Empirical in-stream flow assessment tools for British Columbian channels

by

Daniel McParland

B.Sc, Queen's University, 2011

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Geography)

The University Of British Columbia

(Vancouver)

September 2013

Abstract

Empirical hydraulic distribution equations have been proposed as simple and inexpensive alternatives to traditional data-intensive flow assessment methodologies. Two proposed depth and three proposed velocity empirical equations were compared to measured hdraulic distributions for two channels in the Interior Region of British Columbia. Empirical velocity distributions adequately reproduced the measured velocity distribution for both channels. An empirical depth distribution was able to replicate measured depth distributions at a relatively undisturbed channel (Harris Creek) but were unable to predict the measured depth distribution following morphological change at a channel recently disturbed by forest fire (Fishtrap Creek). Furthermore, the empirical distributions were compared to modelled depth and velocity distributions produced by a 2-dimensional hydrodynamic model (River2D). The empirical distributions provided reasonable representation of the hydraulic distributions for flows < 3 m^3 s^{-1}. At flows approaching bankfull the empirical methods, in particular the velocity equations, were unable to adequately reproduce the distributions produced in River2D. Additionally, a joint frequency depth-velocity distribution was paired with habitat suitability indices to quantify available habitat across a range of flows at Harris Creek using reach average hydraulic conditions generated by River2D. The statistical habitat model produced similar habitat values to River2D at low flows and was able to recreate the general shape and trends of the habitat indices. As well, a proposed at-a-station hydraulic geometry simulator was used alongside a channel regime model to approximate reach average channel conditions at Harris Creek. The proposed hydraulic simulator was able to accurately predict reach average depth (mean error of 1.06%) and velocity (4.47%) for discharges ranging from daily low flow to bankfull flow. The hydraulic simulator was coupled with the statistical habitat model to generate hydraulic distributions and subsequently habitat indices for the modelled discharges. The incorporation of the regime models allows users to examine the influence of variable flow regimes and riparian vegetation (inherent of a changing climate) on available aquatic habitat. The proposed aquatic habitat model provides practitioners with a low-input, user-friendly flow assessment tool that can be used for preliminary habitat assessments and basin-wide habitat studies in British Columbia.

Preface

This dissertation is original and unpublished work by the author, D. McParland. Assistance with developing the at-a-station hydraulic geometry simulator that is described in Chapter 4 was provided by B. Eaton.

Table of Contents

List of Tables

List of Figures

List of Variables

b	index of channel shape
C	speed of sound (m^3 s^{-1})
d	depth (m)
$\bar{d}$	reach average depth (m)
d_b	mean depth at bankfull discharge (m)
d_{max}	maximum water depth (m)
D_n	particle size associated with the nth percentile (mm)
Fr	reach average Froude number
g	acceleration due to gravity (m sec^{-2})
H	representative rooting depth (m)
H_o	initial representative rooting depth (m)
n	number of bins
P_{wetted}	channel wetted perimeter (m)
Q	discharge (m^3 s^{-1})
Q_b	bankfull discharge (m^3 s^{-1})
Q_{bo}	initial bankfull discharge (m^3 s^{-1})
R	hydraulic radius (m)
Res	flow resistance
S	energy slope, estimated from water surface slope (m m^{-1})
s	shape parameter for statistical velocity distribution
S_{mix}	shape parameter for joint frequency distribution
t	shape parameter for statistical depth distribution
v	velocity (m s^{-1})
$\bar{v}$	reach average velocity (m s^{-1})

W	reach average width (m)
W_b	mean width at bankfull discharge (m)
μ	mean of distribution
σ	standard deviation of distribution

Glossary

ADCP acoustic Doppler current profiler

ADV acoustic Doppler velocimeter

ASHGS at-a-station hydraulic geometry simulator

HSI habitat suitability indexes

HV habitat value

IFIM Instream Flow Incremental Methodology

LW large wood

PHABSIM Physical Habitat Simulation Model

UBCRM University of British Columbia Regime Model

USGS United States Geological Survey

WUA weighted usable area

Acknowledgments

First and foremost, I would like to thank my supervisor Dr. Brett Eaton. Brett's technical expertise, practical thinking, and sense of humour allowed this project to reach its potential and made the experience worthwhile. I am also grateful to my two other committee members, Dr. Jordan Rosenfeld and Dr. Andre Zimmerman, for their advice and encouragement throughout this journey. Many thanks to Alistair Davis, Byeong Gyu Kim, Holly Buehler, Lesley Winterhalt, and Sarah Davidson for their hard work and enthusiasm while completing field work for this project. Special thanks to Aaron Tamminga for being a constant source of knowledge and humour. My parents and sister have supported me on all my endeavors including this one and I cannot thank them enough for that. Sara made the journey, through the challenges and achievements, a worthwhile experience and I am truly grateful for all of her support. Funding for this project was provided by the Pacific Institute for Climate Solutions.

Chapter 1

Introduction

1.1 Motivation for the study

Across the world, increased out-of-stream water demand has led to a convoluted dispute between river development and aquatic conservation [Tharme, 2003]. The complexity of fluvial systems makes finding a balance between development and conservation an extremely difficult task. The unknown impacts of climate and land use change on channel dynamics complicates the matter further [Conallin et al., 2010, Anderson et al., 2006]. Practitioners have and will continue to need scientific tools to aid them in establishing flows that withhold the ecological integrity of the channel as well as satisfy flow abstraction demand [Hardy, 1998, Saraeva and Hardy, 2009a, Jowett, 1997, Hatfield and Bruce, 2000]. This need has led to the science of flow assessment.

Environmental flow assessment methodologies were first developed in the Pacific Northwest at the end of the 1940s. Starting in the 1970s, new environmental and freshwater legislation as well as pressure from practitioners led to significant progress in the development of flow assessment tools [Tharme, 2003]. For instance, in 1986, the Canadian Department of Fisheries and Oceans implemented its Habitat Policy which required no net loss of productive capacity of channels. This policy highlighted the need to continually develop and refine aquatic habitat assessment tools for Canadian channels [Ahmadi-Nedushan et al., 2006]. The range and scope of environmental flow assessment tools has broadened over the past 20 years due to advances in computational technology [Gard, 2009, Jowett, 1997, Conallin et al., 2010].

A multitude of in-stream flow methodologies have been developed and implemented across North America with varying degrees of resolution, complexity, and subsequently success [Annear et al., 2004, Tharme, 2003, Jowett, 1997, Saraeva and Hardy, 2009b]. In the flow assessment community, there has been both efforts to refine and extend existing methodologies as well as develop new tools [Hardy, 1998]. Each methodology has its own unique set of advantages and limitations. The most commonly applied methodology in North America is the Instream Flow Incremental Methodology (IFIM) and in particular the Physical Habitat Simulation Model (PHABSIM) component. PHABSIM links a hydraulic model based on cross-sectional data to habitat suitability indexes (HSI) to quantify habitat for a given reach as a function of flow [Hardy, 1998, Jowett, 1997]. This methodology is considered the most comprehensive and legally defensible but is heavily criticized for being technical, time consuming, and expensive and for ignoring ecological interactions [Hatfield and Bruce, 2000, Saraeva and Hardy, 2009b].

Low-input, transparent alternatives to PHABSIM have and need to be continually developed and refined in order to give practitioners practical in-stream flow assessment tools [Conallin et al., 2010]. Empirical hydraulic distributions have been proposed as a simple alternative to PHABSIM assessments [Lamouroux et al., 1995, Lamouroux, 1998, Schweizer et al., 2007]. The ability of these empirical methodologies to approximate reach average hydraulic distributions and thus quantify physical habitat availability in British Columbian channels is relatively unknown. Furthermore, the ability of empirical equations to model future physical habitat availability under different climate and land use change scenarios needs to be assessed. The following section will provide a literature review of the relevant in-stream flow methodologies used in British Columbia. This will be followed by the research objectives of this project.

1.2 Literature review

1.2.1 Physical methods

Historical methodologies use archived discharge data usually in the form of monthly or daily flow records to make flow recommendations [Tharme, 2003]. These methods provide minimum flow values and flow duration within the historic range that are needed to support aquatic life. They are considered to be effective and appropriate in the preliminary stages of waterway development. Historical methods require little to no fieldwork. The most well known and used historical flow method is the Tennant [1976] method. It is the second most used flow assessment tool in the United States of America [Reiser et al., 1989].

Historical flow methods are simplistic and are readily used when there is an established flow record. However, due to their simplicity, and thus their numerous assumptions, they have many shortcomings. These methodologies are unable to quantify available habitat. As well, minimum flows vary amongst aquatic species and life stages [Hatfield and Bruce, 2000, Tharme, 2003]. Furthermore, historical methodologies ignore limiting conditions such as cover availability, minimum depth for fish passage, excess velocities, stream temperature, and food availability [Hogan and Church, 1989, Jowett, 1997].

Moreover, applying the same minimum flows to different channels will have contrasting results due to differences in channel geometry [Jowett, 1997]. Minimum flow values embedded in historical methodologies are often based on flows relative to the mean annual flow [Tharme, 2003]. However, bankfull flows set the channel geometry and thus potential habitat. The ratio of bankfull flow to mean annual flow for nival channels are much greater than pluvial channels. Applying the same minimum flow values (e.g. 10% of mean annual flow) to channels with different flow regimes and therefore channel geometry will correspond to contrasting water levels relative to bankfull channel conditions and thus differences in usable habitat.

Hydraulic geometry assessment tools are based on cross-sectional data and include both "at-a-station" and "downstream" methods [Leopold and Maddock, 1953]. Cross-sections are appropriately placed to survey the variation in morphological and hydraulic conditions within a reach. Flow requirements are often determined from the observed wetted perimeter at each cross-section [Jowett, 1997]. Hydraulic geometry methods provide only summary geomorphic and hydrologic conditions of the channel and do not offer detail on local variability within a reach [Hogan and Church, 1989]. However, hydraulic geometry methods can assess whether the geometry conditions are approaching a threshold (e.g. minimum acceptable depth) and thus indicate the need for a more robust habitat assessment [Jowett, 1997].

1.2.2 Habitat methods

Habitat methods (or combined hydraulic-habitat methods) are the most commonly used in-stream flow methodology in the world, and in particular in North America [Conallin et al., 2010, Tharme, 2003]. Habitat methods divide the reach into cells of a similar size, often in the form of closely spaced cross-sections. Within each cell a deterministic hydraulic model is incorporated with univariate HSI to quantify habitat suitability. HSI define the biological requirements (usually for depth, velocity, and substrate) of an individual aquatic species and life stage [Jowett, 1997, Lamouroux et al., 1998, Guay et al., 2000]. The sum of the calculated habitat suitability of all the cells determines the potential habitable area of the reach. Habitat methods are considered to be a reliable method of assessing available aquatic habitat because they quantify habitat for the entire reach and use a biological component [Jowett, 1997].

Physical habitat simulation model

The most well-known and used habitat method in North America is PHABSIM [Jowett, 1997, Tharme, 2003, Hatfield and Bruce, 2000, Parasiewicz and Walker, 2007]. PHABSIM [Bovee, 1982] was developed in the 1970s by biological and physical scientists at the U.S. Fish and Wildlife Service. It is considered to be the most comprehensive and legally defensible methodology currently available [Hatfield and Bruce, 2000, Tharme, 2003, Lee Lamb et al., 2004, Hardy, 1998]. There have been regional modifications of the original model (e.g. RHYHAB-SIM, CASIMIR, EVHA); however, the underlying principles of PHABSIM are maintained [Parasiewicz and Walker, 2007]. The primary output of PHABSIM is weighted usable area (WUA) which is the amount of area in the channel deemed habitable. PHABSIM can calculate WUA across a range of flows for target aquatic species and life stages.

Hydrodynamic models

Over the past 20 years, advances in computational technology has allowed the underlying principles of habitat methods/PHABSIM to be incorporated into 2-dimensional hydrodynamic models (e.g. River2D, CCHEW2D, FEWMS-2DH). Hydrodynamic models are considered superior and seen as a potential replacement of traditional PHABSIM methods because they predict depth and velocity both laterally and longitudinally throughout a reach by explicitly using mechanistic processes such as conversion of mass and momentum [Leclerc et al., 1995, Gard, 2009]. Hydrodynamic models avoid the confusion of transect placement as all mesohabitats within the reach are modelled. As well, 2-dimensional models perform better in complicated channels because they account for local bed topography and roughness and they can be used to assess hydraulic conditions at different discharges for an established channel boundary. Currently there are finite difference, finite volume, and finite element hydrodynamic models commercially available [Steffler and Blackburn, 2002].

Criticisms of habitat models

Despite their widespread use, PHABSIM and 2-dimensional hydrodynamic models are highly criticized, most notably for being costly, complex, and time-consuming [Hatfield and Bruce, 2000, Armour and Taylor, 1991, Lamouroux and Capra, 2002, Saraeva and Hardy, 2009a,b, Lamouroux and Souchon, 2002, Lamouroux and Jowett, 2005]. They require intensive site-specific field data collection which includes numerous point depth and velocity measurements along geo-referenced cross-sections, substrate and cover classification, and a complete topographic survey [Lamouroux and Jowett, 2005]. Data collection is followed by meticulous technical analyses of calculated hydraulic conditions, the use of simulation models, and the application of HSI [Saraeva and Hardy, 2009b].

Other criticisms of PHABSIM and 2-dimensional models are that the results are not monitored or verified and the underlying assumptions of the models are rarely tested [Hatfield and Bruce, 2000]. Also, the application of these methodologies have been limited to case studies as they require extensive calibration [Lamouroux and Capra, 2002]. As well, PHABSIM output can only represent current channel conditions. It is unable to predict available habitat following geomorphic change [Bovee et al., 1998]. Moreover, HSI have long been scrutinized for not being transferable between streams and ignoring ecological interactions [Hatfield and Bruce, 2000, Hardy, 1998]. Lastly, limited resources, lack of environmental data, and need for immediate assessment often exclude these methodologies as legitimate in-stream flow tools for many practitioners [Conallin et al., 2010].

1.2.3 Statistical methods

Simple alternatives to PHABSIM and 2-dimensional hydrodynamic models have been sought in recent decades. Prediction of depth and velocity distributions using empirical statistical models have become increasingly common. Early work on empirical statistical equations for the purposes of aquatic habitat modelling began in France [Lamouroux et al., 1995, Lamouroux, 1998] and was later adopted in New Zealand [Lamouroux and Jowett, 2005, Schweizer et al., 2007]. Statistical methods relate the form and shape of reach-scale depth and velocity distributions to easily attainable predictor variables. The predictor variables are usually a reach average hydrological or geomorphological condition (e.g. reach average Froude number or reach average relative roughness). Research has yielded both independent distribution equations for depth and velocity [Lamouroux et al., 1995, Lamouroux, 1998] as well as a joint frequency depth-velocity distribution equation [Schweizer et al., 2007].

Statistical methods are desirable because they do not require a complete bed topography survey and have low computational costs compared to habitat methods and 2-dimensional hydrodynamic models. Statistical methods are thought to be of particular use for preliminary assessment of habitat conditions as well as simulating changing flow conditions and channel boundaries [Schweizer et al., 2007]. They have also been proposed as a rapid assessment tool when numerous channels need evaluation [Saraeva and Hardy, 2009a]. As well, Schweizer et al. [2007] suggests that empirical statistical equations have some degree of universality.

Aquatic habitat models created by pairing empirical hydraulic equations with HSI have produced comparable habitat indices to more data-intensive habitat models in French and New Zealand channels [Lamouroux and Capra, 2002, Lamouroux and Jowett, 2005]. Statistical hydraulic distributions have recently been evaluated in channels in the Pacific Northwest. Saraeva and Hardy [2009a] examined distribution equations developed in France [Lamouroux et al., 1995, Lamouroux, 1998] in the Nooksack River watershed in Washington State. Their results showed a slight manipulation of the original velocity distribution equation allowed for adequate prediction of available habitat in channels with a mean annual flow less than 3.5 m^3 s^{-1}. The empirical equations performed poorly in large and irregularly shaped channels.

Furthermore, Rosenfeld et al. [2011] examined a joint frequency distribution equation developed in New Zealand [Schweizer et al., 2007] and locally derived gamma distributions among contrasting habitat types in a small (approximate bankfull discharge of 0.6 m^3 s^{-1}) coastal stream. They found that gamma distributions in conjunction with simple hydraulic geometry adequately represented reach scale hydraulic conditions in the trout-bearing stream. The joint frequency distribution performed poorly suggesting that empirical frequency distributions cannot be easily transferred to other biogeoclimatic regions without some form of local calibration.

While empirical statistical methods are an intriguing alternative to habitat models and 2-dimensional modelling they do come with limitations. First and foremost, statistical methods do not provide any information on the spatial distribution of hydraulic variables unlike PHABSIM and hydrodynamic models [Ahmadi-Nedushan et al., 2006, Lamouroux et al., 1995]. As well, statistical methods are best suited for channels with relatively natural morphology and flow regime [Parasiewicz and Dunbar, 2001, Schweizer et al., 2007]. There has been little use of these methodologies outside of the geographies in which they were developed and the universality of the distribution equations is questionable [Schweizer et al., 2007, Rosenfeld et al., 2011]. Also, the mechanistic rationale behind the empirical distributions and how the distributions evolve with changing flow and morphology is poorly understood [Rosenfeld et al., 2011]. Furthermore, habitat models associated with empirical hydraulic equations are often designed for individual species and are not suited for the analyses of multiple species [Ahmadi-Nedushan et al., 2006].

1.3 Research objectives

A review of the relevant literature in Section 1.2 highlights the need for further development of low-input, user-friendly aquatic habitat models for British Columbian channels. The overarching objective of this research project is to determine if and to what extent empirical hydraulic equations can be used alongside channel regime models to adequately predict changes in available aquatic habitat for British Columbian channels stemming from changes in flow regime and riparian vegetation dynamics. In order to meet this overarching objective there are three sub-objectives that have to be considered:

1. The applicability of depth and velocity empirical distribution equations developed in France [Lamouroux et al., 1995, Lamouroux, 1998] and New Zealand [Schweizer et al., 2007] need to be evaluated on British Columbian channels. British Columbia has many unique biogeoclimatic regions and using distribution equations developed on different continents may be inappropriate. The ability of statistical methods to reproduce both measured velocity and depth distributions as well as velocity and depth distributions produced from 2-dimensional hydrodynamic model simulations will be evaluated.

2. Empirical hydraulic equations need to be tested in both a disturbed and undisturbed watershed. The underlying hypothesis is that the statistical methods should be able to adequately predict depth and velocity distributions for an undisturbed watershed, as the predictive equations were developed on channels that had relatively natural flow regime and morphology. However, the ability of statistical methods to adequately predict depth and velocity distributions in morphologically disturbed reaches has yet to be fully explored.

3. Evaluate whether future channel dimensions resulting from climate and land use change can be adequately modelled with a channel regime model. Future reach average hydraulic conditions predicted with a regime model will

be paired with applicable empirical hydraulic equations to determine future habitat indices for a species found in British Columbian channels.

The remainder of this dissertation is organized as follows. Chapter 2 reviews the study sites and relevant data collection procedures. Chapter 3 examines the ability of statistical distributions to reproduce measured and modelled (hydrodynamic model) depth and velocity distributions as well as WUA in British Columbian channels. Chapter 4 proposes a low-input, user-friendly aquatic habitat model. Chapter 5 provides a summary of key conclusions and provides insight on future aquatic habitat modelling research.

Chapter 2

Study sites and data collection

2.1 Harris Creek

2.1.1 Site description

Harris Creek is a tributary of the Shuswap River located in the Interior Region of British Columbia near the town of Lumby (Figure 2.1). The drainage area of the channel is 220 km^2 with approximately half of the catchment area above 1500 m elevation on the Okanagan Plateau [Fletcher and Wolcott, 1991]. The terrain is characterized by gneisses and plateau basalts that are covered by a thin layer of glacial drift [Day and Fletcher, 1989]. Mean annual flood is 19 m^3 s^{-1} but the largest recorded flood reached 35 m^3 s^{-1}. Discharge was recorded by a Water Survey of Canada stream gauge (station no. 08LC042) just downstream of the study reach. Floods are dominated by melting snowpack on the plateau in late April and early May [Fletcher and Wolcott, 1991, Hassan and Church, 2001]). Mean annual flow is approximately 1.5 m^3 s^{-1}. Unseasonably high spring precipitation in 2012 caused flooding to persist into late June.

A 150 m study reach measured along the thalweg was used for this project (Figure 2.2). The reach was previously a study site for investigating bed load [Church and Hassan, 2002, Hassan and Church, 2001] and precious metals [Day and Fletcher, 1989, Fletcher and Wolcott, 1991] transport. The average gradient of the reach is 0.011 m m^{-1} (Figure 2.3) and widths range from 10 to 20 m with an

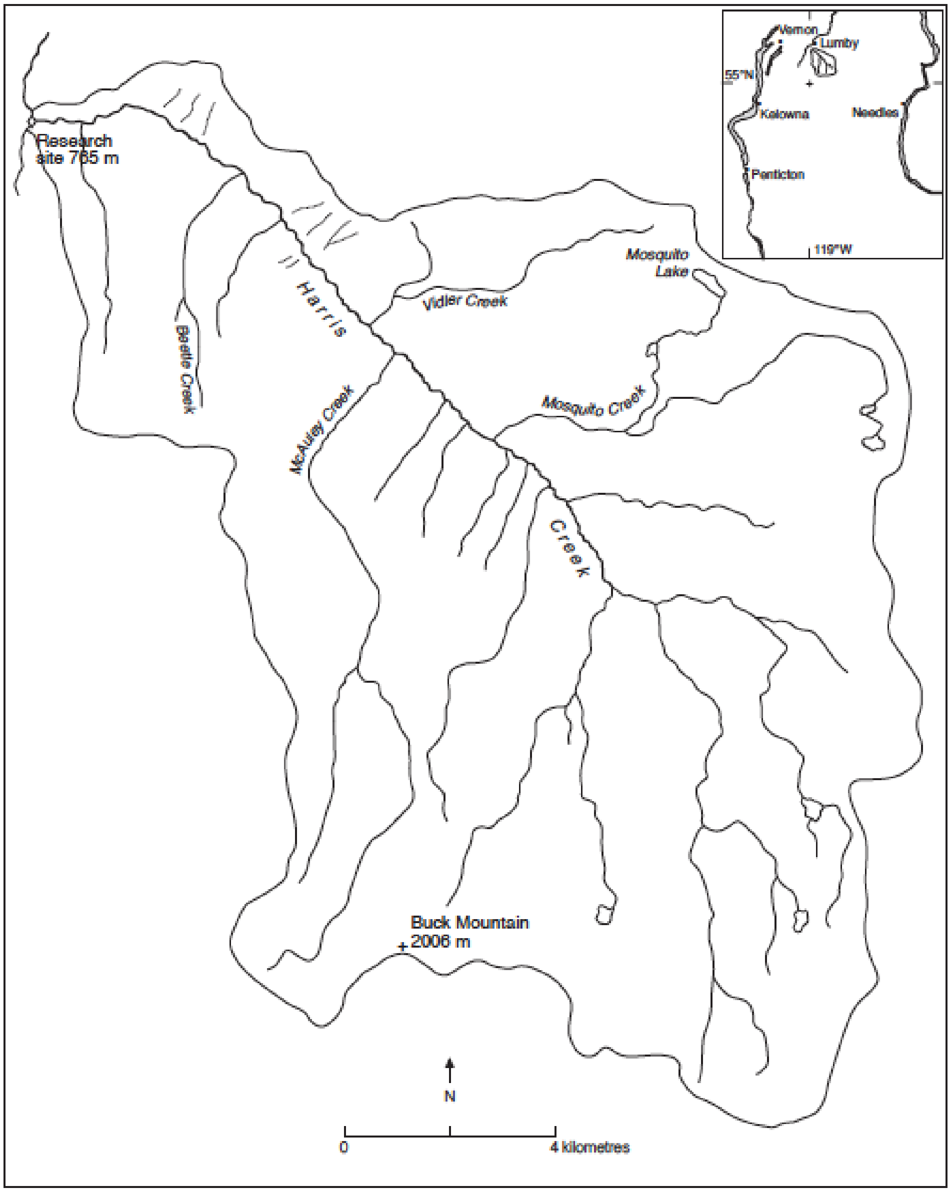

Figure 2.1: Location (inset) and boundaries of the Harris Creek watershed, tributaries, and study site

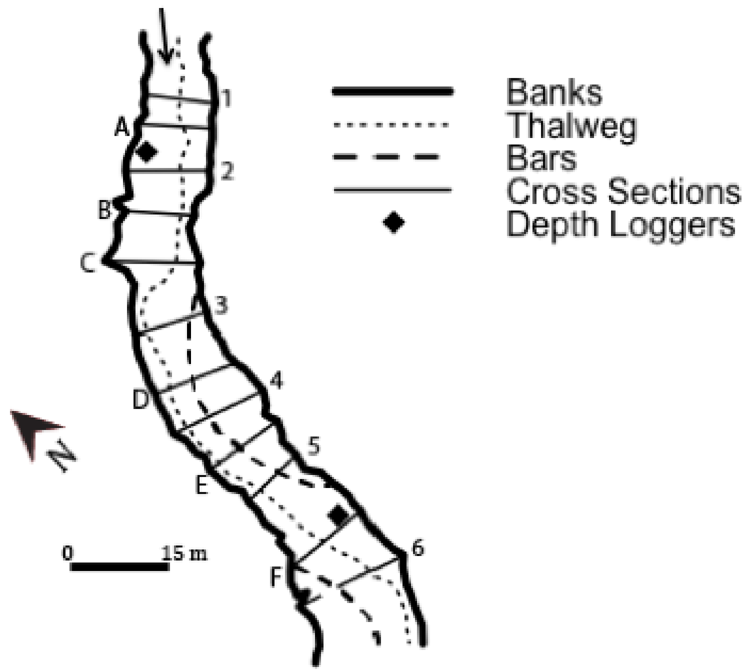

Figure 2.2: Location of banks, bars, and thalweg, and placement of cross sections and depth loggers at Harris Creek

average width of approximately 15 m. The riparian vegetation is mature coniferous trees and there are few pieces of large wood (LW) within the channel.

