.17	0.22	20.4	2.2	4.6	2.9	281	181	193	184	0.71	0.21	0.33	0.26
B3	0.27	0.00	0.21	0.21	20.4	1.5	3.5	3.3	281	177	187	187	0.71	0.14	0.27	0.29
B4	0.25	0.17	0.23	0.24	4.7	2.0	2.9	2.5	194	179	184	182	0.35	0.19	0.26	0.23
	Weir 2 drop				**Weir 2 Ratio**				**Weir 2 EDF**				**W2 Velocity**			
B1	0.26	0.16	0.25	0.26	6.7	2.7	3.2	2.9	1161	105	241	145	0.84	0.24	0.38	0.30
B3	0.27	0.16	0.25	0.26	6.7	2.6	3.0	3.0	1161	63	176	169	0.84	0.15	0.31	0.33
B4	0.26	0.25	0.26	0.26	3.2	2.7	2.9	2.8	247	90	142	120	0.40	0.22	0.29	0.27
	Weir 3 drop				**Weir 3 Ratio**				**Weir 3 EDF**				**W3 Velocity**			
B1	0.20	0.18	0.19	0.20	6.9	2.9	3.4	3.1	1415	168	329	186	0.94	0.42	0.56	0.49
B3	0.20	0.18	0.19	0.20	6.9	2.7	3.2	3.1	1415	119	252	244	0.94	0.32	0.50	0.52
B4	0.20	0.19	0.20	0.19	3.4	2.8	3.0	3.0	336	150	211	215	0.59	0.39	0.48	0.45
ADULT STEELHEAD																
	Weir 1 drop				**Weir 1 Ratio**				**Weir 1 EDF**				**W1 Velocity**			
AS1	0.270	0.052	0.247	0.11	8.1	1.5	2.2	6.3	213	177	180	203	0.47	0.14	0.20	0.41
AS2	0.268	0.052	0.233	0.18	8.1	1.6	2.6	4.2	213	177	183	191	0.47	0.15	0.22	0.33
AS3	0.241	0.052	0.176	0.17	8.1	2.4	4.4	4.7	213	181	192	194	0.47	0.22	0.33	0.35
AS4	0.184	0.052	0.137	0.15	8.1	4.1	5.5	5.3	213	191	199	197	0.47	0.33	0.38	0.37
	Weir 2 drop				**Weir 2 Ratio**				**Weir 2 EDF**				**W2 Velocity**			
AS1	0.265	0.229	0.261	0.24	4.0	2.6	2.7	3.6	448	63	104	344	0.54	0.15	0.23	0.48
AS2	0.265	0.229	0.259	0.25	4.0	2.6	2.8	3.1	448	66	127	219	0.54	0.16	0.25	0.38
AS3	0.261	0.229	0.250	0.25	4.0	2.7	3.2	3.2	448	113	228	247	0.54	0.26	0.37	0.40
AS4	0.251	0.229	0.243	0.24	4.0	3.1	3.4	3.4	448	214	297	281	0.54	0.37	0.44	0.43
	Weir 3 drop				**Weir 3 Ratio**				**Weir 3 EDF**				**W3 Velocity**			
AS1	0.197	0.190	0.196	0.192	4.2	2.7	2.9	3.8	573	119	167	450	0.71	0.32	0.40	0.65
AS2	0.197	0.190	0.196	0.194	4.2	2.8	3.0	3.3	573	123	194	302	0.71	0.33	0.43	0.56
AS3	0.196	0.190	0.194	0.193	4.2	2.9	3.4	3.4	573	178	314	336	0.71	0.44	0.56	0.59
AS4	0.194	0.190	0.193	0.193	4.2	3.3	3.6	3.6	573	297	395	376	0.71	0.56	0.62	0.61