The upper reach is characterized by a relatively straight series of glides and runs. The middle and lower reach are comprised of an alternating pool-riffle sequence with the presence of two large bars [Montgomery and Buffington, 1997]. Twelve cross-sections (1 through 6 and A through F) perpendicular to flow were established along the reach and were distributed to evenly represent four morphological units (Figure 2.2). Classification of each cross section into one of the four morphological units was strictly from visual inspection (Table 2.1). Furthermore, pressure transducers surrounded by PVC pipe were embedded in the substrate at the upstream and downstream ends of the reach to record water stage every 15 minutes. A transducer was also attached to a riparian tree to record barometric pressure.

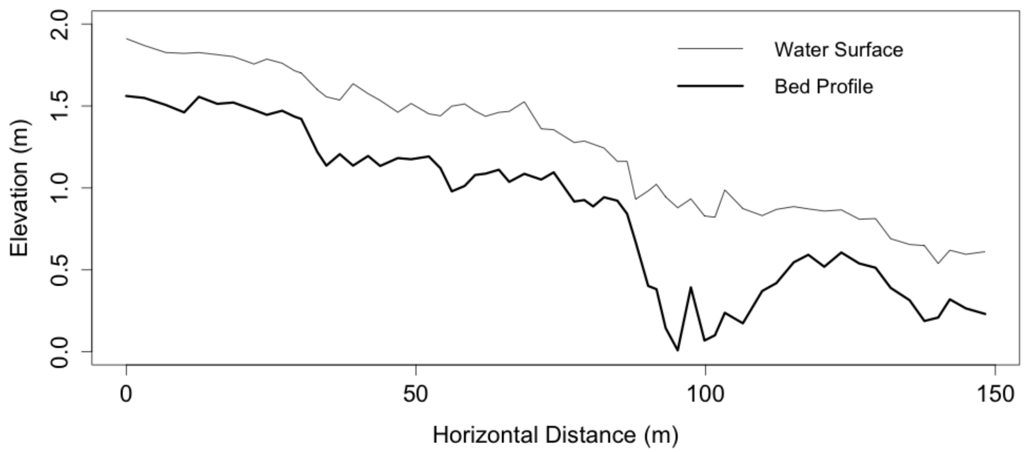

Figure 2.3: Longitudinal bed profile and water surface elevation along the thalweg

Table 2.1: The morphological unit, its defining characteristics, and the representative cross-sections from Harris Creek

Unit	Characteristics	Cross Sections
Pool	0 - 0.5% gradient, slow velocity, deep	3, E, 5
Glide	0.5 - 1% gradient, relatively slow, undisturbed water surface	1, A, F
Run	1 - 2% gradient, turbulent flow, shallow	2, B, C
Riffle	1 - 3% gradient, fast current, protruding substrata	D, 4, 6

The bar heads are comprised of cobble-gravel surface and gravel and coarse sand subsurface. The bar tails are dominated by small pebbles with coarse sand in the voids. The wetted bed is well armoured with a median surface grain size ranging from 64 mm (pools) to 76 mm (riffles) and a median subsurface grain size ranging from 22 to 45 mm. The organized bed structure leads to small bed load fluxes at Harris Creek [Hassan and Church, 2001].

2.1.2 Data collection

High flows

High flow data were collected between April 29 and May 9th at discharges ranging from 1.61 to 4.82 m^3 s^{-1}. Depth and velocity data were collected at cross-sections 1 through 6 on three separate occasions. Hydraulic measurements at each cross-section were taken as close to the bank as possible and then approximately every 0.5 m across the channel until the far bank.

A hand-held SonTek (firmware version 3.3, software version 2.20) acoustic Doppler velocimeter (ADV) was used to collect both depth and velocity data for depths less than approximately 0.3 m (i.e. near the banks). Water depths were determined from a measuring rod attached to the ADV. The ADV probe was placed at 60% water depth for 30 seconds. A transmitter within the probe generates sound concentrated in a narrow beam at a frequency of 10 Hz. The emitted pulse travels through the water column interacting with particulate matter (mostly sediment and bubbles) causing the sounds to be reflected in all directions. Two receivers are mounted on the probe so that they are receiving signals from water located 10 cm from the tip of the probe [SonTek, 2007]. The Doppler shift determines the velocity of the water:

$$Velocity = \frac{f_{observed}}{f_{source}} \cdot C \tag{2.1}$$

where $f_{observed}$ is the received frequency, f_{source} is the frequency of the emitted pulse (10 Hz), and C is the speed of sound (331 m s^{-1}). The probe was pointed directly into the direction of the current, leading to negligible lateral velocity. Velocity measurements were averaged over 30 seconds at each vertical.

A floating QLiner acoustic Doppler current profiler (ADCP) was used to measure velocity at verticals that had water depths greater than approximately 0.3 m (i.e. close to the thalweg). The ADCP is ineffective in shallow waters due to a 20 cm blanking distance. Similar to the ADV, the ADCP uses the Doppler shift to quantify velocity. Three 1 Hz beams are emitted from a sensor located on the front of the boat (Figure 2.4). The Doppler shift was recorded every second for a duration of at least 30 seconds at each vertical. Beam 3 was ignored as the turbulent water at high flows often caused the front of the boat and thus beam 3 to be lifted out of the water resulting in erroneous measurements. Beam 1 and 2 recorded the Doppler shift in 10 cm increments from the sensor (i.e. the first measurement was taken at 30 cm depth, then 40 cm depth, 50 cm so on and so forth).

The location of all ADV and ADCP measurements were geo-referenced with a total station surveyor (Leica TPS800 Series) and reflective prism. The depth that corresponded to each ADCP velocity measurement was recorded as the difference in altitude of the boat minus the altitude of the bed (bathymetric survey would take place at low flow). ADCP measurements recorded for depths greater than the measured depth were dismissed at each vertical. The remaining ADCP velocity data was corrected for the pitch of the boat at the time of the measurement. The corrected velocity data were averaged between beam 1 and 2 and then averaged over the depth of the vertical.

Discharge at each cross-section was determined by assigning each vertical a width half the distance to its neighbouring verticals. The discharge within each vertical was determined by multiplying the area of the assigned rectangle (depth x width) by the corresponding velocity. The bins that extended from the bank to half the distance to the near bank verticals were assigned a velocity of zero. The discharge of the verticals were then summed for the cross-section to determine the total discharge [Corbett, 1962].

Low flows

Low flow data were collected between July 18 and 23 at discharges ranging from 0.76 to 2.02 $m^3\ s^{-1}$. Data were collected at cross-sections 1 through 6 and A to F on three separate occasions. Hydraulic measurements at each cross-section were taken as close to the bank as possible and then subsequently every 0.5 m across the channel until the far bank. All velocity and depth data were measured with an ADV as described above.

A complete bathymetric survey was conducted from approximately 30 m upstream of cross-section 1 to 50 m downstream of cross-section 6. A total station surveyor and reflective prism were used to record the northing, easting, and elevation of all points relative to a set starting point. The bed was surveyed in a series

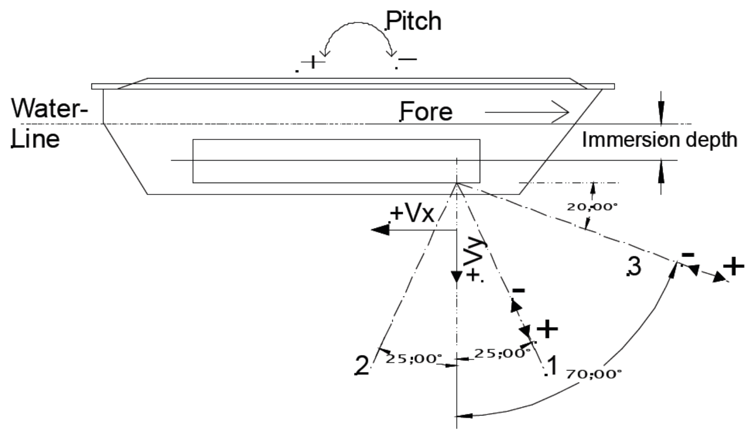

Figure 2.4: The position of the ADCP boat in the water as well as the coordinate system of the three emitted beams [QLiner, 2005]

of cross-sections perpendicular to flow. An elevation was recorded on top of both banks at each cross-section. Points within the cross-section were spaced to allow for a representative bed topography. Once a cross-section was complete a new cross-section was established approximately 2 to 3 m downstream of the previous cross-section and the process was repeated. 1942 elevation points were collected.

Collection of bed elevation data along cross-sections 1 through 6 was thorough to allow for accurate interpolation of depths corresponding to high flow ADCP locations. However, the unforeseen flooding events in late June lead to a noticeable restructuring of the channel. Thus, bed topographies recorded along the cross-sections 1 through 6 at low flow were probably different than the topographies of the cross-sections when the ADCP data were collected. This could have led to not only erroneous depth data for high flow ADCP measurements but also inaccurate mean velocity data as the calculation of velocity was dependent on the depth of the individual vertical.

Furthermore, the location and elevation of the thalweg were recorded with a total station surveyor and reflective prism. Depth and velocity data were recorded along the thalweg using an ADV. The survey data were used to estimate the reach average energy gradient of the channel.

Grain size distributions were examined at the head of the two large bars (repre-

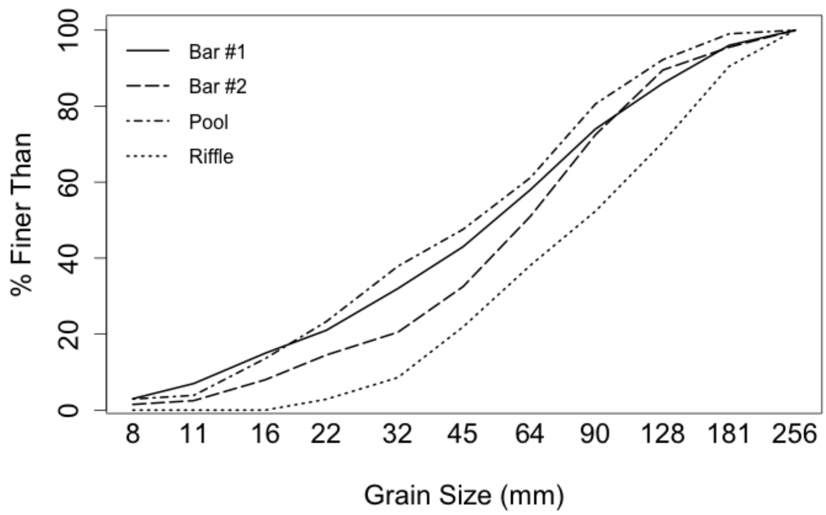

Figure 2.5: Grain size distributions determined from the Wolman pebble count procedure [Wolman, 1954] at two bar heads, a riffle, and a pool

sentative of within channel substrate) as well as in a pool and in a riffle. Distributions were quantified using the Wolman pebble count procedure [Wolman, 1954]. Recorded grain size distributions (Figure 2.5) were very similar to distributions recorded in the late 1980s and early 1990s at Harris Creek [Church and Hassan, 2002, Hassan and Church, 2001].

The pressure transducers were removed from the channel on October 18, 2012. The barometric pressures were subtracted from the pressure data recorded by the in-channel transducers to determine water stage as a function of time (Figure 2.6). The hydrograph is unusual for Harris Creek as peak discharges were pushed well into June due to the unseasonably late spring floods. This resulted in the high flow sampling period (dashed vertical lines on Figure 2.6) not occurring at the highest flows. However, high flow data were collected above the mean annual discharge for Harris Creek. Furthermore, the shift in the hydrograph led to low flow sampling (dotted vertical lines) to occur around the mean annual discharge, instead of below it. Low flows appeared to occur in late August and September.

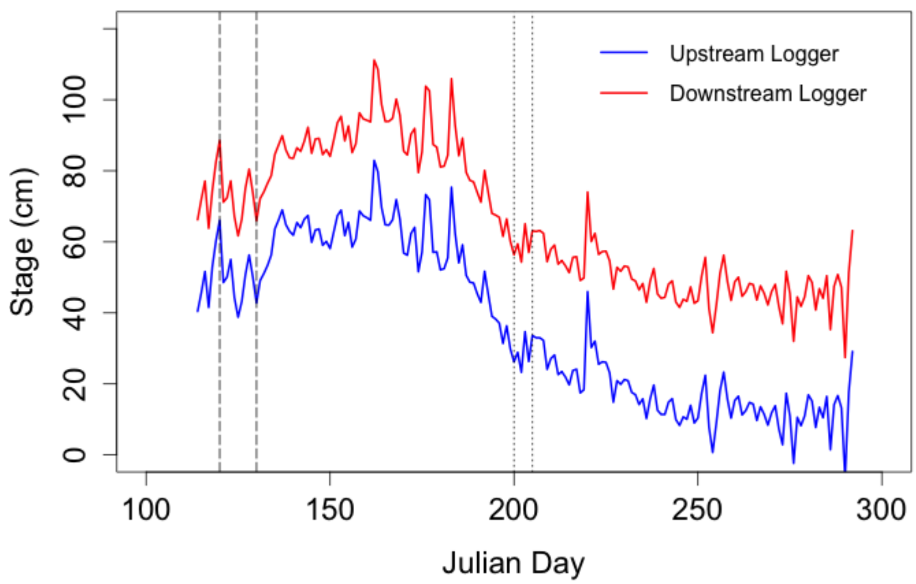

Figure 2.6: The recorded stage at data loggers located at the upstream and downstream ends of the study reach. The dashed vertical lines represents the high flow sampling period and the dotted lines represents the low flow sampling period

2.2 Fishtrap Creek

2.2.1 Site description

Fishtrap Creek is a tributary of the North Thompson River located in the Interior Region of British Columbia approximately 50 km north of Kamloops (Figure 2.7). The nival channel drains a watershed of 158 km^2 with a mean annual peak flow of about 7.5 $m^3\ s^{-1}$ [Eaton et al., 2010a,c]. Summer and autumn flows are typically less than 0.5 $m^3\ s^{-1}$. The watershed contains thick deposits of glacial drift with thin and poorly developed soils. The region is characterized by short and mild winters and hot and dry summers [Leach and Moore, 2010].

In August of 2003, a high intensity forest fire burned 62% of the watershed (re-

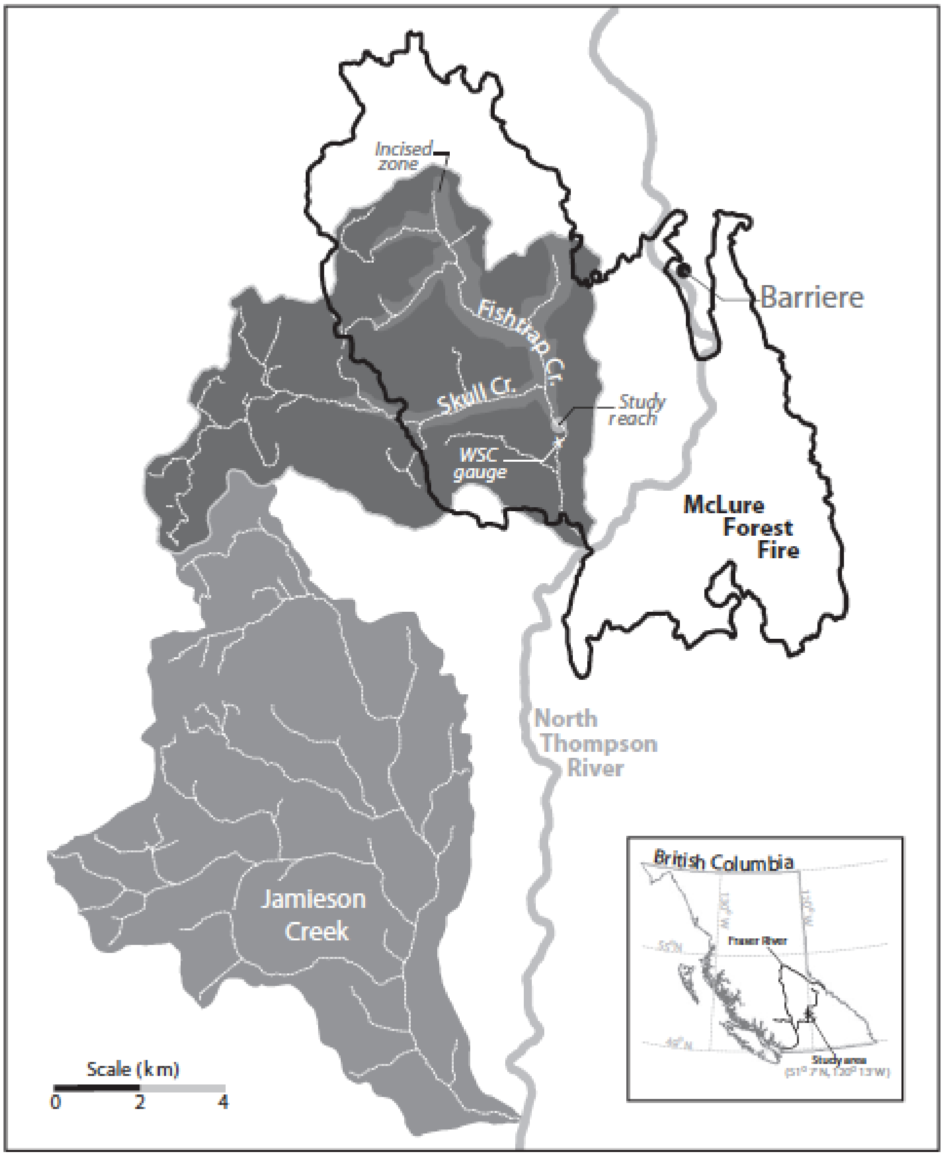

Figure 2.7: Location of Fishtrap Creek's watershed (dark grey shading), the extent of the forest fire (dark black line), and location of the study reach and Water Survey of Canada stream gauge [Eaton et al., 2010c]

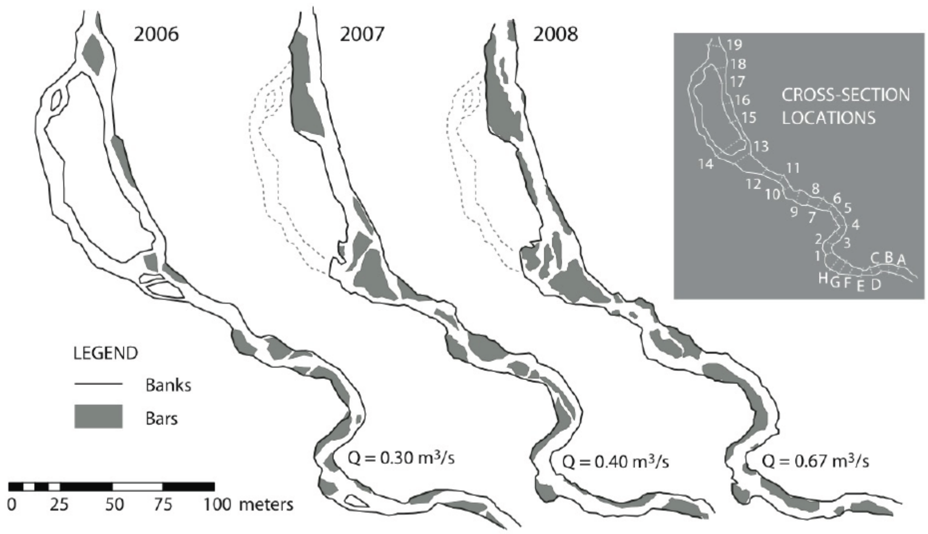

Figure 2.8: Location of banks and bars from 2006 to 2008 and placement of cross-sections (inset) at Fishtrap Creek [Eaton et al., 2010a]

fer to Figure 2.7) and all the riparian vegetation. Since the fire, Fishtrap Creek has been a site of ongoing hydrologic and geomorphic research [Eaton et al., 2010a,c, Leach and Moore, 2011, 2010, Petticrew et al., 2006, Phillips et al., 2009]. As well, there was a significant input of large wood (LW) into the channel following the fire. A large morphological change began to take place in late April 2007, which is attributed to a loss of bank strength from the decaying root system [Eaton et al., 2010c]. Figure 2.8 documents the alteration of the banks and bars from 2006 through 2008.

A 440 m long study reach, measured along the thalweg, was established just upstream of a Water Survey of Canada stream gauge (station no. 08LB024). The reach alternates between riffle-pool and plane-bed morphologies [Montgomery and Buffington, 1997] with an increase in pool-rifle morphology since the fire. There are several LW jams throughout the reach. The mean bed gradient is approximately 0.02 m m^{-1} and has a relatively coarse substrate (D_{50} = 55 mm, D_{84} = 128 mm). The average channel width of the reach is approximately 10 m [Eaton et al., 2010a].

2.2.2 Archived data

High flow cross-sectional data were collected during the spring runoff in 2006 and 2007 by Dr. Brett Eaton's graduate students and research assistants. For 2006, there are depth and velocity data for cross-sections 1 through 5 (see inset of Figure 2.8). These data were collected from April 29 to May 10 during flows ranging from 3.7 to 7.5 m^3 s^{-1}. An ADCP was used to collect velocity at each vertical as described above. Depths were calculated by subtracting the recorded elevation of the bed from the observed water surface elevations at 0.3 m intervals across the channel.

For 2007, depth and velocity data were collected at cross-sections 1,2,3 and 5. These data were collected from April 9 to 27 during flows ranging from 1.95 to 5.68 m^3 s^{-1}. In shallow sections of the channel, depth and velocity were measured using an ADV (i.e. near shore verticals). An ADCP was used to collect velocity and subsequently determine depth at verticals closer to the thalweg.

Channel topography was measured during low flow conditions at cross-sections 1 through 11 from 2005 to 2008. The water surface elevation was recorded at each cross section during the topographic survey. Point depths were calculated as the difference between the elevation of the bed and the water surface at 0.3 m intervals across the channel. Reach average depth ($\bar{d}$) for each year was calculated as the section-weighted mean of the point depth data. Reach average velocity ($\bar{v}$) for each year was determined using the following equation:

$$\bar{v} = \frac{Q}{W \cdot \bar{d}} \tag{2.2}$$

where Q was the recorded daily discharge on the day of the sampling measured at the gauge downstream of the study reach and W is the reach average width.

Chapter 3

Empirical hydraulic distributions in British Columbian channels

3.1 Introduction

The hydraulic habitat is a principal determinant of within-channel ecosystem structure and function [Allan and Castillo, 2007]. Anthropogenic channel alteration and increased out-of-stream water use in channels throughout the world has led to extensive alteration of channel hydraulics. Over the past quarter century, there has been increased pressure to develop tools to help practitioners assess hydraulic habitat conditions required to protect aquatic species [Jowett, 1997, Hardy, 1998, Tharme, 2003].

The most commonly used habitat assessment tool in North America is the Instream Flow Incremental Methodology (IFIM) and in particular its Physical Habitat Simulation (PHABSIM) component [Annear et al., 2004, Conallin et al., 2010, Hatfield and Bruce, 2000, Lamouroux and Jowett, 2005]. PHABSIM combines a hydraulic model, usually in the form of cross-sectional data with habitat suitability indices (HSI) to quantify habitat at the reach scale. There are many regional variations of PHABSIM but the underlying principles remain the same [Tharme, 2003]. PHABSIM is considered the most thorough and legally defensible aquatic habitat tool available to practitioners [Saraeva and Hardy, 2009a]. Furthermore, mechanistic 2-dimensional hydrodynamic models are increasingly being used to predict depth and velocity patterns in rivers [Schweizer et al., 2007, Gard, 2009]. Similar to PHABSIM, the hydraulic conditions produced by the 2-dimensional models are combined with HSI to quantify habitat.

Despite their wide spread use, PHABSIM and 2-dimensional hydrodynamic models have received their fair share of criticism, most notably for being technical, time consuming, and for ignoring ecological interactions [Hatfield and Bruce, 2000, Saraeva and Hardy, 2009a,b, Schweizer et al., 2007]. Moreover, often the goal of aquatic habitat assessment is prediction of future habitat conditions. PHABSIM and 2-dimensional hydrodynamic models can only deal with current channel boundaries and cannot consider future channel geometry. Thus, practitioners cannot use these methodologies to model future habitat availability [Schweizer et al., 2007].

Beginning in the mid-1990s, simpler, statistical approaches have been developed and refined for the purpose of predicting the reach-average distribution of hydraulic conditions in rivers. These approaches predict the form and shape of the depth and velocity distributions from easily obtainable predictor variables [Lamouroux et al., 1995, Lamouroux, 1998, Saraeva and Hardy, 2009a, Schweizer et al., 2007]. The predictor variables are most often reach average hydrological and/or geomorphic conditions. To date, statistical methods have been primarily developed in French and New Zealand riverscapes. Depth and velocity distribution equations have been treated as both independent [Lamouroux et al., 1995, Lamouroux, 1998, Saraeva and Hardy, 2009a] and as a joint frequency distribution [Schweizer et al., 2007].

Statistical methods are desirable because they do not require detailed data on channel geometry and have low computational costs. As well, conceptually they highlight the primary controls of hydraulic habitat for many different channels [Schweizer et al., 2007]. Statistical methods can also be used to model the distributions of depth and velocity for predicted future channel geometries by simply estimating the future reach average channel conditions. Additionally, they provide a rapid assessment tool of hydraulic conditions because of their low-input nature [Saraeva and Hardy, 2009a, Schweizer et al., 2007].

The overarching objective of the research presented in this chapter was to determine if empirical hydraulic distributions developed in France and New Zealand could estimate reach average hydraulic distributions in British Columbia channels.

The performance of statistical methods on both a relatively undisturbed (Harris Creek) and disturbed (Fishtrap Creek) channel were evaluated. As well, depth and velocity distributions produced by a 2-dimensional hydrodynamic model and empirical statistical distributions were compared across a range of flows at Harris Creek. Finally, a low-input, rapid assessment statistical habitat model is proposed for British Columbia channels.

3.2 Methods

3.2.1 Field data and 2-dimensional hydrodynamic simulations

Point depth and velocity data were collected at Harris Creek just outside of Lumby, British Columbia at both low and high flow conditions in 2012. Furthermore, archived point depth and velocity from high flow conditions at Fishtrap Creek for 2006 and 2007 are available as well as low flow point depth data from 2005 through 2008. For more information on the data collection and data refinement procedures refer to Chapter 2.

River2D was chosen as the 2-dimensional hydrodynamic model to be used for this project because it is customized for aquatic habitat evaluation studies [Steffler and Blackburn, 2002]. The model is a depth-averaged finite element model that solves both the basic mass conservation equation and two horizontal components of momentum conservation. The bathymetric survey conducted at Harris Creek in July 2012 was used as the bed topography for the simulations. The no-flow boundary nodes were set as the first and last points (on top of banks) along each cross-section used during the collection of bathymetric data. A curvilinear triangulated mesh comprised of 6651 nodes was created from the inputted bed topography file [Steffler and Blackburn, 2002, Gard, 2009].

The first simulation was run using a discharge (Q) of 1.32 m^3 s^{-1}. Water surface elevations at each of the cross-sections were known for this particular flow. The inflow and outflow water surface elevations were approximated as these boundaries were beyond the reach where hydraulic data collection occurred (refer to Chapter 2). The downstream water surface elevation was adjusted until a nodal convergence between time steps of less than 1 x 10^{-6} m was reached. To calibrate River2D the bed roughness was adjusted until the difference between the measured and simulated water surfaces elevations at cross-section 1 was negligible and the water surface elevations at the rest of the cross-sections differed by less than 3 cm. Bed roughness was considered uniform for the channel because there was limited data on the spatial variability of substrate when the simulations were run. A roughness value of 0.37 m was used for all simulations.

Upon calibration, 18 simulations were run at Harris Creek for Q ranging from 0.75 to 19 m^3 s^{-1}. The accuracy of River2D was deemed sufficient and the point depth and velocities produced by the model were considered to be reasonable representations of the actual depth and velocity fields. Reach average depth ($\bar{d}$) and velocity ($\bar{v}$) were determined by weighting each point depth and velocity by the area of the corresponding cell and then dividing by the total wetted area.

3.2.2 Empirical statistical distributions

Independent velocity and depth distributions

Most of the preliminary work of developing independent velocity and depth distributions was conducted on French channels. Lamouroux et al. [1995] developed an empirical equation for predicting the relative point velocity ($v/\bar{v}$) distribution comprised of a decentered (exponential distribution) and centered (Gaussian distribution) models, with the proportion of each model varying according to a shape parameter (s):

$$\begin{aligned} f(x = v/\bar{v}, s) = s\left(3.33\exp\left(-\frac{x}{0.193}\right) + 0.117\exp\left(-\left(\frac{x-2.44}{1.73}\right)^2\right)\right) \\ +(1-s)\left(0.653\exp\left(-\left(\frac{x-1}{0.864}\right)^2\right)\right) \end{aligned} \tag{3.1}$$

$$s = -0.150 - 0.252\ln(Fr) \tag{3.2}$$

where Fr is the Froude number. The first term in Equation 3.1 represents the decentered model and the second term represents the centered model.

Similarly, Lamouroux [1998] proposed modelling the relative depth ($d/\bar{d}$) distribution as a mixture of Gaussian and exponential models, with the proportion of each model varying according to a shape parameter (t):

$$f(x = d/\bar{d}, t) = t \cdot \exp(-x) \quad + \quad (1-t) \cdot 0.951 \exp\left(-\left(\frac{x-1}{0.593}\right)^2\right) \tag{3.3}$$

$$t = -0.7 \ln(\bar{d}) \tag{3.4}$$

where the first term in Equation 3.3 represents the exponential model and the second term is the Gaussian model.

Saraeva and Hardy [2009a] found that Equation 3.1 was unable to capture the full range of velocity data collected from channels in the Nooksack River basin in Washington State. They proposed a slightly altered empirical velocity distribution equation, using the same shape parameter (s):

$$\begin{aligned} f(x = v/\bar{v}, s) = s &\left(3.33 \exp\left(-\frac{x}{0.693}\right) + 0.117 \exp\left(-\left(\frac{x-8}{1.73}\right)^2\right)\right) \\ &+ (1-s)\left(0.653 \exp\left(-\left(\frac{x-1.1}{0.664}\right)^2\right)\right) \end{aligned} \tag{3.5}$$

Joint frequency distribution

Building upon the work using independent empirical distributions, Schweizer et al. [2007] proposed a joint frequency depth-velocity distribution that utilizes a single shape parameter (S_{mix}). Similar to the independent empirical distributions, the relative velocity and depth distributions were predicted using a combination of centered and decentered models. However, Schweizer et al. [2007] used a log-normal distribution as opposed to an exponential distribution to model the decentered portion of the hydraulic distributions. The predictive joint frequency equations are as follows:

$$f(v/\bar{v}, S_{mix}) = (1 - S_{mix}) \cdot N_u(\mu_{uN}, \sigma_{uN}) + (S_{mix}) \cdot LN_u(\mu_{uLN}, \sigma_{uLN}) \tag{3.6}$$

where μ_{uN} = μ_{uLN} = 1, σ_{uN} = 0.52, σ_{uLN} = 1.19, and

$$f(d/\bar{d}, S_{mix}) = (1 - S_{mix}) \cdot N_d(\mu_{dN}, \sigma_{dN}) + (S_{mix}) \cdot LN_d(\mu_{dLN}, \sigma_{dLN}) \tag{3.7}$$

where μ_{dN} = μ_{dLN} = 1, σ_{dN} = 0.52, σ_{dLN} = 1.09, and

$$\ln\left(\frac{S_{mix}}{1 - S_{mix}}\right) = -4.72 - 2.84 \cdot ln(Fr) \tag{3.8}$$

All the empirical equations presented above were compared to both the collected hydraulic data at Harris and Fishtrap Creek as well as hydraulic data modelled in 18 River2D simulations. The empirical distributions were examined across a range of $0 < v/\bar{v} < 3$ and $0 < d/\bar{d} < 3$ using 30 equidistant bins.

3.2.3 Habitat indices

Weighted usable area (WUA) were generated for three aquatic species: *Oncorhynchus mykiss* (rainbow trout), *Micropterus dolomieu* (smallmouth bass), and *Rhinichthys cataractae* (longnose dace). Adult, juvenile, and spawning rainbow trout life stages were examined. These species were chosen as they all present unique and contrasting preferences for depth and velocity. Adult rainbow trout prefer shallow channels with moderate flow. Juvenile rainbow trout prefer slightly deeper and slower currents in comparison with adult rainbow trout. Spawning rainbow trout reside in very specific combinations of velocity (0.49 to 0.92 m s^{-1}) and depth (0.21 to 2.5 m). Smallmouth bass (adult) prefer deep water and slow currents (i.e. pools). Longnose dace (adult) are a benethic species that reside in fast and shallow current (i.e. riffles). HSI curves produced by the United States Geological Survey (USGS) were used for the analyses and can be found in Appendix A.

For the River2D simulations, WUA was calculated by inputting the chosen HSI data into the program. At each node, a depth and velocity preference was determined. These preferences (varied between 0 to 1) were multiplied together and then multiplied by the area of the associated cell to determine the WUA of each cell. The total WUA was determined as the sum of the WUA of all the individual cells.

For the statistical distributions, a preference was determined for each bin by comparing the absolute bin value to HSI. Absolute bin values were determined by multiplying the $d/\bar{d}$ and $v/\bar{v}$ distributions by $\bar{d}$ or $\bar{v}$ respectively. The total suitability of the velocity and depth distributions were determined as follows for n number of bins:

$$\text{Velocity Suitability} = \frac{\sum_{i=1}^{n} \text{bin frequency} \cdot \text{bin suitability}}{\sum_{i=1}^{n} \text{bin frequency}} \tag{3.9}$$

$$\text{Depth Suitability} = \frac{\sum_{i=1}^{n} \text{bin frequency} \cdot \text{bin suitability}}{\sum_{i=1}^{n} \text{bin frequency}} \tag{3.10}$$

where n is the number of bins. The total WUA produced by the statistical distributions was calculated from the following equation:

$$WUA = \text{Wetted Surface Area} \cdot \text{Velocity Suitability} \cdot \text{Depth Suitability} \tag{3.11}$$

The WUA calculated using the statistical distributions does not contain any spatial explicit detail and thus is not a ‘true’ WUA measure.

3.2.4 Model evaluation

All statistical analyses were conducted using Matlab (version 7.9.0) statistical programme. For the purposes of the evaluation, depths and velocities predicted by the empirical statistical distributions were treated as ‘Predicted’ (P). The depths and velocities measured in the field or modelled using River2D will be treated as ‘Observed’ (O). Model performance evaluation was based on literature presented by Willmott [1982] and Willmott et al. [1985]. The primary evaluation tool will be the index of agreement (I), a dimensionless index ranging from 1 (perfect agreement between the distributions) to 0 (no agreement):

$$I = 1 - \left[\frac{n(RMSD)^2}{\sum_{1}^{n}(|P_i'| + |O_i'|)^2} \right] \tag{3.12}$$

where n is the sample size, P_i' = P_i - $\bar{O}$, O_i' = O_i - $\bar{O}$, $\bar{O}$ is the mean observed value, and *RMSD* (root mean squared difference) is calculated as follows:

$$RMSD = \left[\frac{1}{n} \sum_{1}^{n} (P_i - O_i)^2 \right]^{1/2} \tag{3.13}$$

For the purposes of this project, *I* values greater than 0.95 will be considered a strong fit, *I* values greater than 0.9 will be considered a reasonable fit, and *I* values less than 0.9 will be considered a poor fit.

3.3 Results

3.3.1 Measured data

Harris Creek

The empirical depth distribution proposed by Schweizer et al. [2007] provided a superior fit to the measured depth data at both low and high flows (Figure 3.1). At low flow, the measured data was relatively normally distributed with a small tail (positively skewed). Both the normal distribution and tail were adequately predicted by Schweizer et al. [2007] distribution. The Lamouroux [1998] distribution contains an exponential component which greatly over predicted low depths and under predicted mid to high depths.

At high flow, the measured depth distribution was approximately normal (high Froude number) with a very small tail. Again, the Schweizer et al. [2007] distribution adequately modelled the observed depth distribution and was the superior fit (Table 3.1). Lamouroux [1998] greatly over predicted low depths due to its exponential component.

The three proposed empirical velocity distributions provided a solid fit to the

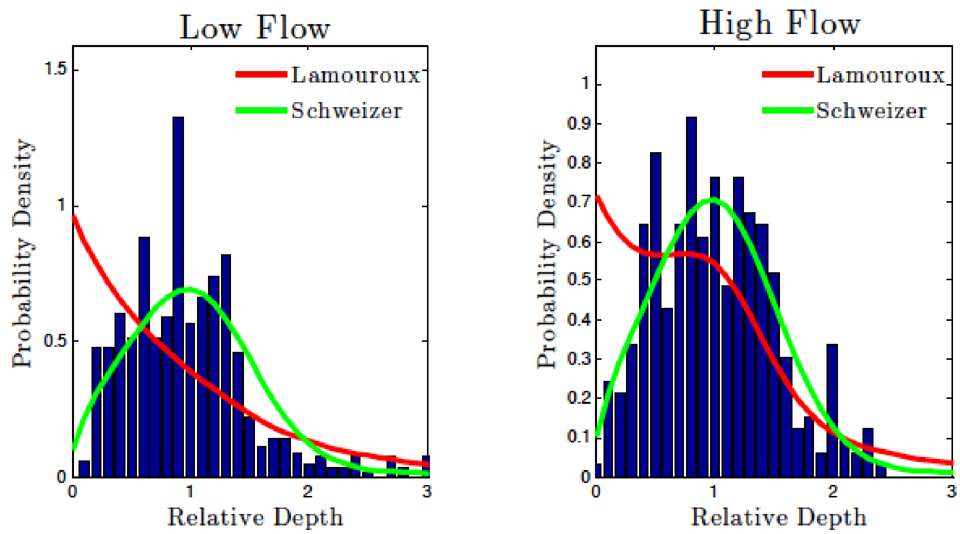

Figure 3.1: Relative depth distributions for low and high flow conditions at Harris Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions. The Lamouroux [1998] distribution was developed in France and the Schweizer et al. [2007] distribution in New Zealand.

observed velocity data at both low and high flow (Figure 3.2 and Table 3.2). At low flow conditions, the measured velocity distributions had a peak at very low velocities (slow moving water on channel periphery and over bars) as well as a peak close to $\bar{v}$. The Lamouroux et al. [1995] and Saraeva and Hardy [2009a] distributions are able to model both peaks using a mixture of the exponential and normal distributions. The Schweizer et al. [2007] distribution was unable to capture the peak at very low velocities (key habitat for some species and life stages) but

Table 3.1: Index of Agreement (I) for proposed statistical depth distributions at Harris Creek

Flow	Lamouroux	Schweizer
High	0.879	0.968
Low	0.748	0.939

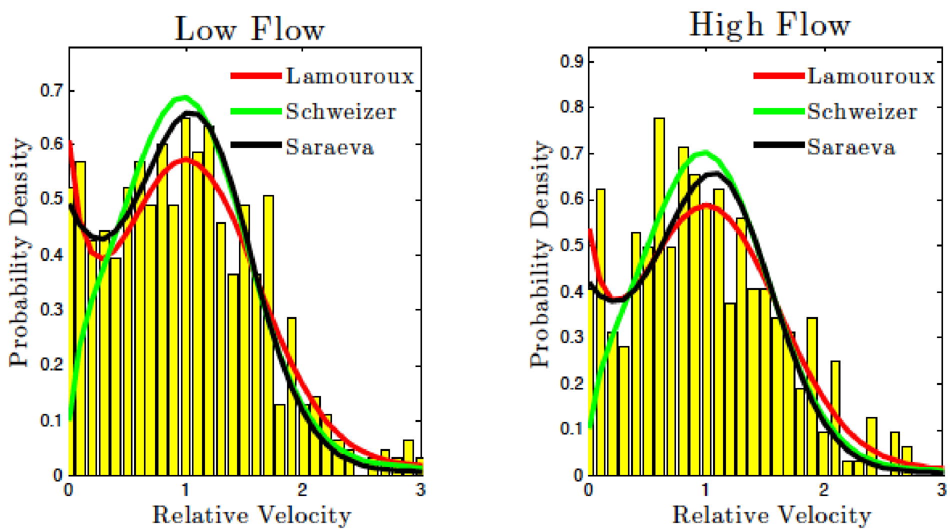

Figure 3.2: Relative velocity distributions for low and high flow conditions at Harris Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions. The Lamouroux et al. [1995] distribution was developed in France, the Schweizer et al. [2007] distribution in New Zealand, and the Saraeva and Hardy [2009a] distribution in Washington State.

adequately recreated the remainder of the measured distribution.

The measured velocity data at high flow had similar form and shape to the low flow velocity distribution. However, at high flow conditions there were less low velocities and the distribution in more normally distributed (high Froude number). Again, the Lamouroux et al. [1995] and Saraeva and Hardy [2009a] distributions were able to model both the small peak at low velocities and the peak that is normally distributed about the mean. The Schweizer et al. [2007] distribution is unable to capture the peak at very low velocities using a log-normal decentered model.

Fishtrap Creek

High Flow

The observed high flow velocity distribution at Fishtrap Creek for both 2006 and 2007 is relatively normally distributed (Figure 3.3). There does not exist a peak

Table 3.2: Index of Agreement (I) for proposed statistical velocity distributions at Harris Creek

Flow	Lamouroux	Schweizer	Saraeva
High	0.971	0.955	0.968
Low	0.986	0.957	0.984

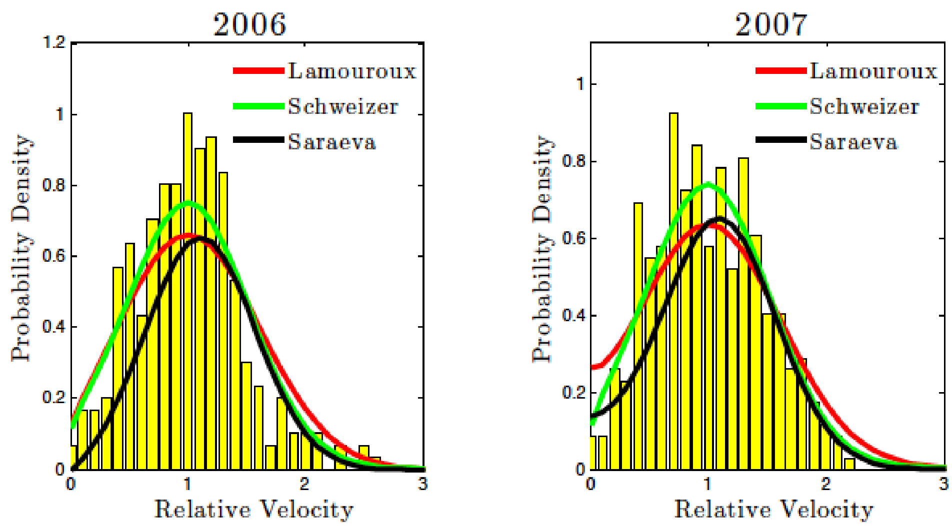

Figure 3.3: Relative velocity distributions for 2006 and 2007 high flow data at Fishtrap Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions.

at a very low velocities as seen at Harris Creek. All three proposed velocity distributions provided a strong fit to the measured data. The Schweizer et al. [2007] velocity distribution provides the strongest fit (Table 3.3) for both years as it was able to predict the high densities for bins surrounding $\bar{v}$.

For 2006 depth data, there exists both a peak at very low depths and a slightly larger peak close to $\bar{d}$ (Figure 3.4). The Schweizer et al. [2007] depth distribution is able to capture the larger peak surrounding $\bar{d}$ but erroneously predicts low densities for very shallow depths. The Lamouroux [1998] depth distribution was able to capture the peak at very low depths using an exponential model as well as ade-

Table 3.3: Index of Agreement (I) for proposed statistical velocity distributions at Fishtrap Creek

Year	Lamouroux	Schweizer	Saraeva
2006	0.959	0.974	0.906
2007	0.962	0.979	0.947

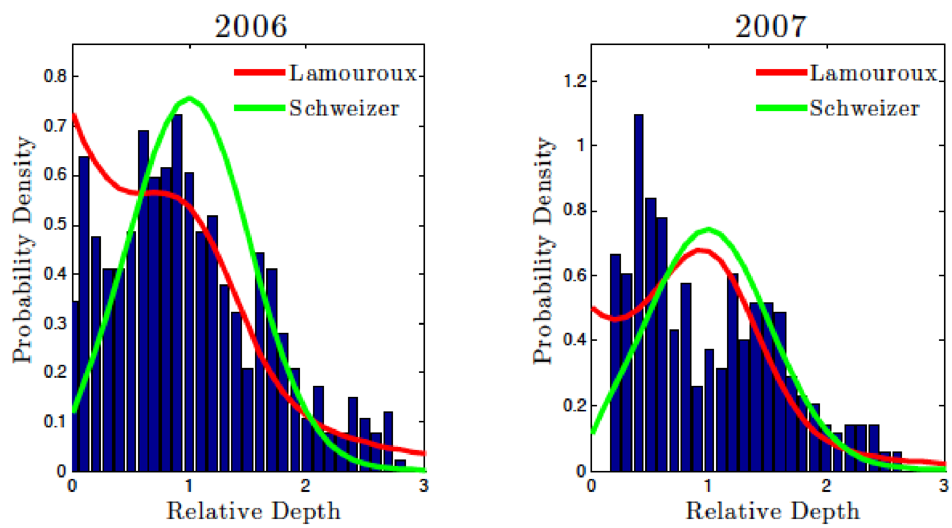

Figure 3.4: Relative depth distributions for 2006 and 2007 high flow conditions at Fishtrap Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions.

quately modelling the peak surrounding $\bar{d}$ making it the superior statistical depth distribution for 2006 (Table 3.4).

The measured depth distribution for 2007 is rather peculiar as there exists a peak before and after $\bar{d}$. This unusual distribution is most likely attributed to the rapid widening that began to occur at Fishtrap Creek in late April 2007 (i.e. during the field season) due to the decay of the riparian root system [Eaton et al., 2010a,c]. Both the Schweizer et al. [2007] and Lamouroux [1998] distributions provide a poor fit (Table 3.4) as their normal distribution component are distributed about $\bar{d}$.

Table 3.4: Index of Agreement (I) for proposed statistical high flow depth distributions at Fishtrap Creek

Year	Lamouroux	Schweizer
2006	0.960	0.937
2007	0.873	0.872

Measured depth and velocity data for 2007 was divided into pre-morphological change and post-morphological change datasets and compared to the proposed statistical hydraulic distributions. Before the morphological change, there are still two peaks in the measured depth data on either side of $\bar{d}$ (Figure 3.5). However, both of the proposed depth distributions provide reasonable fits to the measured data (Table 3.5). Following the morphological change there is a very large peak at low depths which is attributed to shallow depths that form as the channel widens and spreads onto the channel periphery. As well, there are little depth data surrounding $\bar{d}$ but a noticeable presence of high depth data. The proposed statistical depth distributions do a poor job of modelling the post-morphological depth distribution.

Table 3.5: Index of Agreement (I) for proposed statistical 2007 high flow depth distributions for 2007 high flow conditions at Fishtrap Creek

Condition	Lamouroux	Schweizer
Before morphological change	0.913	0.924
After morphological change	0.710	0.664

Prior to the morphological change, the measured velocity distribution is relatively normally distributed with a slight positive skewness (Figure 3.6). All three statistical velocity distributions are able to model the measured distribution. The Schweizer et al. [2007] distribution provides the best fit as it is able to capture the high densities surrounding $\bar{v}$ (Table 3.6). Following morphological change, the measured velocity distribution becomes negatively skewed and there is a peak at

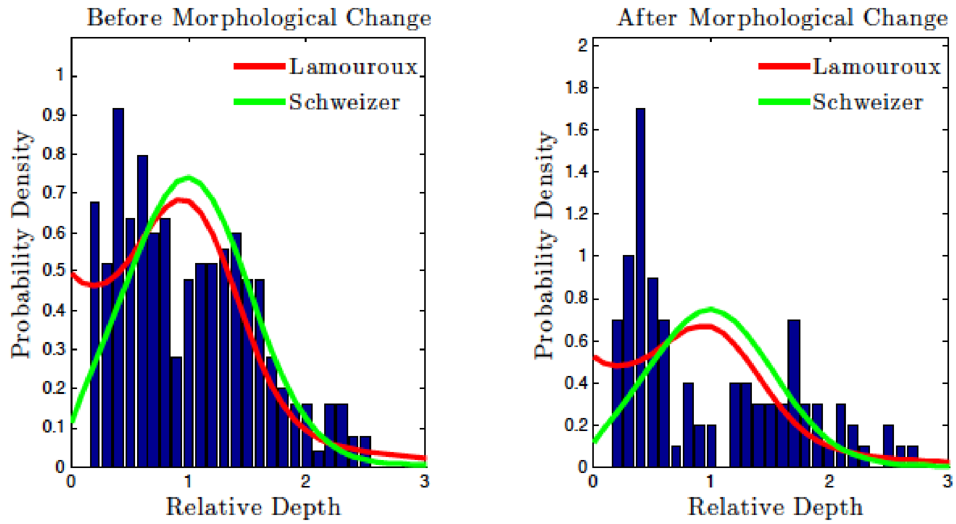

Figure 3.5: Relative depth distributions for 2007 high flow conditions before and after a rapid morphological change at Fishtrap Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions.

velocities slightly greater than $\bar{v}$. The Schweizer et al. [2007] and Lamouroux et al. [1995] provide a reasonable fit to the measured data. Unlike the measured depth distribution, the velocity distribution did not undergo a drastic change in shape and form following morphological change.

Table 3.6: Index of Agreement (I) for proposed statistical velocity distributions for 2007 high flow conditions at Fishtrap Creek

Condition	Lamouroux	Schweizer	Saraeva
Before morphological change	0.944	0.962	0.929
After morphological change	0.903	0.915	0.888

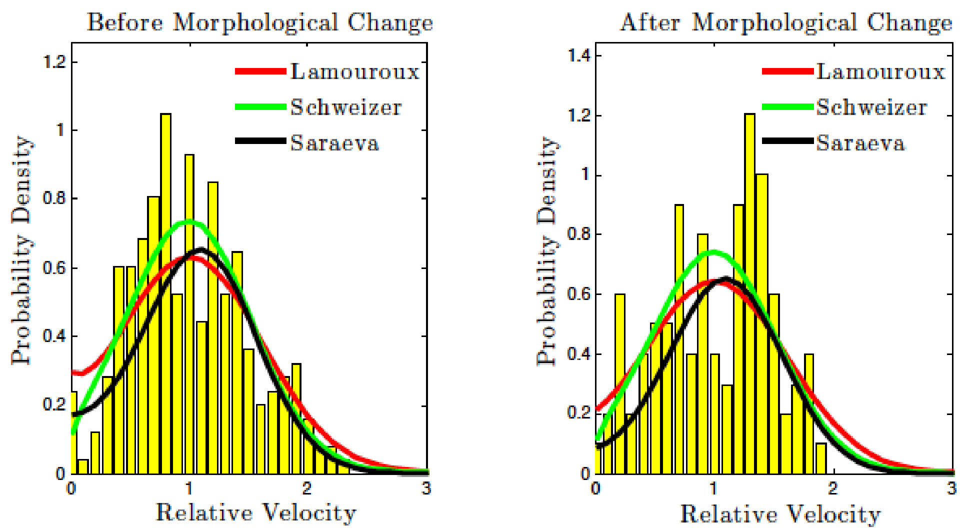

Figure 3.6: Relative velocity distributions for 2007 high flow conditions before and after a rapid morphological change at Fishtrap Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions.

Low Flow

At low flow conditions the Schweizer et al. [2007] depth distribution was able to adequately model the positively skewed measured depth distributions in 2005 and 2006 (Figure 3.7). The Lamouroux [1998] distribution under predicted mid to high depth for these years. The 2007 and 2008 depth data were collected after the rapid morphological change. Similar to high flow conditions, the proposed statistical depth distributions were unable to model the measured depth distributions following morphological change (Table 3.7).

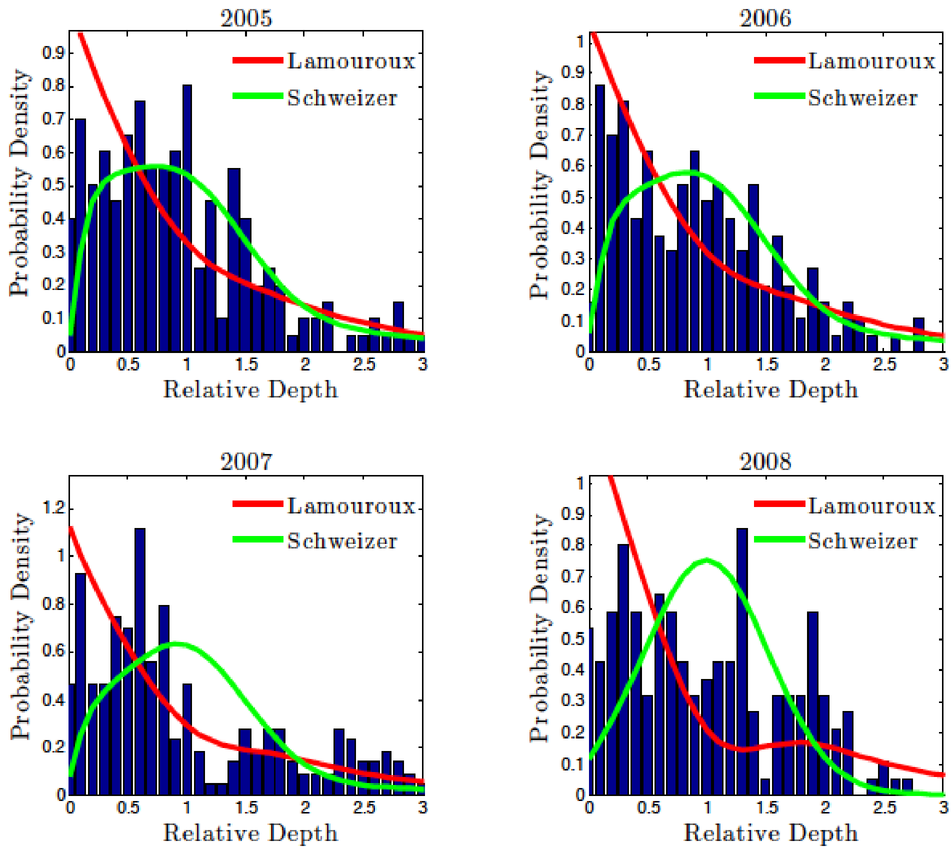

Figure 3.7: Relative depth distributions for 2005 through 2008 at low flow conditions at Fishtrap Creek. The bars represent the actual measured distributions. The lines are proposed statistical distributions.

3.3.2 River2D data

There was a gradual shift in both the depth and velocity distributions produced by River2D for Harris Creek towards negatively skewed distributions as flow approached bankfull (See Figures 3.8 through 3.11 and Appendix B). As flow increased, the depth distribution went from a relatively normal distribution with platykurtic kurtosis and slight positive skewness to a distribution with leptokurtic

Table 3.7: Index of Agreement (I) for proposed statistical depth distributions for low flow conditions at Fishtrap Creek

Year	Lamouroux	Schweizer
2005	0.889	0.929
2006	0.882	0.921
2007	0.891	0.794
2008	0.816	0.731

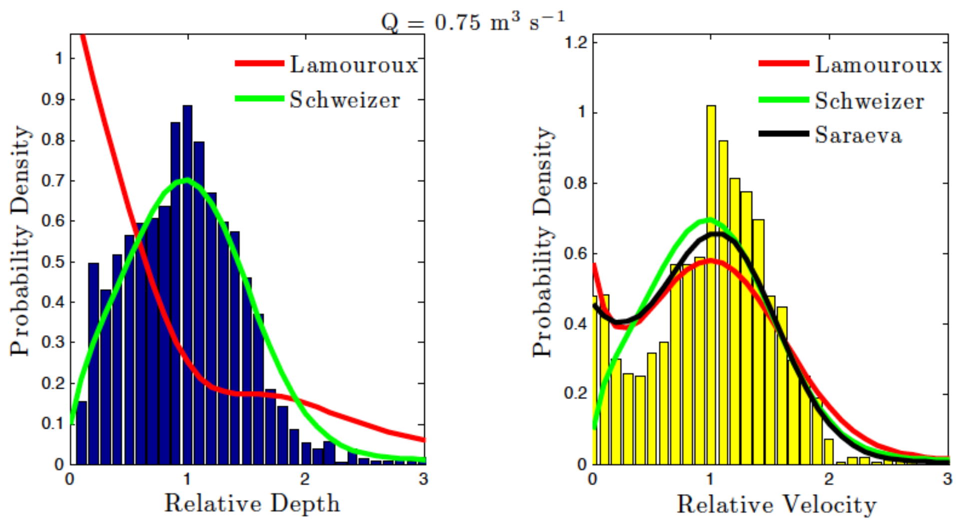

Figure 3.8: Relative depth and velocity distributions for Harris Creek at Q = 0.75 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

kurtosis and negative skewness at high flow. At low flows, the velocity distribution had a small peak at very low velocities and a larger peak at velocities slight greater than $\bar{v}$. As flows increased, the peak at low velocities lessened and the velocity distribution became more leptokurtic and negatively skewed. As flows approach bankfull, the depth and velocity distributions had similar shape and form due to a decrease in relative roughness and flows becoming more homogeneous across morphological units [Stewardson and McMahon, 2002].

In terms of the empirical depth distributions, the Schweizer et al. [2007] pro-

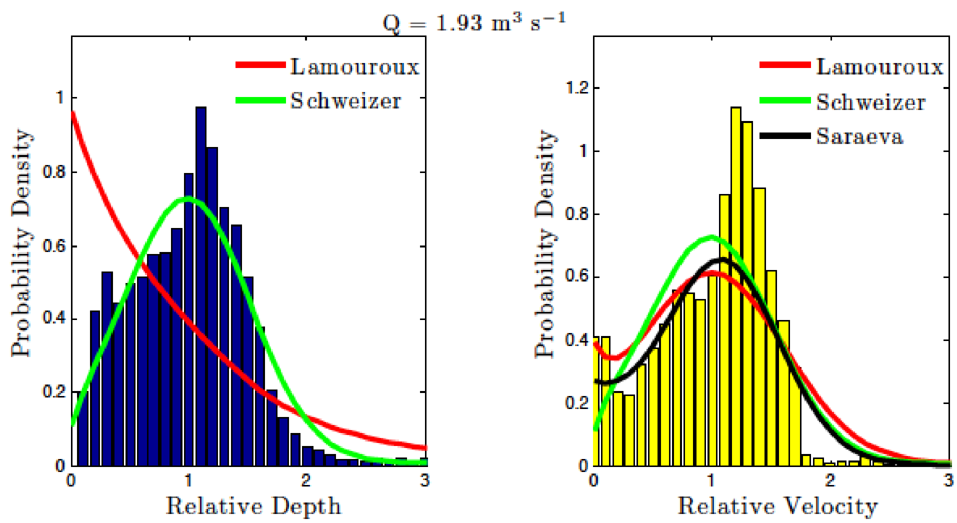

Figure 3.9: Relative depth and velocity distributions for Harris Creek at Q = 1.93 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

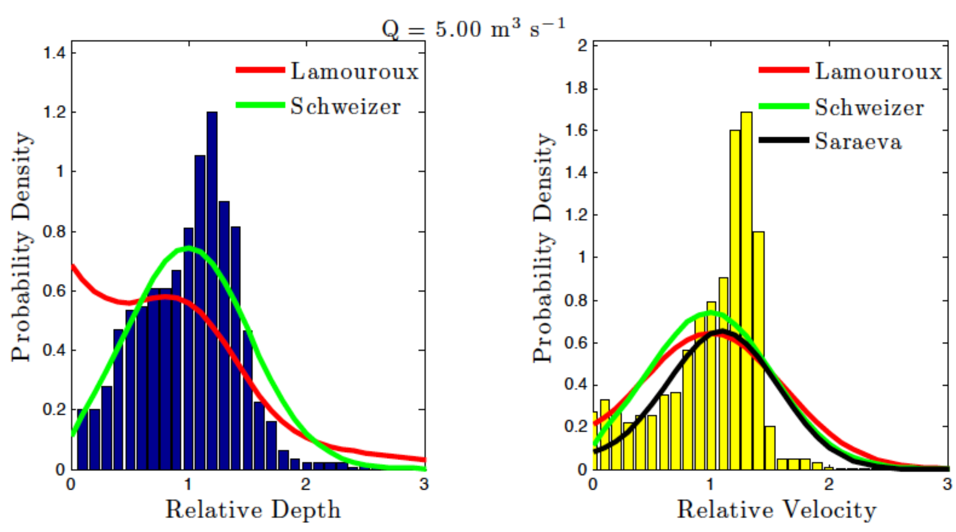

Figure 3.10: Relative depth and velocity distributions for Harris Creek at Q = 5.00 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

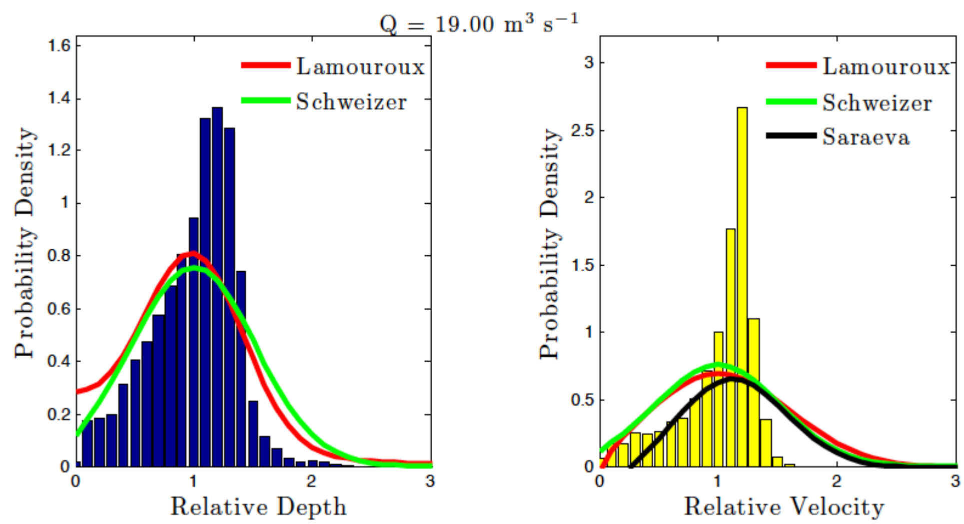

Figure 3.11: Relative depth and velocity distributions for Harris Creek at Q = 19.00 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

vides a far superior fit to the River2D depth distribution across the range of simulated flows (Table 3.8). Low flows are particularly relevant because they are the flow conditions experienced in a channel most of the year and are the limiting flow for many species and life stages [Dakova et al., 2000]. At low flows the Lamouroux [1998] distribution greatly over predicted low depths and under predicted mid to high depths whereas the Schweizer et al. [2007] distribution was able to capture the normally distributed nature of the River2D depth data. As flows increased the Lamouroux [1998] performance improved and it's I value approached that of the Schweizer et al. [2007] distribution. However, the Schweizer et al. [2007] distribution was hands down the superior distribution at flows (< 3 m^3 s^{-1}) experienced at Harris Creek for the majority of the year.

At low flows (< 2.29 m^3 s^{-1}) all three proposed statistical velocity distributions provide reasonable fits to the velocity distributions simulated using River2D. However, the Saraeva and Hardy [2009a] distribution provides the best fit as it modelled both the peak at very low velocities and the larger peak that occurs at velocities slightly greater than $\bar{v}$ (Figure 3.9). The Schweizer et al. [2007] distribu-

Table 3.8: Index of Agreement (I) for proposed statistical depth distributions and River2D depth data at Harris Creek

Q ($m^3\ s^{-1}$)	Lamouroux	Schweizer
0.75	0.635	0.987
1.00	0.668	0.988
1.23	0.702	0.986
1.32	0.715	0.986
1.61	0.731	0.980
1.93	0.754	0.982
2.29	0.776	0.983
2.61	0.791	0.979
3.08	0.803	0.977
3.51	0.812	0.973
3.98	0.822	0.969
4.47	0.830	0.965
5.00	0.838	0.960
5.55	0.849	0.959
7.50	0.874	0.950
10.00	0.893	0.942
15.00	0.915	0.927
19.00	0.922	0.917

tion is unable to model the peak at very low velocities because it does not have an exponential component. At $Q = 2.61\ m^3\ s^{-1}$, the Schweizer et al. [2007] becomes the superior fit as the peak at the low velocities becomes small and the densities around the $\bar{v}$ becomes large. At flows greater than 3.08 $m^3\ s^{-1}$ all three proposed velocity distributions become poor as they are unable to model the high densities surrounding $\bar{v}$.

3.3.3 Habitat model

The Schweizer et al. [2007] depth distribution was chosen as the empirical depth distribution for the proposed habitat model because it provided the best fit to both the measured depth distributions and depth distributions modelled using River2D. Furthermore, the Schweizer et al. [2007] velocity distribution was chosen as the

Table 3.9: Index of Agreement (*I*) for proposed statistical velocity distributions and River2D velocity data at Harris Creek

Q (m^3 s^{-1})	Lamouroux	Schweizer	Saraeva
0.75	0.948	0.953	0.968
1.00	0.944	0.952	0.965
1.23	0.940	0.949	0.959
1.32	0.939	0.945	0.957
1.61	0.933	0.943	0.951
1.93	0.923	0.937	0.940
2.29	0.911	0.928	0.928
2.61	0.898	0.918	0.915
3.08	0.881	0.904	0.898
3.51	0.861	0.889	0.879
3.98	0.851	0.880	0.867
4.47	0.831	0.863	0.847
5.00	0.818	0.851	0.833
5.55	0.809	0.842	0.822
7.50	0.775	0.810	0.784
10.00	0.759	0.793	0.763
15.00	0.742	0.775	0.737
19.00	0.729	0.760	0.719

empirical velocity distribution that will be used for the proposed statistical habitat model. Overall it provided the best fit to the River2D velocity data. It was also able to adequately model measured velocity distributions at Harris Creek (although the other two distributions were slightly better) and provided the best fit to the Fishtrap Creek velocity data. As well, using the Schweizer et al. [2007] velocity distribution alongside the Schweizer et al. [2007] depth distribution requires the calculation of only one shape parameter and allows for consistency in the model.

For all species/life stages under investigation there was a clear difference in absolute values of WUA produced by River2D (i.e. a reasonable representation of actual conditions) and the proposed statistical habitat model (Figures 3.12 through 3.16). This was especially true at high flows as the ability of the empirical statistical distributions to model hydraulic conditions, in particular the velocity distribution, became poor. For all species there is an over prediction of WUA at flows greater than 3.51 m^3 s^{-1}. However, for the most part the relative shape and trends of the WUA data as a function of discharge were similar between the proposed statistical habitat model and River2D. The location of peak WUA were slightly different for some species, in particular spawning rainbow trout.

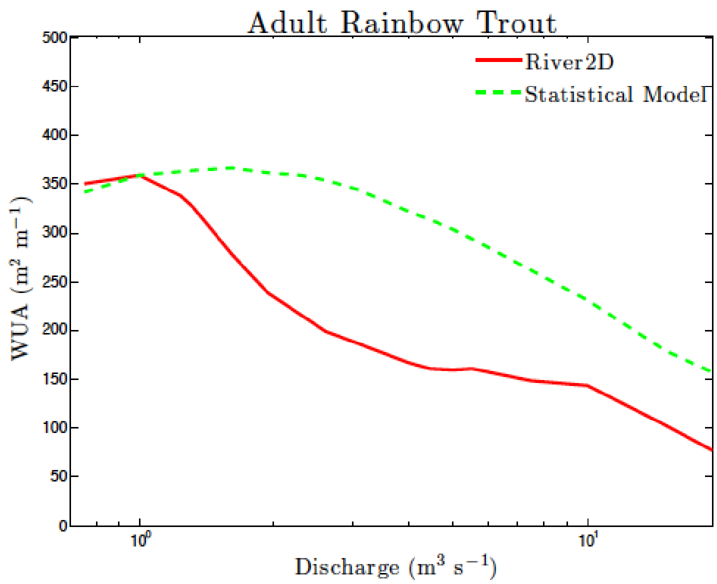

Figure 3.12: WUA produced by River2D and a proposed joint frequency statistical distribution model for adult rainbow trout at Harris Creek

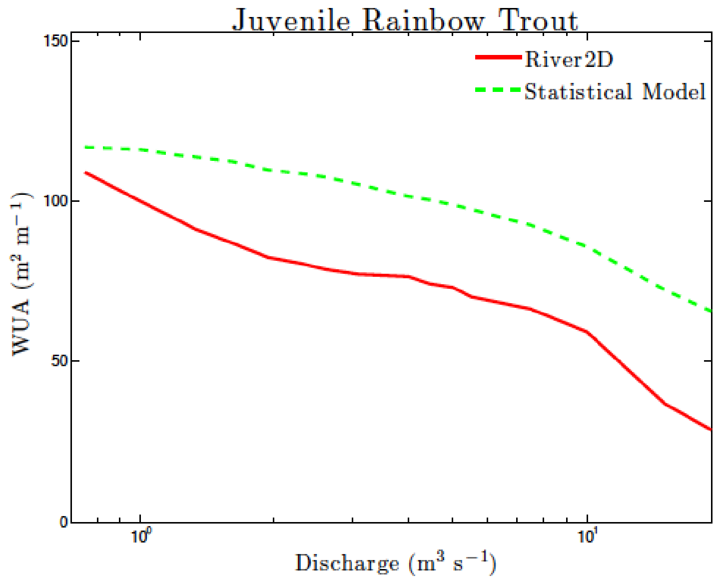

Figure 3.13: WUA produced by River2D and a proposed joint frequency statistical distribution model for juvenile rainbow trout at Harris Creek

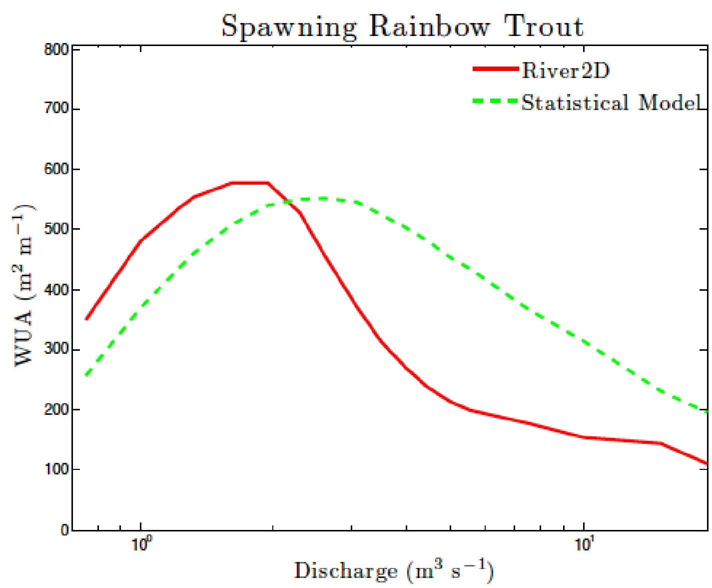

Figure 3.14: WUA produced by River2D and a proposed joint frequency statistical distribution model for spawning rainbow trout at Harris Creek

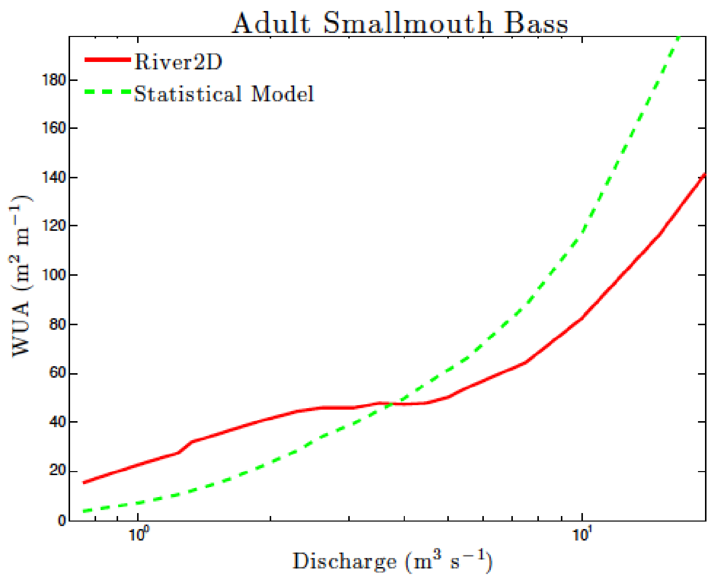

Figure 3.15: WUA produced by River2D and a proposed joint frequency statistical distribution model for adult smallmouth bass at Harris Creek

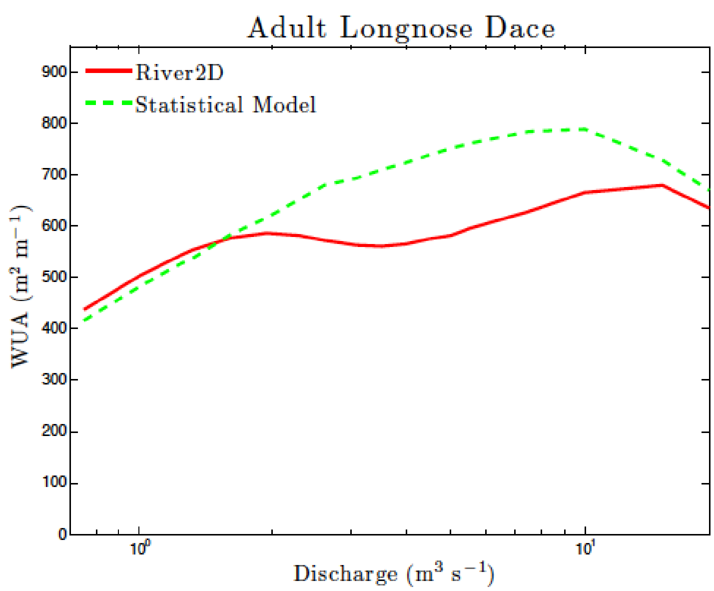

Figure 3.16: WUA produced by River2D and a proposed joint frequency statistical distribution model for adult longnose dace at Harris Creek

3.4 Discussion

At Harris Creek, a combination of exponential and normal models provided the best fit to the measured velocity data as these distributions were able to adequately capture the peak at very low velocities (Figure 3.2). This could suggest that a statistical distribution with an exponential and normal component provides a superior fit to velocity data or that the log-normal model embedded in the Schweizer et al. [2007] velocity distribution needs refining. At Fishtrap Creek, there was not a distinct peak at very low velocities and all three proposed statistical distributions were able to capture the shape and form of the measured distribution.

An empirical depth equations comprised of an exponential and normal model [Lamouroux, 1998] was unable to replicate the measured depth distributions at Harris and Fishtrap Creek. The frequency of low depths was considerably over predicted using an exponential model. Saraeva and Hardy [2009a] found that the Lamouroux [1998] depth distributions resembled actual depth conditions on channels much smaller than Harris Creek and Fishtrap Creek but over predicted low depths on channels of similar size to Harris Creek and Fishtrap Creek. Statistical distributions comprised of log-normal and normal components provide the best representation of actual depth conditions.

The proposed statistical velocity distributions provide strong fits to the measured distributions at both Harris and Fishtrap Creek. This suggests that the proposed statistical velocity distributions can adequately predict velocity distributions for both undisturbed and disturbed channels. Furthermore, the Schweizer et al. [2007] depth distribution provided a strong fit to the measured depth distributions at Harris Creek as well as an adequate fit at Fishtrap Creek before morphological change. The statistical depth distribution performed poorly at Fishtrap Creek following morphological change at both high and low flow suggesting the Schweizer et al. [2007] depth distribution is unable to capture the unique depth distribution in a morphologically disturbed channel. Some of the channels in which the statistical depth distributions were developed had some form of flow regulation for flood control or hydro power purposes. However, it does not appear that any of the channels used to develop the statistical models were severely disturbed [Schweizer et al., 2007, Lamouroux et al., 1995, Lamouroux, 1998, Saraeva and Hardy, 2009a].

In general, as discharge increased the ability of statistical distributions to reproduce hydraulic conditions simulated using River2D became poorer. The statistical distributions become questionable at discharges > 3 m^3 s^{-1}. The poor performance of the empirical distributions at higher discharges stem from the statistical distributions being developed on channels that were usually experiencing flows less than mean annual flow (flows > 3 m^3 s^{-1} are higher than mean annual flow at Harris Creek). For instance, Schweizer et al. [2007] collected and modelled hydraulic data for channels that were experiencing discharges 5 to 100 % of their mean annual flow. They warned that the use of statistical distributions at discharges greater than mean annual flow could lead to poor fits as relative roughness and channel heterogeneity decrease.

Furthermore, Saraeva and Hardy [2009a] found that the statistical distributions were only effective for channels with mean annual flow less than 3.5 m^3 s^{-1} in the Nooksack River basin in Washington State. This appears to coincide with the statistical distributions performance at Harris Creek. It is encouraging that the statistical distributions are adequately modelling depth and velocity distributions at low flows. Low flows are most often the limiting flows for aquatic species and thus being able to model the distribution of these two important hydraulic variables at low flows is critical [Hatfield and Bruce, 2000, Dakova et al., 2000].

The proposed statistical habitat model is the early makings of a rapid habitat assessment tool for practitioners. The general shape and trends of the WUA curve can be predicted using empirical statistical distributions. The errors in absolute WUA values are of similar magnitude to errors observed by Saraeva and Hardy [2009a] using a comparable statistical habitat model. Differences in absolute WUA values were expected because of the different methodologies used by River2D and the proposed statistical habitat model to calculate WUA. River2D calculates WUA using a bivariate pair of depth and velocity at each node whereas the statistical methods calculate WUA by examining the depth and velocity distributions independently (i.e. not a true WUA calculation).

Furthermore, errors in WUA arise from the inability of statistical velocity distributions to model actual conditions. This becomes apparent when calculating the independent WUA of each hydraulic variable and comparing them between River2D and the statistical habitat methods (Figure 3.17). The differences in depth WUA

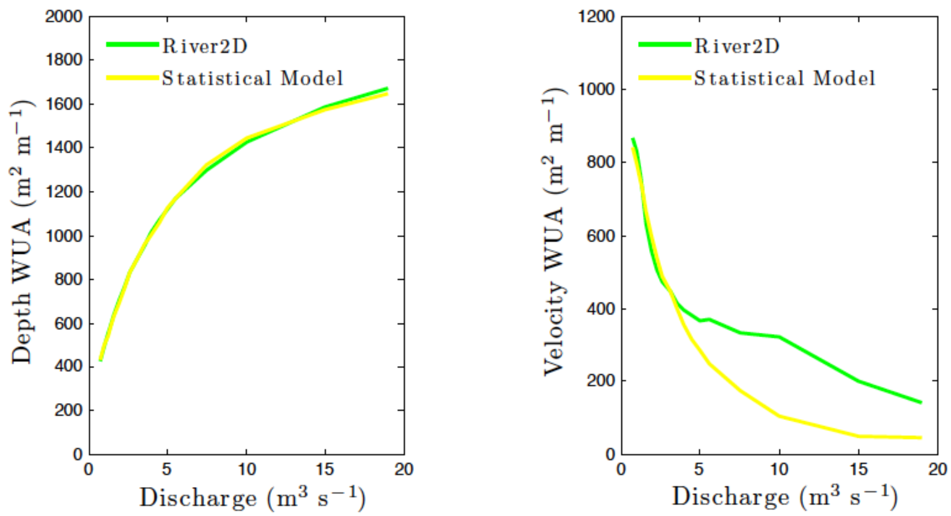

Figure 3.17: WUA produced by examining depth and velocity distributions separately for adult rainbow trout

produced by the two models for adult rainbow trout is negligible. Velocity WUA is comparable between River2D and the proposed statistical habitat model at low flow but significantly deviates at flows greater than approximately 3.5 m^3 s^{-1}. As well, biological models are more sensitive to velocity errors as velocity preferences are usually more complex and dynamic (i.e. velocity HSI curves have many abrupt shifts) in relation to depth preferences [Lamouroux, 1998]. Therefore, to improve the proposed statistical habitat model, especially at high flows, statistical velocity distributions need to be improved.

There exists some obvious limitations to the statistical habitat model. First, the habitat model was developed and tested on one channel. Ideally, the statistical habitat model will be tested and refined on many British Columbian channels with varying morphology and flows regimes. Furthermore, evaluation of the proposed habitat model on more species and life stages is imperative. Saraeva and Hardy [2009a] found that a similar statistical habitat model adequately predicted habitat indices for adult and spawning fish but provided poor prediction for juvenile and fry species that prefer lower velocities.

Moreover, cover and substrate preferences were ignored in River2D simulations. Thus, WUA was calculated from only depth and velocity data in River2D, which made for a simple comparison between models. There is no simple way to incorporate cover and substrate data into the statistical habitat model which makes the proposed habitat model appropriate for preliminary assessments but not for detailed analyses. Cover and substrate are extremely important to aquatic habitat, especially for younger life stages and spawning species [Bovee, 1982]. Comparing WUA that does not incorporate cover and substrate data for species that are very sensitive to cover and substrate conditions is dubious [Saraeva and Hardy, 2009a]. As well, treating the hydraulic distributions produced by River2D as reasonable representations of the actual depth and velocity fields is a valid assumption but an assumption nonetheless. There is certainly potential for River2D to produce slightly erroneous depth and velocity data and thus WUA.

3.5 Conclusion

Empirical statistical distributions can be used for preliminary assessment of hydraulic conditions in British Columbian channels. In particular, a joint frequency depth-velocity distribution developed on New Zealand channels can reproduce both measured depth and velocity distributions for an undisturbed channel. The joint frequency distribution was also able to reproduce depth and velocity distributions produced using a 2-dimensional hydrodynamic model (River2D) for flows close to and less than mean annual flow. As flows increase towards bankfull conditions prediction of the hydraulic distributions produced by River2D become poor. A statistical depth distribution containing a log-normal and a normal model was able to replicate depth distributions at Harris Creek and at Fishtrap Creek prior to rapid channel widening in late April 2007. The empirical depth distributions performed poorly at Fishtrap Creek after the rapid morphological change, suggesting empirical distributions are unable to reproduce hydraulic conditions in recently disturbed channels.

The early makings of a low-input, rapid aquatic assessment tool that can be used by practitioners across British Columbia for preliminary habitat assessments and basin-wide aquatic habitat studies is presented above. The model inputs are simply reach average depth and velocity which can often be collected in one day of field work. The statistical habitat model can highlight channels that are in need of further in-depth assessment as well as set the experimental boundaries for future aquatic habitat research [Hatfield and Bruce, 2000]. The general form and shape of WUA data produced by 18 River2D (data-intensive hydrodynamic model) simulations at Harris Creek were reproduced using the proposed statistical habitat model.

The proposed aquatic habitat model needs further refinement. The ability of empirical statistical distributions to replicate depth and velocity distributions in channels that have different morphologies and flow regimes than Harris Creek needs to be examined. The empirical velocity equations embedded in the statistical habitat model needs to be refined or replaced to allow for more accurate prediction of habitat indices. As well, the proposed statistical habitat model does not account for many environmental factors that determine habitat (e.g. cover availability, substrate). Finally, the proposed habitat model should be compared to River2D or PHABSIM outputs for more species and life stages. Using the proposed methodology as anything but a preliminary assessment tool is ill-advised.

Chapter 4

Evaluation of a hydraulic geometry simulator in British Columbian channels

4.1 Introduction

Increased flow abstraction for agriculture, industry, electricity production, and recreation has led to decreased flows in channels throughout the world. Practitioners are continually faced with the difficult task of recommending and enforcing in-stream flow requirements that can both maintain the ecological integrity of the channel and meet out-of-stream demand [Saraeva and Hardy, 2009a]. Changes in magnitude and timing of channel inputs associated with climate and land use change further complicates the task [Tharme, 2003].

Considerable effort has been made in recent decades to improve in-stream flow assessment tools [Hardy, 1998]. The most well known and used aquatic habitat tool is the Instream Flow Incremental Methodology (IFIM) and in particular its Physical Habitat Simulation (PHABSIM) component [Lamouroux and Jowett, 2005, Jowett, 1997]. PHABSIM [Bovee, 1982] combines point depth, velocity, and substrate measurements with habitat suitability indices (HSI) to calculate weighted usable area (WUA) for the reach under investigation [Saraeva and Hardy, 2009a].

Furthermore, the underlying principles of PHABSIM are being incorporated into 2-dimensional hydrodynamic models as they can predict depth and velocity both longitudinally and laterally throughout a reach. Similarly, depth and velocities produced using 2-dimensional models are combined with HSI to predict WUA. 2-dimensional models are desirable because they avoid problems with transect placement, they can model complex habitats (provided the underlying assumptions of the model are met), they take into account roughness and bed topography, and they rely on mechanistic processes [Gard, 2009].

Despite the widespread use of PHABSIM, and more recently 2-dimensional hydrodynamic models, they do come with their fair share of criticism. The most common criticisms are the expensive, time consuming, and technical nature of the models as well as their inability to model ecological interactions [Gard, 2009, Hatfield and Bruce, 2000, Hardy, 1998, Saraeva and Hardy, 2009a,b, Lamouroux and Souchon, 2002, Lamouroux and Jowett, 2005]. The models require intensive site specific data collection including numerous point depth and velocity measurements, substrate and vegetation cover quantification, and complete bathymetric surveys (essential for 2-dimensional modelling). Upon data collection, expertise is needed in processing the data, calibrating the models, and applying appropriate HSI.

Moreover, often the purpose of aquatic habitat modelling is the prediction of future habitat conditions. Quantifying the impact of proposed hydroelectric dams, water diversions, rehabilitation projects, and climate and land use change on aquatic habitat all require prediction of future channel dimensions. PHABSIM and 2-dimensional models are adequate at predicting current WUA using measured channel conditions [Saraeva and Hardy, 2009b, Gard, 2009]. However, as the fluvial system is perturbed there are inherent changes in stream morphology and substrate (i.e. changes in boundaries) which greatly influence physical habitat. The boundaries of PHABSIM and 2-dimensional models cannot be readily changed thus these tools cannot be used to predict future hydraulic conditions and subsequently available habitat [Hatfield and Bruce, 2000].

There has been a push to develop more simplistic and cost-effective tools for water practitioners that can be readily applied to multiple channels in a watershed [Ahmadi-Nedushan et al., 2006, Saraeva and Hardy, 2009a, Schweizer et al., 2007].

According to Conallin et al. [2010] for an aquatic habitat model to be considered by water practitioners for current use the following criteria must be met:

1. clearly demonstrates the links between the physical data and biological requirements using easily obtainable data;
2. inputs and results are transparent (i.e. can be presented to different stakeholders)
3. the model is user-friendly (i.e. shouldn't require intensive training)
4. have a large spatial scale and can be applied for many different aquatic species

PHABSIM and 2-dimensional models require intensive site specific data collection and technical expertise which often leads to these models being dismissed by practitioners. More simplistic and transparent aquatic habitat models are needed.

Presented below is a user-friendly, low-input aquatic habitat model that generates WUA as a function of flow. The model uses a low input regime model to set the reach average bankfull channel conditions from which a reach average cross-sectional shape is inferred. The water level (flow) is sequentially lowered from bankfull conditions with hydraulic properties being recalculated for every iteration. The hydraulic properties are then used with a joint frequency depth-velocity distribution which are combined with applicable HSI to generate WUA for a range of species and life stages. Furthermore, future channel conditions and thus habitat can be predicted for different climate and land use change scenarios by conducting sensitivity analyses. The model outputs are not intended to be treated as the 'truth'. However, the model can be used to conduct preliminary assessments of channel altering projects and the outputs can help assess future research needs as well as determine if in-depth habitat assessments (e.g.PHABSIM) are justified.

4.2 Rational regime model

Regime theories use optimality criteria over a suitably long time scale to determine equilibrium channel geometry [Kirkby, 1976, Chang, 1979, White et al., 1982, Huang et al., 2004, Nanson and Huang, 2008, Eaton et al., 2010b]. The physically

Figure 4.1: The assumed channel geometry and characteristic rooting depth, H, embedded within UBCRM.

based University of British Columbia Regime Model (UBCRM) was chosen as the rational regime model to predict reach average bankfull channel dimensions [Eaton et al., 2004]. It has been developed and continually refined through the collaboration of researchers in the Department of Geography and the Civil Engineering Department at UBC. UBCRM requires modest data inputs thus making it more useful to environmental practitioners than data intensive, numerically demanding models. Furthermore, the extremal hypotheses embedded within UBCRM are easily understood and have been tested against flume and field data. The inclusion of a simple yet useful bank strength criteria has led to agreement between observed channel form and model predictions [Eaton et al., 2004, Eaton and Church, 2007, Eaton and Millar, 2004].

The model determines the channel geometry that allows for the highest system-scale flow resistance for the given inputs [Eaton et al., 2004] as this is deemed the most stable and thus most probable channel configuration [Huang et al., 2004]. UBCRM assumes a channel geometry of a cohesionless gravel toe below a vertical upper bank section controlled by a representative rooting depth, H (Figure 4.1). The model requires five user-specified input measures: bankfull discharge (Q_b), reach average bed gradient (S), D_{50}, D_{84}, H. These input measures are known for Harris and Fishtrap Creek (refer to Chapter 2). Model outputs were calibrated from reach average bankfull width (W_b) and depth (d_b) observed from cross-sectional data in the field. If significant deviation occurred between the model outputs and cross-sectional data, H was adjusted until there was agreement between the outputs and observed data.

UBCRM can provide current channel geometry as well as approximate channel dimensions resulting from changes in bankfull flow (Q_b) and/or riparian vegetation (H). Thus, future bankfull channel dimensions stemming from out-of-stream water use and climate and land use change can be predicted. For the purposes of the proposed aquatic habitat model, UBCRM outputs of interest are the predicted W_b and d_b as they set the reach average bankfull channel dimensions and are essential for calibration purposes.

As with all models there are some limitations to UBCRM. First, UBCRM formulates channel dimensions for an idealized system which the input parameters can sufficiently describe the system. Natural fluvial systems are complex and the influence of hillside processes, large wood (LW), channel sinuosity, heavily armoured bed, etc. can cause large deviations in predicted and observed values. Second, the model assumes the system is in equilibrium. However, many natural systems are not stable and exhibit ongoing reach average channel change. For more detailed description of the limitations of UBCRM refer to Eaton et al. [2004] and Eaton [2006].

4.3 At-a-station hydraulic geometry simulator

The at-a-station hydraulic geometry simulator (ASHGS) was developed following the approach proposed by Ferguson [2003] to incorporate lateral variation in bedload transport in 1-dimensional models of longitudinal profile development. In most natural channels flow strength varies across the channel due to changes in depth, presence of bank friction, or from flow impediments upstream. The Ferguson [2003] model looked at the variation of shear stress and thus the variation in depth in a 1-dimensional model as means of calculating total bed load flux. Ferguson [2003] found that simply applying the average depth across the whole channel leads to an underestimation of bedload flux. For the purposes of the proposed habitat model we are not interested in the variation of shear stress but that of depth.

In channels that have approximately a rectangular geometry the lateral variation in depth is negligible. However, for channels that exhibit pool-riffle morphology this cannot be assumed [Ferguson, 2003]. The variance around the average depth is a defining characteristic of these morphologies and has huge implications for aquatic habitat [Eaton et al., 2006, Saraeva and Hardy, 2009a, Schweizer et al.,

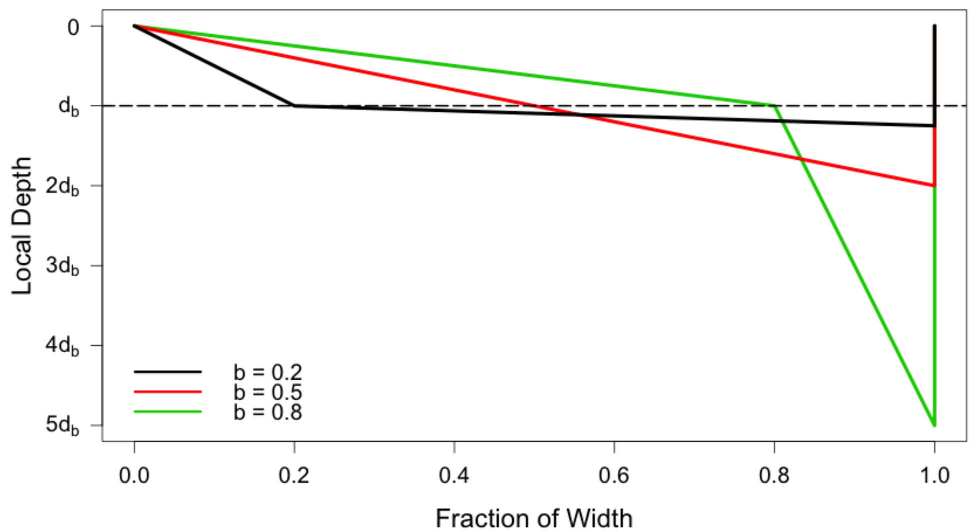

Figure 4.2: Cumulative distribution functions of depth for b values of 0.2, 0.5, and 0.8. Note the dashed line represents average depth at banfull flow, d_b

2007].

All modelling was completed using Matlab (version 7.9.0) statistical programme. To begin, W_b and d_b are determined using UBCRM. The cumulative depth probability distribution is determined from an index of channel shape (b). Depths are less than d_b in proportion b of W_b. In this section, b, depths increase linearly from 0 to d_b. In the remaining portion of the channel, 1 - b, the depths are greater than d_b and increase linearly from d_b to $d_b/(1 - b)$ [Ferguson, 2003]. The cumulative depth distributions for different channel geometries (b-values) are found in Figure 4.2.

Each cumulative distribution contains two linear segments that make a dog-leg shape, except when b = 0.5 which contains a single uniform linear segment. The total cross section area (W_b x d_b) remains the same for all b values. Small b values are representative of canal-like conditions which exhibit small variation in depth and the maximum depth (d_{max}) is slightly greater than d_b. High b values represent increasingly non-uniform channel conditions with a large proportion of depths below d_b (e.g. channel margins and bars) and d_{max} is much greater than d_b.

Often these channel shapes are associated with large meandering channels, braided channels, and the presence of multiple thalwegs [Ferguson, 2003]. The resulting cumulative distributions for $b \geq 0.7$ seem highly unlikely in natural channels and b-values of 0.1 to 0.5 seem more representative of fish-bearing channels in BC.

Ferguson estimated b by matching moments with fitted distributions of shear stress and water depth. A simpler way of estimating b is desirable for the proposed model. Estimating b linearly from W_b/d_b is proposed:

$$b = \frac{W_b/d_b}{100} \tag{4.1}$$

A linear relationship between b and W_b/d_b is a major assumption of the model but some conceptual and physical evidence is provided. Plane bed channels will have small W_b/d_b (close to 10) due to their narrow rectangular form. These channels have minimal lateral variation in flow and thus depth [Montgomery and Buffington, 1997], resulting in b values approaching 0. Wider gravel bed rivers contain bars and exhibit pool riffle morphology. These channels have significant lateral variation in flow [Church, 2006] resulting in a skewed cumulative depth distribution. Very large single thread meandering channels can reach W_b/d_b of close to 60 [Eaton et al., 2010b]. The resulting cumulative depth distribution in these large channels is estimated at 0.6. Thus, increased width leads to a larger proportion of bars, pools, and riffles resulting in more lateral variation in depth.

Furthermore, Ferguson [2003] determined b ranged from approximately 0.4 to 0.7 for the lower unconfined Fraser River, British Columbia. Published W_b/d_b for this section of Fraser River range from 43 for stable sand beds to 78 for unstable beds [Desloges and Church, 1989, Rice et al., 2009], thus b values of 0.43 to 0.78 using Equation 4.1. Channels with $\mathrm{W}_b/\mathrm{d}_b$ greater than 60 (estimated b = 0.6) are likely to form multiple threads [Eaton et al., 2010b]. The remainder of this chapter will deal with b values less than 0.5 as this simplifies the model and is representative of the majority of fish bearing channels in British Columbia.

Once the cumulative depth distribution and thus reach average cross-sectional geometry is established for the reach, the distribution is divided laterally into increments of 0.0001 x W_b. A bankfull water elevation is imposed onto the cross-section (i.e. a vertical line across the top of the distribution). The depth (d) at each of the lateral increments is determined by subtracting the elevation of the bed from the cumulative depth distribution. A wetted perimeter (P_{wetted}) is calculated as the linear length of the bed determined to be under water. The hydraulic radius (R) is determined using the following equation:

$$R = \frac{A_{xsection}}{P_{wetted}} = \frac{W \cdot \bar{d}}{P_{wetted}} \tag{4.2}$$

where W is the wetted width and $\bar{d}$ is the average depth. At bankfull flow the wetted area is simply W_b x d_b. The reach average resistance (Res) of the channel for the imposed water level is determined from the following resistance law:

$$Res = \frac{a_1 \cdot a_2 \cdot (R/D_{84})}{\sqrt{a_1^2 + a_2^2 \cdot (R/D_{84})^{5/3}}} \tag{4.3}$$

where a_1 = 6.5, a_2 = 2.5 [Ferguson, 2007]. This particular resistance law was used as it has the lowest prediction error of the well known resistance laws and it was developed by the same researcher that proposed the cumulative distributions of depth [Ferguson, 2003] which allows for consistency in the proposed model. The average velocity ($\bar{v}$) in the cross section was calculated as follows:

$$\bar{v} = Res\sqrt{g \cdot R \cdot S} \tag{4.4}$$

where g = 9.81 m s^{-2}. The discharge (Q) associated with the imposed water level is calculated according to the law of continuity:

$$Q = \bar{v} \cdot A_{xsection} \tag{4.5}$$

Q will equal Q_b (or at least very close to) for the first iteration (bankfull conditions). Finally, the Froude number (Fr) is calculated from the following equation:

$$Fr = \frac{\bar{v}}{\sqrt{g \cdot \bar{d}}} \tag{4.6}$$

Once A_{wetted}, P_{wetted}, R, Res, $\bar{v}$, Q, and Fr are calculated for bankfull water level the water level is sequentially dropped by 0.001*d_{max} and these measures are recalculated for the new values of W and $\bar{d}$. This process repeats itself until the water elevation is just above the elevation of d_{max} (i.e. very low flow).

4.4 Application of a habitat model

A joint frequency depth-velocity distribution [Schweizer et al., 2007] was chosen as the statistical habitat method to be used alongside UBCRM and ASHGS. For more information on statistical habitat methods and rationale for choosing the joint frequency distribution refer to Chapter 3. The joint frequency distribution utilizes a single mixing parameter (S_{mix}) to predict both the relative velocity ($v/\bar{v}$) and depth distributions ($d/\bar{d}$) using a mixture of normal (N) and log-normal (LN) probability density functions according to the following equations:

$$f(v/\bar{v}, S_{mix}) = (1 - S_{mix}) \cdot N_v(\mu_{vN}, \sigma_{vN}) + (S_{mix}) \cdot LN_v(\mu_{vLN}, \sigma_{vLN}) \tag{4.7}$$

where $\mu_{vN} = \mu_{vLN} = 1$, $\sigma_{vN} = 0.52$, $\sigma_{vLN} = 1.19$, and

$$f(d/\bar{d}, S_{mix}) = (1 - S_{mix}) \cdot N_d(\mu_{dN}, \sigma_{dN}) + (S_{mix}) \cdot LN_d(\mu_{dLN}, \sigma_{dLN}) \tag{4.8}$$

where $\mu_{dN} = \mu_{dLN} = 1$, $\sigma_{dN} = 0.52$, $\sigma_{dLN} = 1.09$, and

$$\ln\left(\frac{S_{mix}}{1 - S_{mix}}\right) = -4.72 - 2.84 \cdot ln(Fr) \tag{4.9}$$

All inputs needed for the joint-frequency distribution are determined using ASHGS. The distribution equations were examined for $0 < v/\bar{v} < 3$ and $0 < d/\bar{d} < 3$ using 30 equidistant bins.

The absolute values of the bins were determined by multiplying the bins of the relative hydraulic distributions by their respective mean. Subsequently, the absolute bin values were compared to HSI to determine the suitability of each bin. The total suitability of the empirical velocity and depth distributions was determined from the following equations:

$$\text{Velocity Suitability} = \frac{\sum_{i=1}^{n} \text{bin frequency} \cdot \text{bin suitability}}{\sum_{i=1}^{n} \text{bin frequency}} \quad (4.10)$$

$$\text{Depth Suitability} = \frac{\sum_{i=1}^{n} \text{bin frequency} \cdot \text{bin suitability}}{\sum_{i=1}^{n} \text{bin frequency}} \quad (4.11)$$

where n is the total number of bins in each distribution. Upon calculating these measures the WUA was calculated from the following equation:

$$WUA = W \cdot \text{Velocity Suitability} \cdot \text{Depth Suitability} \quad (4.12)$$

For this chapter WUA will be evaluated as an area per unit length ($m^2\ m^{-1}$) to avoid having to estimate the wetted area. The habitat value (HV), a dimensionless measure that allows for easy comparison between reaches, was calculated from the following equation:

$$HV = \text{Velocity Suitability} \cdot \text{Depth Suitability} \quad (4.13)$$

Habitat indices calculated using the statistical distributions do not contain any spatial explicit detail. Hydraulic distributions are determined for every water level observed with ASHGS. Thus, $WUA(Q)$ and $HV(Q)$ are determined across a range of possible flow conditions.

4.5 Model testing

The following are the calibrated input values used for Harris Creek: Q_b = 19 m^3 s^{-1}, S = 0.011 m m^{-1}, D_{50} = 68 mm, D_{84} = 135 mm, H = 0.35 m. UBCRM predicted reach average W_b = 14.36 m, d_b = 0.705 m and $\bar{v}$ = 1.88 m s^{-1}. These values are quite similar to an observed mean W_b = 14.57 m (mean of 12 cross sections) and d_b = 0.702 m and $\bar{v}$ = 1.866 m s^{-1} produced from a River2D simulation. Using Equation 4.1, a b-value of 0.203 was estimated for Harris Creek (Figure 4.3). This value seems reasonable as Harris Creek has a relatively plane bed upper reach (b

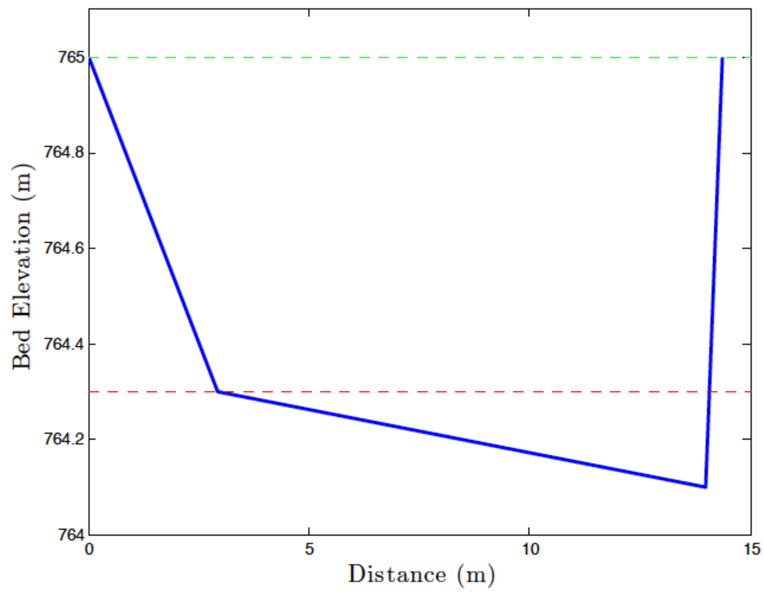

Figure 4.3: Predicted reach average channel geometry at Harris Creek (b = 0.203).

values closer to 0.1) and a pool-riffle morphology in the mid to lower reach (b range from 0.15 to 0.5).

The $\bar{v}$ and $\bar{d}$ values produced by ASHGS were compared to the $\bar{v}$ and $\bar{d}$ produced in 18 River2D simulations (Tables 4.1 and 4.2). $\bar{d}$ had a maximum deviation of -0.011 m (6.08 %) at Q = 0.75 m^3 s^{-1} and a mean deviation of 1.06 %. In general, ASHGS over-predicted $\bar{d}$ at low flows and under-predicted $\bar{d}$ at high flows (Table 4.1). $\bar{v}$ had a maximum deviation of -0.077 m s^{-1} (16.96 %) at Q = 0.75 m^3 s^{-1} and a mean deviation of 4.47 %. ASHGS under-predicted $\bar{v}$ at low flows and over-predicted at high flows (Table 4.2). The larger deviation associated with $\bar{v}$ is likely due to the different flow resistance laws utilized by River2D and ASHGS. There always exists uncertainty in the input parameters which manifests as prediction error in flow resistance equations. Also, large relative errors are inherent during conditions of partial submergence ($R/D_{84} < 1$), which occurred during low flow conditions at Harris Creek [Ferguson, 2007]. Furthermore, UBCRM was calibrated to bankfull conditions. As flow simulations move further from bankfull conditions the prediction error is likely to become higher.

Table 4.1: Modelled $\bar{d}$ using River2D and ASHGS for a range of flows at Harris Creek

Q (m^3 s^{-1})	$\bar{d}_{River2D}$ (m)	$\bar{d}_{ASHGS}$ (m)	Difference
0.75	0.181	0.170	-0.011 (6.08 %)
1.00	0.200	0.192	-0.008 (4.00 %)
1.23	0.214	0.209	-0.005 (2.34 %)
1.32	0.219	0.216	-0.003 (1.37 %)
1.61	0.236	0.234	-0.002 (0.85 %)
1.93	0.254	0.254	0 (0 %)
2.29	0.272	0.273	0.001 (0.37 %)
2.61	0.290	0.289	-0.001 (0.34 %)
3.08	0.308	0.310	0.002 (0.65 %)
3.51	0.328	0.328	0 (0 %)
3.98	0.346	0.347	0.001 (0.29 %)
4.47	0.365	0.366	0.001 (0.27 %)
5.00	0.385	0.384	-0.001 (0.26 %)
5.55	0.401	0.401	0 (0 %)
7.50	0.458	0.460	0.002 (0.44 %)
10.00	0.519	0.525	0.006 (1.16 %)
15.00	0.632	0.632	0 (0 %)
19.00	0.707	0.702	-0.005 (0.71 %)

The HV generated by the proposed aquatic habitat model was compared to HV produced from River2D and from a statistical habitat model (developed in Chapter 3) using a joint frequency distribution developed by Schweizer et al. [2007]. The Schweizer et al. [2007] habitat model utilized reach average hydraulic conditions produced in the River2D simulations. HV were chosen as the means of comparison because it allows for a direct unbiased comparison (WUA relies on wetted width or wetted area which could be different between River2D and the proposed habitat model).

Three species were used for the comparison: *Oncorhynchus mykiss* (rainbow trout), *Micropterus dolomieu* (smallmouth bass), and *Rhinichthys cataractae* (longnose dace). Adult, juvenile, and spawning rainbow trout life stages were examined. Depth and velocity preferences were obtained from United States Geological Sur-

Table 4.2: Modelled $\bar{u}$ using River2D and ASHGS for a range of flows at Harris Creek

Q (m^3 s^{-1})	$\bar{v}_{River2D}$ (m s^{-1})	$\bar{v}_{ASHGS}$ (m s^{-1})	Difference
0.75	0.454	0.377	-0.077 (16.96 %)
1.00	0.508	0.441	-0.067 (13.19 %)
1.23	0.552	0.494	-0.058 (10.51 %)
1.32	0.565	0.516	-0.049 (8.67 %)
1.61	0.616	0.571	-0.045 (7.31 %)
1.93	0.667	0.630	-0.037 (5.55 %)
2.29	0.718	0.690	-0.028 (3.90 %)
2.61	0.767	0.739	-0.028 (3.65 %)
3.08	0.815	0.804	-0.011 (1.3 %)
3.51	0.867	0.859	-0.008 (0.92 %)
3.98	0.917	0.915	-0.002 (0.22 %)
4.47	0.966	0.970	0.004 (0.41 %)
5.00	1.019	1.025	0.006 (0.59 %)
5.55	1.066	1.072	0.006 (0.56 %)
7.50	1.219	1.243	0.024 (1.97 %)
10.00	1.381	1.342	0.039 (2.82 %)
15.00	1.671	1.696	0.025 (1.50 %)
19.00	1.858	1.866	0.008 (0.43 %)

vey (USGS) HSI. For more information on each species' hydraulic preferences refer to Chapter 3 and Appendix A. Comparison of HV for the species and life stages under consideration are found in Figures 4.4 though 4.8.

In general, ASHGS over-predicted HV in comparison to River2D. This is most likely due to the different ways each model calculate HV (refer to Chapter 3). For most species and life stages HV predicted by ASHGS were very similar to that of the Schweizer et al. [2007] model. Both use the same empirical hydraulic distributions but the Schweizer et al. [2007] model uses hydraulic conditions generated by River2D whereas ASHGS predicts the hydraulic conditions. Similar predicted HV from the two models further suggests ASHGS is adequately predicting hydraulic conditions across a range of flows.

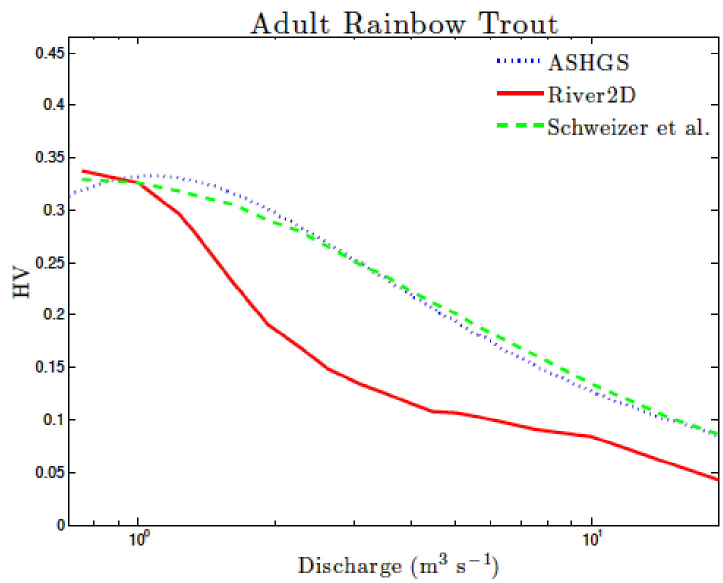

Figure 4.4: HV produced by River2D, Schweizer et al., and ASHGS for adult rainbow trout.

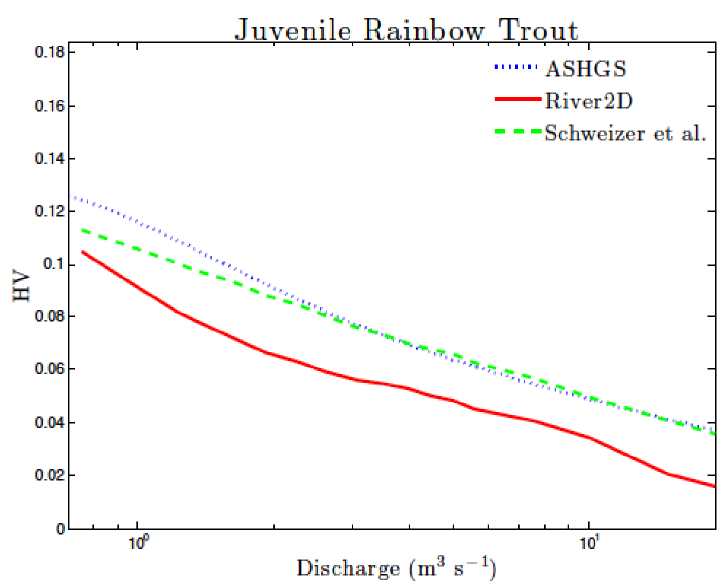

Figure 4.5: HV produced by River2D, Schweizer et al., and ASHGS for juvenile rainbow trout.

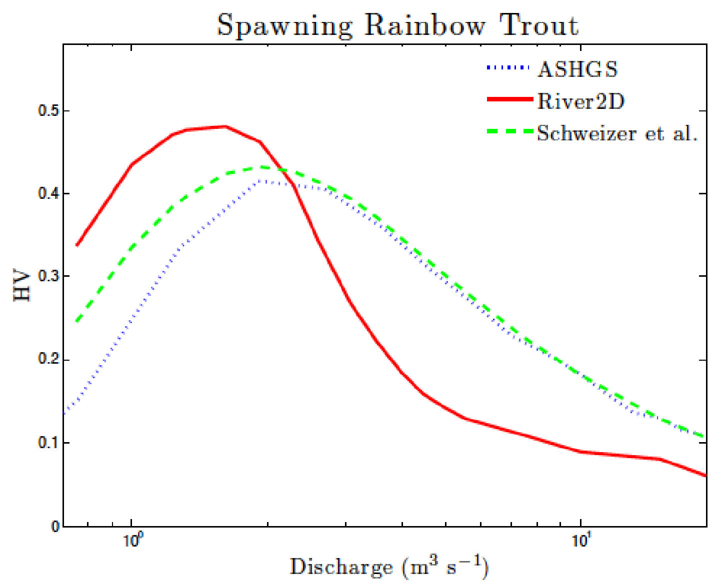

Figure 4.6: HV produced by River2D, Schweizer et al., and ASHGS for spawning rainbow trout.

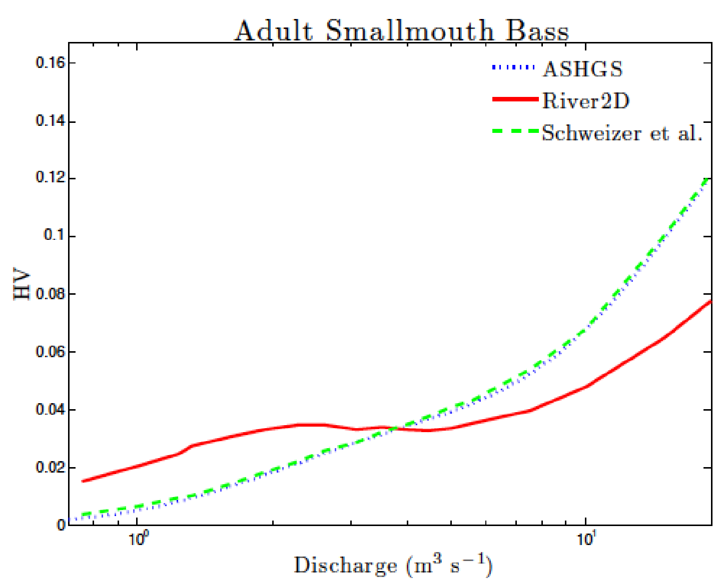

Figure 4.7: HV produced by River2D, Schweizer et al., and ASHGS for adult smallmouth bass.

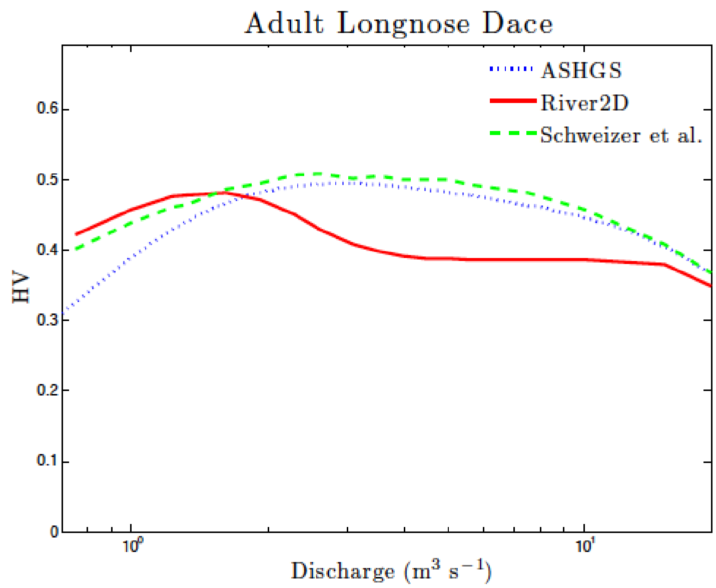

Figure 4.8: HV produced by River2D, Schweizer et al., and ASHGS for adult longnose dace.

4.6 Sensitivity analyses

4.6.1 Harris Creek

Often the goal of aquatic habitat modelling is prediction. Of particular interest is the influence of climate and land use change on aquatic habitat in British Columbian channels. British Columbia is predicted to have greater warming and changes in precipitation patterns than the global average [MFLNR, 2009]. Warming will occur in all seasons but will be greatest in the winter. Winters are expected to be wetter across British Columbia and summers will be drier in Southern and Central British Columbia and wetter in Northern British Columbia.

Increases in the frost free period, reduced snow packs, and earlier spring melting will alter the hydro-graph and influence Q_b. Increases in evaporative demand of the atmosphere and frequency of extremely warm days could potentially lead to a reduction in the mean minimal monthly, weekly, and daily flow which could compromise the biological integrity of the channel [Dakova et al., 2000, Stalnaker,

Table 4.3: Predicted changes in climatic variables at Harris Creek under the Canadian Center for Climate Modelling and Analysis A2 Scenario

Variable	1971 - 2000	2050	2080
Mean Annual Temperature (°C)	5.8	8.2	9.7
Mean Winter Temperature (°C)	-4.6	-2.1	-0.8
Mean Summer Temperature (°C)	16	18.4	19.9
Maximum Mean Summer Temperature (°C)	23.8	26.5	28.2
Mean Annual Precipitation (mm)	546	581	577
Mean Summer Precipitation (mm)	250	246	216
Precipitation as snow (mm)	144	98	63

1979, Tennant, 1976].

There exists many future green house gas emissions scenarios. Two of the most well known are the A2 and B1 emissions scenarios. Under the A2 scenario, there will be little success at curbing future global emissions leading to a 3 to 5 °C warming in British Columbia by 2080. The B1 scenario is representative of a substantial reduction in global emissions leading to a 2 to 3 °C warming in British Columbia by 2080 [MFLNR, 2009]. Some climatic variables that are of importance to flow regime and channel conditions are summarized in Table 4.3 (A2 scenario) and Table 4.4 (B1 scenario). These measures are predicted for a location just upstream of the study site at Harris Creek using ClimateBC_Map which was developed by The Centre for Forest Conservation Genetics at the University of British Columbia. The measures are based on General Climate Models produced at the Canadian Center for Climate Modelling and Analysis.

Warming temperatures and a changing precipitation regime will influence riparian vegetation dynamics. Furthermore, forest fire intensity and frequency will increase due to higher fuel loads under a warming and drier climate [MFLNR, 2009]. Forest fires influence channel morphology by significantly reducing bank strength, increasing the amount of in-channel LW, altering the timing and magnitude of peak flows, and modifying the volume and character of sediment delivered to the channel [Eaton et al., 2010a]. As well, demand for riparian areas as future agricultural, industrial, and recreational sites will lead to changes in riparian vege-

Table 4.4: Predicted changes in climatic variables at Harris Creek under the Canadian Center for Climate Modelling and Analysis B1 Scenario

Variable	1971 - 2000	2050	2080
Mean Annual Temperature ($^{\circ}$C)	5.8	7.6	8
Mean Winter Temperature ($^{\circ}$C)	-4.6	-2.5	-2.2
Mean Summer Temperature ($^{\circ}$C)	16	18	18.5
Maximum Mean Summer Temperature ($^{\circ}$C)	23.8	26	26.4
Mean Annual Precipitation (mm)	546	577	612
Mean Summer Precipitation (mm)	250	256	266
Precipitation as snow (mm)	144	105	103

tation along British Columbian channels. How land use change and climate change will interact and thus influence riparian vegetation in British Columbia is difficult to predict.

To investigate the potential influence of climate and land use change on channel dimensions and aquatic habitat, Q_b and H were varied one at a time to predict future channel trajectories for Harris Creek. Changes in S as well as sediment supply and transport are to some extent stochastic processes and will be excluded from the sensitivity analysis. Q_b was examined over a range of $\pm$ 50 % of its current value (Q_{bo}). Changes in Q_b due to climatic factors or out-of-stream uses are likely to fall within this range. H was examined from - 80% to + 20% of its current value (H_o). Bank strength can fall as low as - 80% of its pre-fire value in the decade following the fire as seen by a model presented by Benda and Dunne [1997]. H was examined up to + 20% of H_o to allow for potential maturation of the rooting system at Harris Creek, which could be a possibility under a warmer, wetter climate.

The model was calibrated to Harris Creek with the same input values as presented in the previous section. The sensitivity of channel dimensions to variable Q_b as determined using UBCRM can be seen in Figure 4.9. The width changes by a maximum of about $\pm$ 40 %, while d_b stays relatively constant across the range of Q_b. Subsequently, the W_b/d_b and thus b follows the same trajectory as W_b. Both the A2 and B1 scenarios indicate a reduced snow pack in the Harris Creek watershed, which will most likely lead to a decrease in Q_b. Under these scenarios the chan-

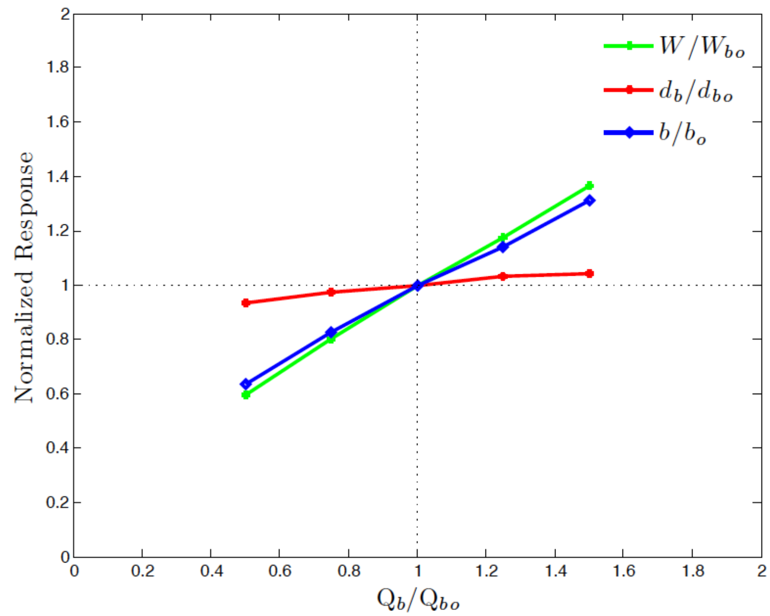

Figure 4.9: Response of W_b, d_b, and b to changes in Q_b at Harris Creek.

nel would become narrower, depth would stay relatively constant, and the channel would have a more canal like structure and less pool-riffle units (smaller b value). If Q_b were to increase due to increased severe storm activity or deforestation in the watershed it is predicted that the channel would become wider, the depth would remain relatively constant, and the channel would establish larger bars and a more prominent pool-riffle morphology (larger b value).

Moreover, the sensitivity of channel dimensions to variable H as determined using UBCRM can be seen in Figure 4.10. Under scenarios where the riparian vegetation becomes slightly more mature, the channel will become narrower, deeper, and have a more canal-like structure. More likely scenarios are a decrease in root strength due to land use change, most notably from a conversion to agricultural land in the Harris Creek watershed, or forest fire. In the years following a forest fire W_b would increase by approximately 70% and d_b would decrease by about 25%. This leads to b increasing by up to 120%, which indicates a wandering channel with many bars and potentially multiple thalwegs.

The sensitivity of WUA and HV to changes in Q_b were also examined for the

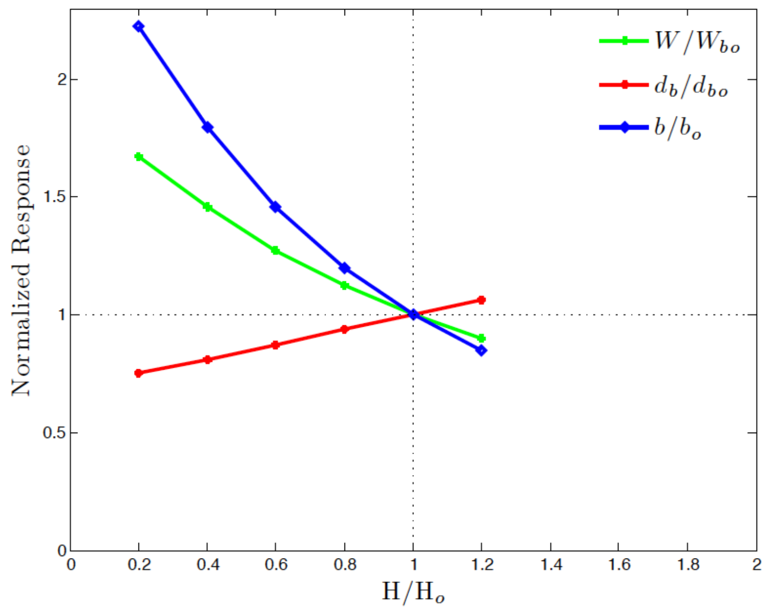

Figure 4.10: Response of W_b, d_b, and b to changes in H at Harris Creek.

species and life stages mentioned above (See Figures 4.11 to 4.13 and Appendix C). Note that mean annual flow was set at 1.5 m^3 s^{-1} and minimum mean monthly flow was estimated to be 0.5 m^3 s^{-1}. In general, WUA curves moved upward as Q_b increased. This is because there is more wetted area with increased Q_b due to a wider channel geometry which leads to more habitat becoming available. There was little difference in adult smallmouth bass WUA across the range of Q_b examined because Harris Creek is very poor habitat for this particular species. HV removes the bias of wetted area. As Q_b increases the HV curves move to the right. This is because as Q_b increases the channel becomes wider. Thus, higher flows are needed to raise the water level to habitable levels. A reduction in Q_b, which is likely under a warmer climate results in decreased habitat availability for rainbow trout and longnose dace.

Furthermore, the sensitivity of WUA and HV to changes in H produced more drastic morphologic change (see Figures 4.14 to 4.16 and Appendix C). In general, decreasing H led to the WUA curves shifting upwards. This is due to the increase in wetted area from the widening channel. $0.2H_o$ does not follow this general trend

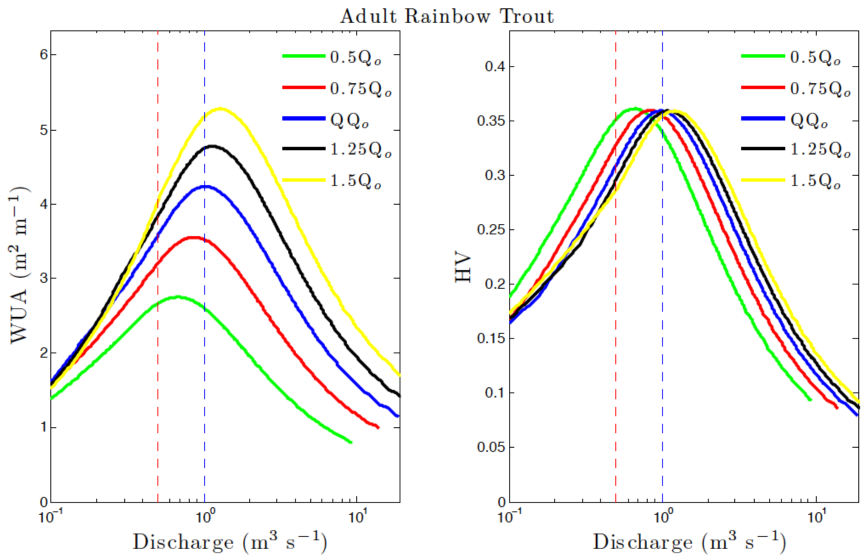

Figure 4.11: Adult rainbow trout WUA and HV at Harris Creek across a range of potential Q_b. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

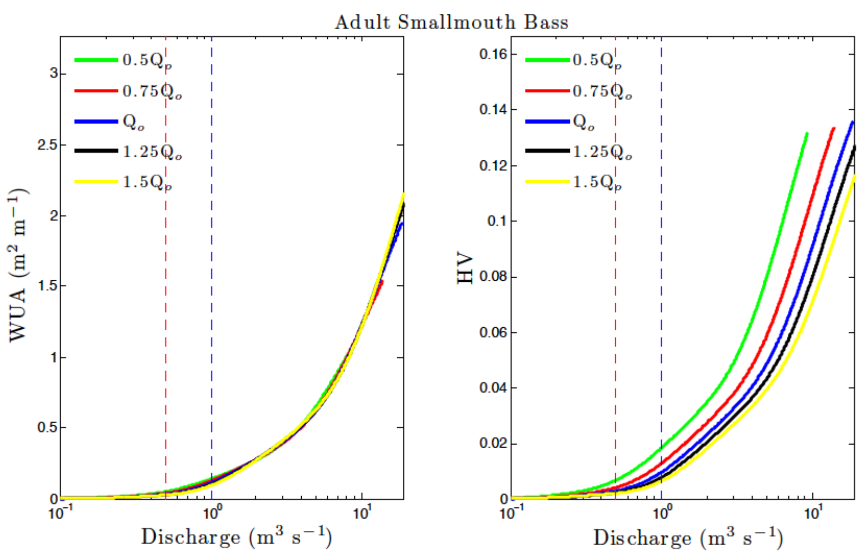

Figure 4.12: Adult smallmouth bass WUA and HV at Harris Creek across a range of potential Q_b. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

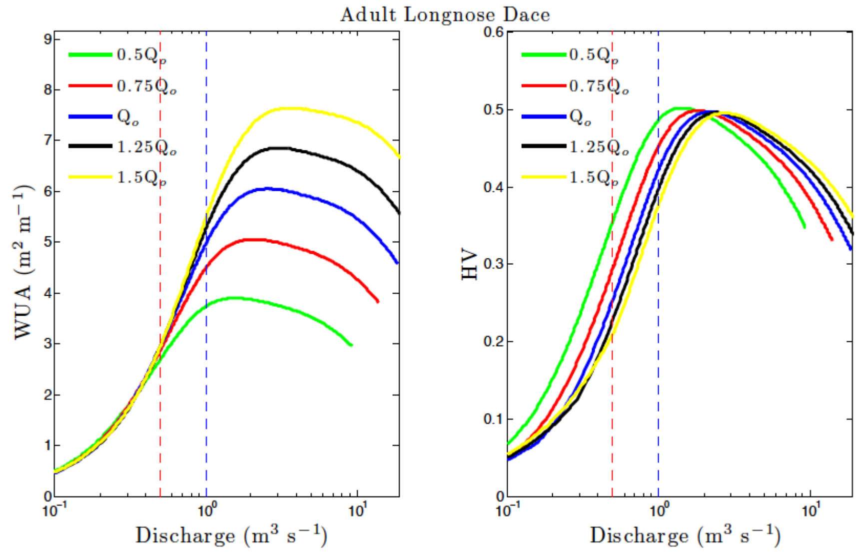

Figure 4.13: Adult longnose dace WUA and HV at Harris Creek across a range of potential Q_b. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

for rainbow trout because the channel becomes too wide and shallow. HV curves shift to the right as H decreases as higher flows are needed to bring the water level to habitable levels in the widened channel. Thus, a reduction in bank strength at Harris Creek due to forest fire or deforestation can increase the amount of available habitat for longnose dace and rainbow trout provided it doesn't cross a threshold.

The sensitivity of WUA at mean annual flow and minimum mean monthly low flow were also examined as these flows are of biological importance (see Figures 4.17 to 4.19 and Appendix C). The sensitivity of these measures are species specific. As well, the maximum WUA was also examined across a range of Q_b and H. As expected, maximum WUA for the most part increases with increasing Q_b values and increases with decreasing H values as the channel becomes wider and more wetted area becomes available. However, at very small H values the channel becomes too wide for the flow regime to produce habitat water levels for rainbow trout, which leads to a drop in maximum WUA at low H values.

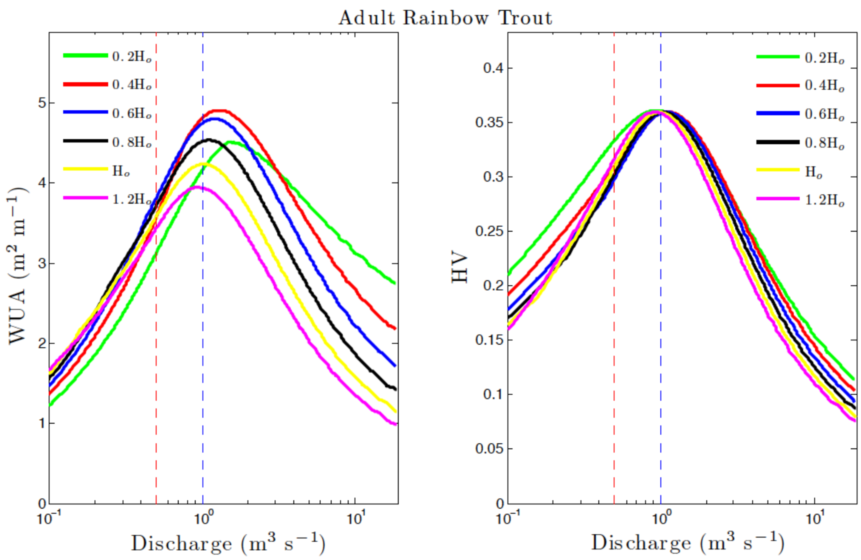

Figure 4.14: Adult rainbow trout WUA and HV at Harris Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

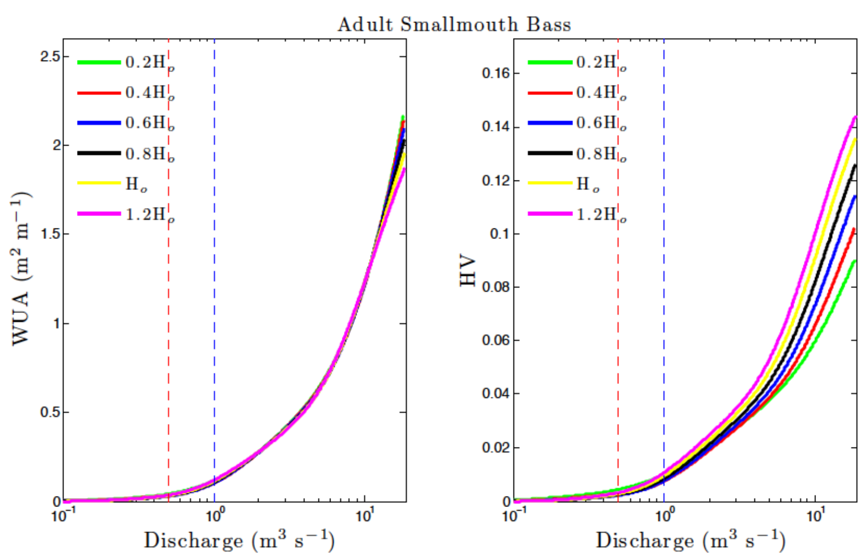

Figure 4.15: Adult smallmouth bass WUA and HV at Harris Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

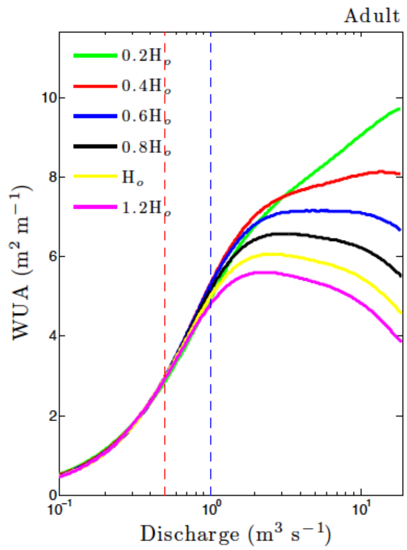

Figure 4.16: Adult longnose dace WUA and HV at Harris Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

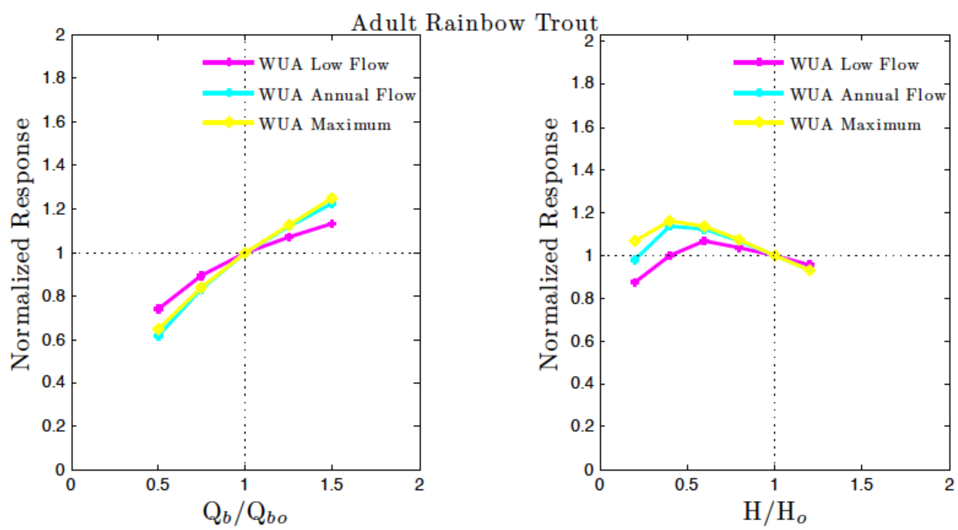

Figure 4.17: Sensitivity of adult rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of Q_b and H.

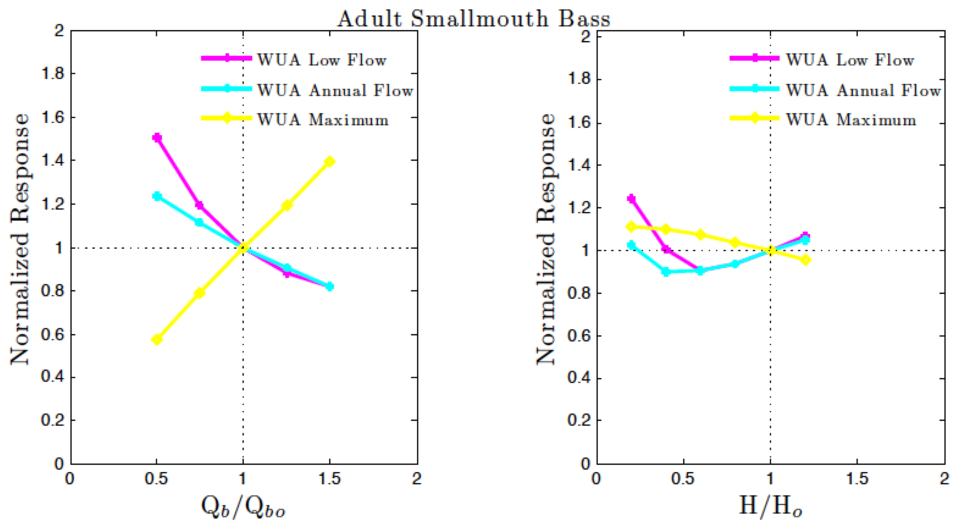

Figure 4.18: Sensitivity of adult smallmouth bass WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of Q_b and H.

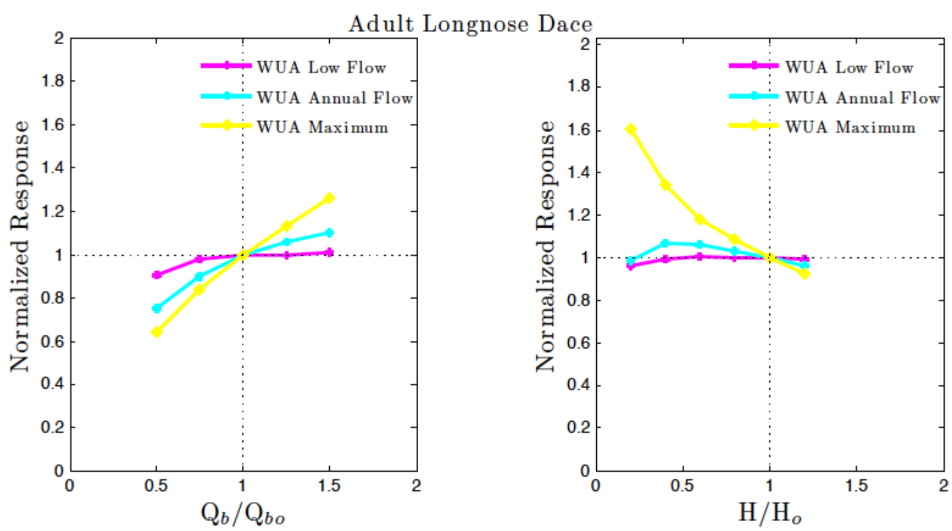

Figure 4.19: Sensitivity of adult longnose dace WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of Q_b and H.

4.6.2 Fishtrap Creek

The high-intensity forest fire that burned most of the riparian vegetation at Fishtrap Creek in 2003 provides interesting sensitivity analysis. The model was calibrated to Fishtrap Creek using the following input values: Q_b = 7.5 m^3 s^{-1}, S = 0.02 m m^{-1}, D_{50} = 55 mm, D_{84} = 128 mm, H = 0.46 m. The mean annual flow was set at 1 m^3 s^{-1} and minimum mean monthly flow was estimated to be 0.5 m^3 s^{-1}. The predicted channel width is 9.4 m, which is comparable to the 9.5 m measured pre-fire width. The pre-fire predicted b value is 0.162, indicating small but significant lateral variation in depth and velocity. Q_b has remained close to historical values following the fire [Eaton et al., 2010a] and it will be held constant during the analyses.

It is predicted from a model presented by Benda and Dunne [1997] that H will fall to as low as 20% of its pre-fire value in the decade following the fire. This drastic drop in H will lead to significant widening of the channel (Figure 4.20). Fishtrap Creek will become shallower due to the widening and aggradation that will occur. As well, b is predicted to increase by up to 300% of its original value, indicating huge lateral variation resulting from the development of bars and multiple channel threads [Eaton et al., 2010b]. Channel widening, aggradation, and the development of bars and multiple thalwegs were observed (although not to the extreme that the sensitivity analysis suggests) at Fishtrap Creek beginning from 2006 through 2008 [Eaton et al., 2010a,c]. Morphological change is most likely still ongoing. Deviation between the suggested dimensions from the sensitivity analysis and observed conditions could be due to the presence and continued influx of LW into the channel as well as changes in the type and volume of sediment supplied to the channel. The channel is likely to drift back to pre-fire conditions and thus channel dimensions and habitat indices will evolve from the extremes associated with $0.2H_o$ to the more stable channel configuration associated with H_o.

Changes in habitat indices (Figure 4.21 to 4.24 and Appendix C) follow similar trajectories as habitat indices at Harris Creek. In general, a decrease in H results in increased WUA for adult, juvenile, and spawning rainbow trout as the channel became wider and shallower. The exception being $0.2H_o$ conditions when the channel becomes very wide and shallow for adult and juvenile life stages resulting

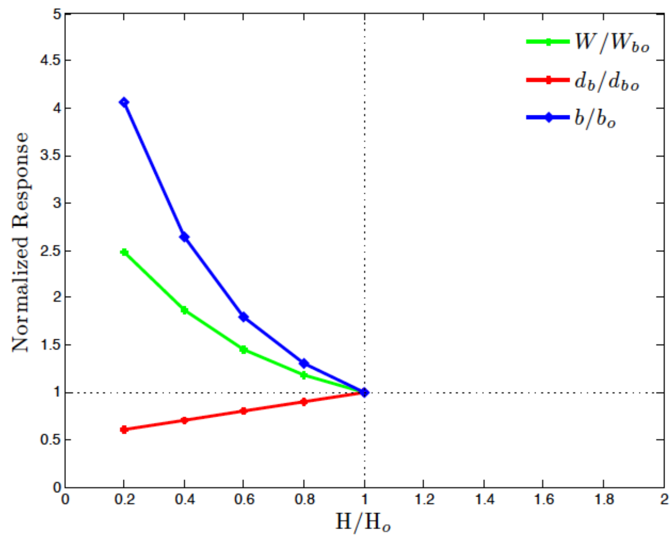

Figure 4.20: Response of W_b, d_b, and b to changes in H at Fishtrap Creek.

in anomalously poor habitat measures. This suggests the post-fire channel could present habitat conditions that are too extreme for adult and juvenile rainbow trout. Habitat remains poor for smallmouth bass over the range of H values examined and thus their habitat indices did not change significantly. Longnose dace WUA increased with decreasing H suggesting Fishtrap Creek is the most habitable for longnose dace when there is a significant reduction in bank strength.

4.7 Model limitations

The proposed habitat model will only be as good as the ability of each of the three components (UBCRM, ASHGS, statistical habitat method). Erroneous predictions by UBCRM will result in inaccurate predictions by ASHGS and the statistical habitat methods. Limitations of UBCRM are briefly highlighted in Section 4.2 and discussed in detail in Eaton et al. [2004] and Eaton [2006]. Similarly, if ASHGS is unable to model observed mean hydraulic conditions there will be errors in the habitat indices. Moreover, ASHGS must be validated on more channels of varying size and ecological regimes. The outputted reach average hydraulic conditions and habitat indices have only been tested at Harris Creek.

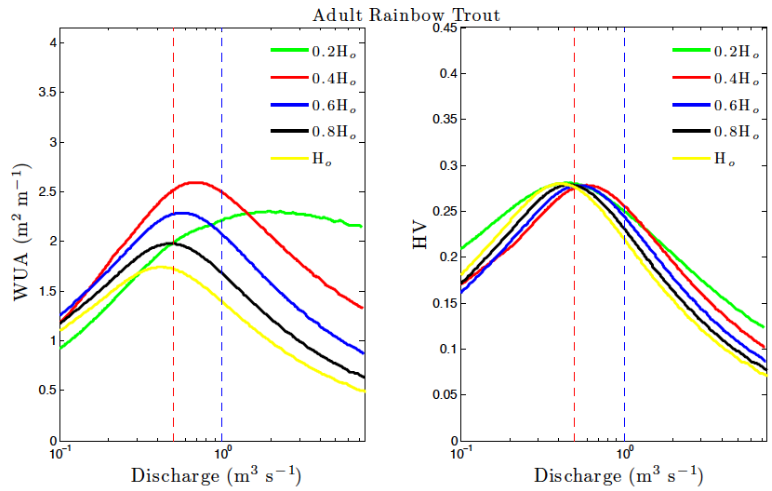

Figure 4.21: Adult rainbow trout WUA and HV at Fishtrap Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

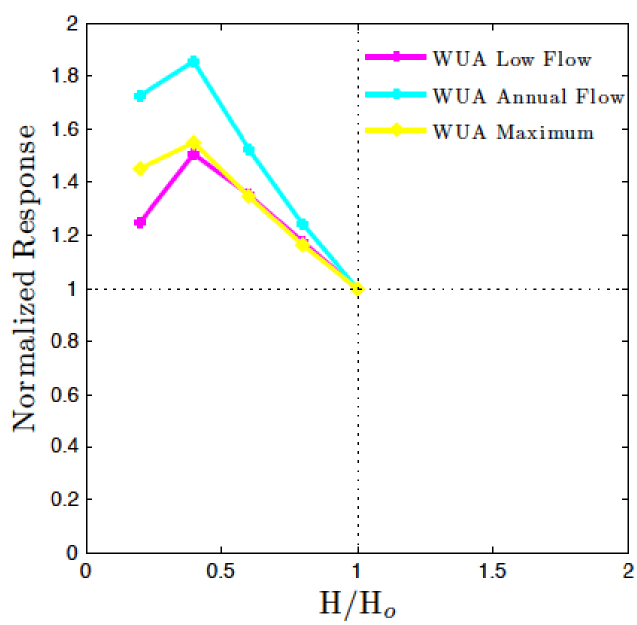

Figure 4.22: Sensitivity of adult rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of H at Fishtrap Creek

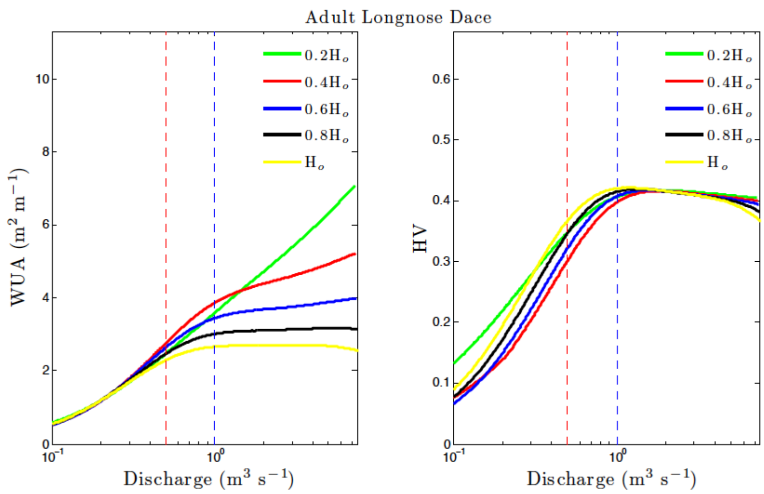

Figure 4.23: Adult longnose dace WUA and HV at Fishtrap Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

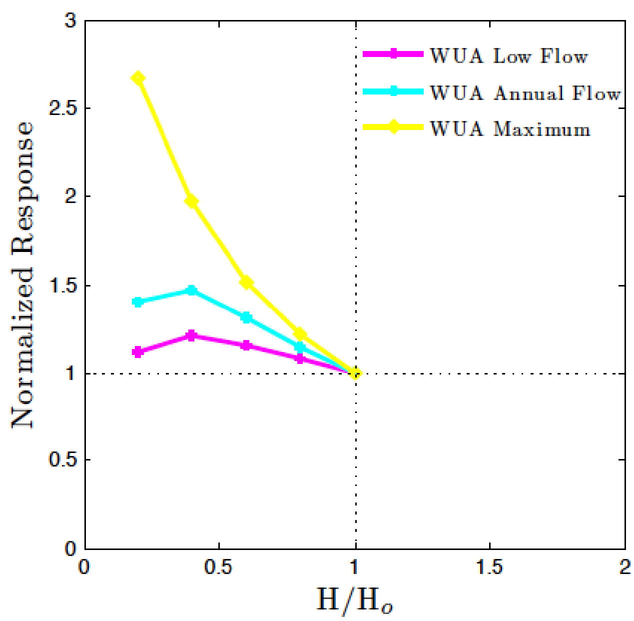

Figure 4.24: Sensitivity of adult longnose dace WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of H at Fishtrap Creek.

Furthermore, assuming b and W_b/d_b are linearly related is a major and untested assumption of ASHGS and is an avenue that requires further research before ASHGS can be used as a legitimate aquatic habitat tool. It is most likely that b is dependent on many factors in a fluvial system that were overlooked by this model. Greater understanding of how b changes longitudinally along a reach, between different morphological units, and between channels is not only of benefit to the proposed model but to fluvial ecological modelling as a whole. As well, greater understanding on how to estimate b in multi-thread channels is needed, as the proposed model only deals with single thread channels.

The proposed model provides predictions of reach average hydraulic conditions and lateral depth probability distributions. However, it does not provide any information on the spatial distribution of hydraulic variables (unlike 2-dimensional models) and thus does not distinguish between different habitat units. Lumping all the unique habitat units of a channel into a reach average geometry can be a huge simplification of complex channel structures and could lead to erroneous habitat quantification and overlook potential habitat. For instance, a channel that has both plane bed and pool-riffle morphology, such as Harris Creek, will be inferred as a channel that has intermediate morphology between those two end members. Thus, the presence of an important habitat unit such as a deep pool will be reduced due to the simplification present within the model. As well, the model ignores the presence of LW and lateral variation in sediment type, both of which are hugely important to aquatic habitat [Ahmadi-Nedushan et al., 2006].

Finally, the statistical habitat method embedded in the proposed model works reasonably well at Harris Creek. However, the transferability of the statistical methods to other channels should be done with caution as they were developed on New Zealand channels that exhibit a relatively natural flow regime and are meant for flow conditions that are below mean annual discharge [Schweizer et al., 2007]. As well, the statistical habitat methods would benefit from examining a wider range of species and life stages. Examining how the model fairs between young and old life stages and between pelagic and benethic species would be very useful. For this to be done a larger database of reliable HSI for British Columbian channels needs to be established and become easily accessible to practitioners. Furthermore, perhaps ASHGS would benefit from the use of non-statistical and/or non-HSI based habitat models such as process-oriented bioenergetic models or fuzzy-rule based models [Anderson et al., 2006]. For more detailed information on limitations of the statistical habitat methods and habitat quantification in general refer to Chapter 3.

4.8 Conclusion

The proposed aquatic habitat model combines a low-input regime model (predicts reach average bankfull channel dimensions) with ASHGS to model reach average hydraulic variables across a range of relevant flows. The reach average hydraulic variables are inputted into statistical habitat models to produce hydraulic distributions which are applied to HSI to generate habitat indices. Hence, the proposed model allows users to predict aquatic habitat indices for different fish species and life stages without the need for extensive data collection and painstaking analysis. Due to its low-input nature, transparency, user-friendliness, and large spatial applicability, the proposed model has the potential to become an accepted tool amongst practitioners [Conallin et al., 2010].

The use of a regime model allows for input variables to be easily varied. Thus, the proposed model provides the framework to quickly and adequately examine aquatic habitat and hypothesize how a changing channel structure will influence hydraulic habitat. To the author's knowledge it is the first aquatic assessment tool to directly link climate and land use change to aquatic habitat. As well, ASHGS can be used to evaluate longitudinal changes in aquatic habitat by simply knowing how Q, S, characteristic grain size, and rooting depth change downstream.

A reduction in Q_b, which is likely to occur at Harris Creek and Fishtrap Creek under a warming climate, results in narrower and deeper channels. This will lead to a reduction in WUA for all species under investigation which suggests practitioners have to be mindful of future flow abstractions at these channels as climatic factors are likely to decrease available habitat over the coming century. As well, a decrease in bank strength due to deforestation or forest fire results in a wider, shallower channel which leads to increases in WUA for longnose dace and rainbow trout. However, at very low bank strengths the channel becomes too wide and shallow for some life stages of rainbow trout resulting in decreased habitat availability.

Thus, loss of bank strength can be beneficial for some species provided it doesn't reach a threshold. Smallmouth bass habitat did not change significantly during the sensitivity analyses because hydraulic conditions were always poor for this particular species.

The proposed model provides the framework of a preliminary assessment or rapid evaluation tool. Due to its low-input nature, the model provides a means of habitat assessment where site-specific data does not exist. The model can be used to evaluate whether anticipated or proposed changes to the channel or riparian area are approaching a habitat threshold and thus indicate the need for more extensive habitat assessment (e.g. PHABSIM, 2-dimensional hydrodynamic models). As well, it is useful when assessments need to be conducted on multiple reaches and channels (e.g. basin-wide habitat assessment). Further research is needed on predicting reach average channel geometry (b) as well as determining the influence of LW and variable sediment supply on habitat indices before this model can become a legitimate aquatic habitat tool.

Chapter 5

Conclusions

5.1 Empirical hydraulic distributions in British Columbian channels

Empirical hydraulic distribution equations were evaluated on two channels in the Interior Region of British Columbia. Measured hydraulic distributions were adequately reproduced for both high and low flow conditions at Harris Creek using statistical distributions. Likewise, statistical velocity distributions were able to recreate the measured velocity distribution for both 2006 and 2007 high flow data at Fishtrap Creek, a channel recently disturbed by forest fire. Empirical depth distributions were unable to model the measured depth distributions at Fishtrap Creek following rapid morphological change. The empirical distributions were developed on channels that had relatively undisturbed morphologies suggesting their use on recently disturbed channels should be done with caution [Schweizer et al., 2007].

Furthermore, the empirical hydraulic equations were compared to depth and velocity distributions produced by a 2-dimensional hydrodynamic model (River2D). Depth and velocity distributions were sufficiently recreated by statistical distributions at flows < 3 m^3 s^{-1}. The empirical equations provided strong fits to the River2D hydraulic distributions at flows close to and below mean annual flow. As flows approached bankfull (19 m^3 s^{-1}), empirical distributions were unable to model the high densities surrounding $\bar{v}$ and $\bar{d}$. In particular, the empirical velocity equations performed very poorly at high flows. These findings concur with results of a similar investigation in the Nooksack River basin [Saraeva and Hardy, 2009a]. Thus, empirical equations are most appropriate at low flow conditions, which are the limiting flows for many aquatic species [Dakova et al., 2000, Hatfield and Bruce, 2000].

A joint frequency depth-velocity empirical distribution [Schweizer et al., 2007] was deemed most suitable for modelling both measured and simulated hydraulic distributions. The joint frequency distribution was paired with HSI to create a low-input aquatic habitat model that generates habitat indices across a range of flows for three species at Harris Creek. WUA produced by the low-input statistical habitat model and River2D (data-intensive 2-dimensional model) compared favourably at low flows. There existed deviation in the absolute values of WUA at high flows. However, the general shape and trends in WUA data simulated by River2D were reproduced by the statistical habitat model.

Empirical hydraulic equations can be useful for future aquatic habitat modelling endeavours in British Columbian channels. In particular, the results show that depth and velocity distributions are adequately recreated at low flow conditions. With knowledge of the channel and expertise with in-stream flow methodologies, empirical hydraulic distributions alongside HSI can be useful for preliminary assessments and basin wide habitat studies, especially when environmental data is lacking.

As with all in-stream flow methodologies there are limitations that need to be acknowledged or addressed. The empirical distributions do not provide any information on the spatial distribution of the predicted hydraulic variables. As well, the proposed habitat model does not incorporate substrate, cover, and wood load data, all of which determine aquatic habitat [Allan and Castillo, 2007]. Finally, for the statistical habitat methodology to be improved there needs to be a huge improvement in the predictive capacity of the empirical velocity equation.

5.2 ASHGS aquatic habitat model

A channel regime model (UBCRM) was paired with ASHGS and a statistical habitat model to predict habitat indices across a range of flows for species and life stages found in British Columbian channels. The proposed methodology is a simple alternative to more widely used data-intensive in-stream flow methodologies (i.e. PHABSIM and 2-dimensional hydrodynamic models). Furthermore, future reach average channel dimensions resulting from climate and land use change can be modelled with UBCRM which allows for future habitat indices to be predicted using the ASHGS aquatic habitat model. Thus, the proposed methodology provides practitioners with a simplistic tool that can highlight future channel dimensions and flow regimes of concern and illustrate ecological thresholds.

In British Columbia, reduced snowpacks and earlier spring melting caused by a warming climate is likely to reduce Q_b in channels across the province. A decrease in Q_b will lead to narrower, deeper channels which will in turn reduce available habitable area for many species found in British Columbian channels. Furthermore, decreases in bank strength due to deforestation of the riparian vegetation and forest fire will lead to wider and shallower channels in British Columbia. Wider channels can be beneficial to many fish species as the wetted area will increase. Severe reduction in bank strength (e.g. 5 -10 years following a forest fire) can lead to extremely wide channels causing hydraulic habitat conditions to become too extreme for some species.

The proposed ASHGS aquatic habitat model is ideal for preliminary assessment and basin-wide studies. The model should be accepted by practitioners as it is transparent, user-friendly, and can be used on a wide range of channels [Conallin et al., 2010]. The required input data are often previously established for a channel or can be obtained within one day of field work. Future research and refinement of the ASHGS habitat model is needed for the methodology to become a legitimate in-stream flow assessment tool. First and foremost, the model needs to be evaluated on channels of varying flow regimes and morphologies across the province. As well, the model's performance at predicting habitat indices for different fish species and life stages is imperative. A stronger understanding of how to predict the reach average channel geometry (b value) is crucial as the relationship between channel morphology and reach average channel geometry is currently poorly understood.

5.3 The future of aquatic habitat modelling in British Columbia

Continued effort is needed to develop and refine in-stream flow assessment tools for British Columbian channels. In particular, greater emphasis needs to be placed on developing low-input, inexpensive tools that are reliable and have a sound scientific base [Conallin et al., 2010, Hatfield and Bruce, 2000]. The use of empirical statistical hydraulic equations and habitat models that use these equations have to be further refined in British Columbia. In particular, further evaluation is needed on a wider range of fish-bearing channels.

The development of British Columbia specific empirical hydraulic equations could be quite useful (although it is a rather large undertaking). The proposed empirical distributions were developed in different biogeoclimatic zones than those found in British Columbia. Manipulation of previous empirical models in the Nooksack River basin provided a more reliable in-stream flow assessment tool [Saraeva and Hardy, 2009a]. Furthermore, the inability of the empirical distributions to adequately model hydraulic conditions in a small pluvial stream in the Coast Mountains [Rosenfeld et al., 2011] and the depth distribution at a recently disturbed channel (Fishtrap Creek) highlights the need for some form of local calibration of existing empirical equations or distribution equations that are developed on the unique riverscapes found across British Columbia.

Future in-stream flow methodologies need to be able to quantify habitat loss or gain resulting from changes in flow regime, sediment supply, and riparian vegetation [Conallin et al., 2010]. The influence of climate change on these environmental conditions is poorly known. Having a better understanding of how environmental conditions will evolve over the coming decades will foster more accurate predictions of future flow regimes and channel morphologies and thus future hydraulic habitat availability [Tharme, 2003].

Furthermore, low-input flow methodologies tools should examine the influence of sediment supply and LW on reach average channel conditions. These two variables were ignored in this project as they are difficult to model due to their stochastic nature. However, substrate and LW undoubtedly influence channel morphology as well as the mesohabitats that are present within the channel. Also, incorporating the distribution of shear stresses can provide more accurate model predictions [Saraeva and Hardy, 2009a]. Within channel shear stress controls substrate distribution and type, which in turn influences channel slope and thus the distribution of depths and velocities.

There has been limited development and use of physical methodologies that examine longitudinal changes in habitat along a given channel [Laliberte et al., 2013, Rosenfeld et al., 2007]. The proposed ASHGS habitat model could be used to examine downstream habitat changes although that is not its intended purpose. Furthermore, aquatic habitat models have long been scrutinized for not incorporating ecological interactions and thus future methodologies would benefit from a broader ecological perspective [Anderson et al., 2006, Conallin et al., 2010].

Lastly, it is very possible that the way forward in aquatic habitat modelling in British Columbian channels is not empirical distributions or any of the in-stream flow methodologies mentioned in this dissertation for that matter. Other approaches such as fuzzy-rule based modelling which incorporate ecological interactions and require modest data inputs are viable options. Furthermore, there are a host of other methodologies that have and are continually being developed to provide water practitioners with the best tools to withhold the ecological integrity of contested channels across the globe. Continual evaluation, refinement, and collaboration will provide the most suitable in-stream flow methodologies moving forward into an era of uncertain climate.

Bibliography

B. Ahmadi-Nedushan, A. St-Hilaire, M. Bérubé, É. Robichaud, N. Thiémonge, and B. Bobée. A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. *River Research and Applications*, 22(5):503–523, 2006. → pages 1, 7, 8, 52, 80

J. D. Allan and M. M. Castillo. *Stream ecology: structure and function of running waters*. Springer, 2007. → pages 22, 84

K. E. Anderson, A. J. Paul, E. McCauley, L. J. Jackson, J. R. Post, and R. M. Nisbet. Instream flow needs in streams and rivers: the importance of understanding ecological dynamics. *Frontiers in Ecology and the Environment*, 4(6):309–318, 2006. → pages 1, 81, 87

T. C. Annear, C. C. Estes, and I. F. Council. *Instream flows for riverine resource stewardship*. Instream Flow Council, 2004. → pages 2, 22

C. Armour and J. Taylor. Evaluation of the instream flow incremental methodology by US Fish and Wildlife Service field users. *Fisheries*, 16(5): 36–43, 1991. → pages 5

L. Benda and T. Dunne. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research*, 33(12): 2849–2863, 1997. → pages 68, 76

K. D. Bovee. Guide to stream habitat analysis using the instream flow incremental methodology. *Available from the National Technical Information Service, Springfield VA 22161 as PB 83-131052. Report*, 1982. → pages 4, 49, 51

K. D. Bovee, B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, and J. Taylor. Stream habitat analysis using the instream flow incremental methodology. Technical report, DTIC Document, 1998. → pages 6

H. H. Chang. Minimum stream power and river channel patterns. *Journal of Hydrology*, 41(3):303–327, 1979. → pages 53

M. Church. Bed material transport and the morphology of alluvial river channels. *Annu. Rev. Earth Planet. Sci.*, 34:325–354, 2006. → pages 57

M. Church and M. Hassan. Mobility of bed material in Harris Creek. *Water Resources Research*, 38(11):1237, 2002. → pages 10, 17

J. Conallin, E. Boegh, and J. K. Jensen. Instream physical habitat modelling types: an analysis as stream hydromorphological modelling tools for eu water resource managers. *Intl. J. River Basin Management*, 8(1):93–107, 2010. → pages 1, 2, 4, 6, 22, 53, 81, 85, 86, 87

D. M. Corbett. Stream-gaging procedure: a manual describing methods and practices of the geological survey. *Geological Survey water-supply paper*, 888, 1962. → pages 15

S. Dakova, Y. Uzunov, and D. Mandadjiev. Low flow: the river's ecosystem limiting factor. *Ecological Engineering*, 16(1):167–174, 2000. → pages 40, 47, 66, 84

S. Day and W. Fletcher. Effects of valley and local channel morphology on the distribution of gold in stream sediments from harris creek, british columbia, canada. *Journal of geochemical exploration*, 32(1):1–16, 1989. → pages 10

J. R. Desloges and M. A. Church. Wandering gravel-bed rivers. *The Canadian Geographer/Le Géographe canadien*, 33(4):360–364, 1989. → pages 57

B. Eaton, M. Church, and R. Millar. Rational regime model of alluvial channel morphology and response. *Earth Surface Processes and Landforms*, 29(4): 511–529, 2004. → pages 54, 55, 77

B. Eaton, C. Andrews, T. Giles, and J. Phillips. Wildfire, morphologic change and bed material transport at Fishtrap Creek, British Columbia. *Geomorphology*, 118(3):409–424, 2010a. → pages 18, 20, 33, 67, 76

B. Eaton, R. G. Millar, and S. Davidson. Channel patterns: braided, anabranching, and single-thread. *Geomorphology*, 120(3):353–364, 2010b. → pages 53, 57, 76

B. Eaton, R. Moore, and T. Giles. Forest fire, bank strength and channel instability: the 'unusual' response of Fishtrap Creek, British Columbia. *Earth Surface Processes and Landforms*, 35(10):1167–1183, 2010c. → pages 18, 19, 20, 33, 76

B. C. Eaton. Bank stability analysis for regime models of vegetated gravel bed rivers. *Earth Surface Processes and Landforms*, 31(11):1438–1444, 2006. → pages 55, 77

B. C. Eaton and M. Church. Predicting downstream hydraulic geometry: A test of rational regime theory. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 112(F3), 2007. → pages 54

B. C. Eaton and R. G. Millar. Optimal alluvial channel width under a bank stability constraint. *Geomorphology*, 62(1):35–45, 2004. → pages 54

B. C. Eaton, M. Church, and T. R. Davies. A conceptual model for meander initiation in bedload-dominated streams. *Earth Surface Processes and Landforms*, 31(7):875–891, 2006. → pages 55

R. Ferguson. The missing dimension: effects of lateral variation on 1-d calculations of fluvial bedload transport. *Geomorphology*, 56(1):1–14, 2003. → pages 55, 56, 57, 58

R. Ferguson. Flow resistance equations for gravel- and boulder-bed streams. *Water Resources Research*, 43(5), 2007. → pages 58, 61

W. Fletcher and J. Wolcott. Transport of magnetite and gold in harris creek, british columbia, and implications for exploration. *Journal of Geochemical Exploration*, 41(3):253–274, 1991. → pages 10

M. Gard. Comparison of spawning habitat predictions of PHABSIM and River2D models. *International Journal of River Basin Management*, 7(1):55–71, 2009. → pages 2, 5, 23, 24, 52

J. Guay, D. Boisclair, D. Rioux, M. Leclerc, M. Lapointe, and P. Legendre. Development and validation of numerical habitat models for juveniles of Atlantic salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Sciences*, 57(10):2065–2075, 2000. → pages 4

T. Hardy. The future of habitat modeling and instream flow assessment techniques. *Regulated Rivers: Research & Management*, 14(5):405–420, 1998. → pages 1, 2, 4, 6, 22, 51, 52

M. Hassan and M. Church. Sensitivity of bed load transport in Harris Creek: Seasonal and spatial variation over a cobble-gravel bar. *Water Resources Research*, 37(3):813–825, 2001. → pages 10, 13, 17

T. Hatfield and J. Bruce. Predicting salmonid habitat–flow relationships for streams from western North America. *North American Journal of Fisheries Management*, 20(4):1005–1015, 2000. → pages 1, 2, 3, 4, 5, 6, 22, 23, 47, 50, 52, 84, 86

D. Hogan and M. Church. Hydraulic geometry in small, coastal streams: progress toward quantification of salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences*, 46(5):844–852, 1989. → pages 3, 4

H. Q. Huang, H. H. Chang, and G. C. Nanson. Minimum energy as the general form of critical flow and maximum flow efficiency and for explaining variations in river channel pattern. *Water Resources Research*, 40(4), 2004. → pages 53, 54

I. Jowett. Instream flow methods: a comparison of approaches. *Regulated Rivers: Research & Management*, 13(2):115–127, 1997. → pages 1, 2, 3, 4, 22, 51

M. Kirkby. *Maximum sediment efficiency as a criterion for alluvial channels*. University of Leeds, School of Geography, 1976. → pages 53

J. Laliberte, J. Post, and J. Rosenfeld. Hydraulic geometry and longitudinal patterns of habitat quantity and quality for rainbow trout (Oncorhynchus mykiss). *River Research and Applications*, 2013. → pages 87

N. Lamouroux. Depth probability distributions in stream reaches. *Journal of Hydraulic Engineering*, 124:224–227, 1998. → pages 2, 6, 7, 8, 23, 26, 29, 30, 32, 33, 36, 40, 46, 48

N. Lamouroux and H. Capra. Simple predictions of instream habitat model outputs for target fish populations. *Freshwater Biology*, 47(8):1543–1556, 2002. → pages 5, 6, 7

N. Lamouroux and I. Jowett. Generalized instream habitat models. *Canadian Journal of Fisheries and Aquatic Sciences*, 62(1):7–14, 2005. → pages 5, 6, 7, 22, 51, 52

N. Lamouroux and Y. Souchon. Simple predictions of instream habitat model outputs for fish habitat guilds in large streams. *Freshwater Biology*, 47(8): 1531–1542, 2002. → pages 5, 52

N. Lamouroux, Y. Souchon, and E. Herouin. Predicting velocity frequency distributions in stream reaches. *Water Resources Research*, 31(9):2367–2375, 1995. → pages 2, 6, 7, 8, 23, 25, 30, 31, 35, 46

N. Lamouroux, H. Capra, and M. Pouilly. Predicting habitat suitability for lotic fish: linking statistical hydraulic models with multivariate habitat use models. *Regulated Rivers: Research & Management*, 14(1):1–11, 1998. → pages 4

J. Leach and R. Moore. Above-stream microclimate and stream surface energy exchanges in a wildfire-disturbed riparian zone. *Hydrological Processes*, 24 (17):2369–2381, 2010. → pages 18, 20

J. Leach and R. Moore. Stream temperature dynamics in two hydrogeomorphically distinct reaches. *Hydrological Processes*, 25(5):679–690, 2011. → pages 20

M. Leclerc, A. Boudreault, T. Bechara, and G. Corfa. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology. *Transactions of the American Fisheries Society*, 124(5):645–662, 1995. → pages 5

B. Lee Lamb, C. Sabaton, and Y. Souchon. Use of the instream flow incremental methodology: introduction to the special issue. *Hydroécologie Appliquée*, 14: 1–7, 2004. → pages 4

L. B. Leopold and T. Maddock. The hydraulic geometry of stream channels and some physiographic implications. *US Geological Survey Professional Paper*, 252, 1953. → pages 3

MFLNR. Climate change. Technical report, Ministry of Forest, Lands, and Natural Resources - Government of British Columbia, 2009. → pages 66, 67

D. Montgomery and J. Buffington. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109(5):596–611, 1997. → pages 12, 20, 57

G. C. Nanson and H. Q. Huang. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. *Earth Surface Processes and Landforms*, 33(6):923–942, 2008. → pages 53

P. Parasiewicz and M. Dunbar. Physical habitat modelling for fish-a developing approach. *Archiv für Hydrobiologie. Supplementband. Large rivers*, 12(2-4): 239–268, 2001. → pages 7

P. Parasiewicz and J. Walker. Comparison of MesoHABSIM with two microhabitat models (PHABSIM and HARPHA). *River Research and Applications*, 23(8):904–923, 2007. → pages 4, 5

E. Petticrew, P. Owens, and T. Giles. Wildfire effects on the quantity and composition of suspended and gravel-stored sediments. *Water, Air, & Soil Pollution: Focus*, 6(5):647–656, 2006. → pages 20

J. Phillips, B. Eaton, et al. Detecting the timing of morphologic change using stage-discharge regressions: A case study at Fishtrap Creek, British Columbia, Canada. *Canadian Water Resources Journal*, 34(3):285–300, 2009. → pages 20

QLiner. Adcp technical user manual, 2005. → pages 16

D. Reiser, T. Wesche, and C. Estes. Status of instream flow legislation and practices in North America. *Fisheries*, 14(2):22–29, 1989. → pages 3

S. P. Rice, M. Church, C. L. Wooldridge, and E. J. Hickin. Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser River, British Columbia, Canada. *Sedimentology*, 56(3):709–736, 2009. → pages 57

J. Rosenfeld, K. Campbell, E. Leung, J. Bernhardt, and J. Post. Habitat effects on depth and velocity frequency distributions: Implications for modelling hydraulic variation and fish habitat suitability in streams. *Geomorphology*, 130: 127–135, 2011. → pages 7, 8, 86

J. S. Rosenfeld, J. Post, G. Robins, and T. Hatfield. Hydraulic geometry as a physical template for the river continuum: application to optimal flows and longitudinal trends in salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences*, 64(5):755–767, 2007. → pages 87

E. Saraeva and T. B. Hardy. Prediction of fisheries physical habitat values based on hydraulic geometry and frequency distributions of depth and velocity. *International Journal of River Basin Management*, 7(1):31–41, 2009a. → pages 1, 5, 7, 22, 23, 26, 30, 31, 40, 46, 47, 48, 49, 51, 52, 55, 84, 86, 87

E. Saraeva and T. B. Hardy. Extrapolation of site-specific weighted usable area curves and instream flow requirements to unmeasured streams within the Nooksack watershed in support of strategic watershed planning. *International Journal of River Basin Management*, 7(1):91–103, 2009b. → pages 2, 5, 23, 52

S. Schweizer, M. E. Borsuk, I. Jowett, and P. Reichert. Predicting joint frequency distributions of depth and velocity for instream habitat assessment. *River Research and Applications*, 23(3):287–302, 2007. → pages 2, 6, 7, 8, 23, 26, 29, 30, 31, 32, 33, 34, 35, 36, 38, 40, 41, 42, 46, 47, 52, 55, 59, 62, 63, 80, 83, 84

SonTek. Flowtracker Handheld ADV Technical Manual, July 2007. → pages 14

C. B. Stalnaker. *Low flow as a limiting factor in warmwater streams*. US Fish and Wildlife Service, 1979. → pages 66

P. Steffler and J. Blackburn. Two-dimensional depth averaged model of river hydrodynamics and fish habitat. *River2D users manual, University of Alberta, Canada*, 2002. → pages 5, 24

M. J. Stewardson and T. A. McMahon. A stochastic model of hydraulic variations within stream channels. *Water Resources Research*, 38(1):1007, 2002. → pages 38

D. Tennant. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, 1(4):6–10, 1976. → pages 3, 67

R. E. Tharme. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River research and applications*, 19(5-6):397–441, 2003. → pages 1, 2, 3, 4, 22, 51, 86

W. R. White, R. Bettess, and E. Paris. Analytical approach to river regime. *Journal of the Hydraulics Division*, 108(10):1179–1193, 1982. → pages 53

C. Willmott. Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society*, 63:1309–1369, 1982. → pages 28

C. Willmott, S. Ackleson, R. Davis, J. Feddema, K. Klink, D. Legates, J. ODonnell, and C. Rowe. Statistics for the evaluation and comparison of models. *Journal of geophysical Research*, 90(C5):8995–9005, 1985. → pages 28

M. G. Wolman. *A method of sampling coarse river-bed material*. American Geophysical Union, 1954. → pages 17

Appendix A

Habitat Suitability Indices

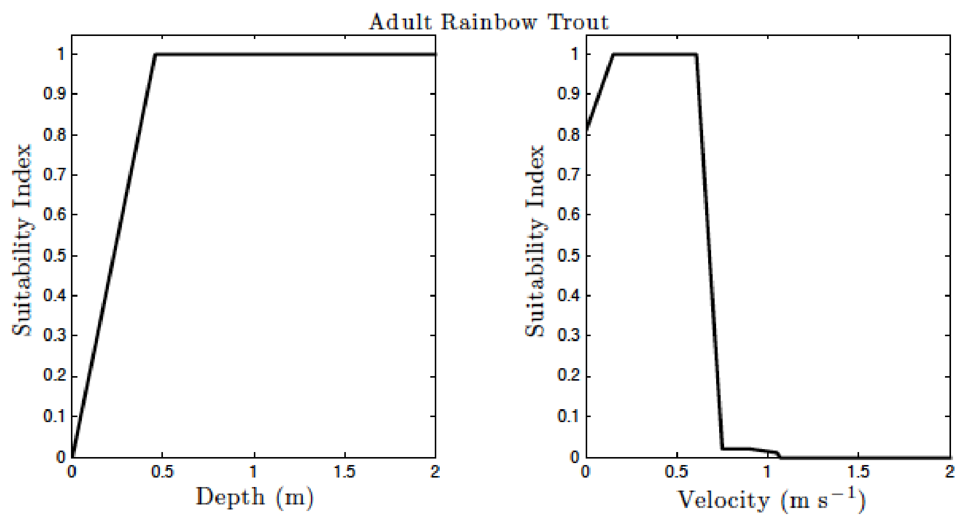

Figure A.1: USGS depth and velocity HSI for adult rainbow trout

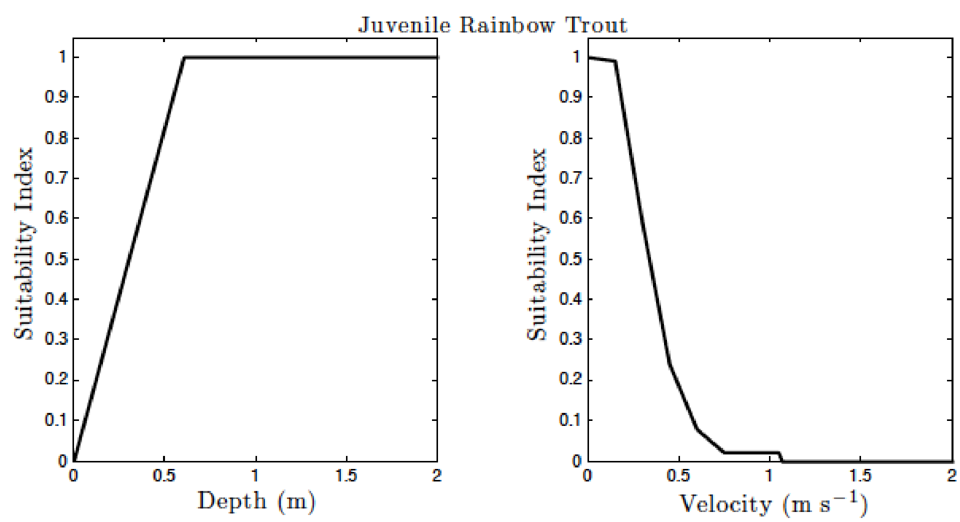

Figure A.2: USGS depth and velocity HSI for juvenile rainbow trout

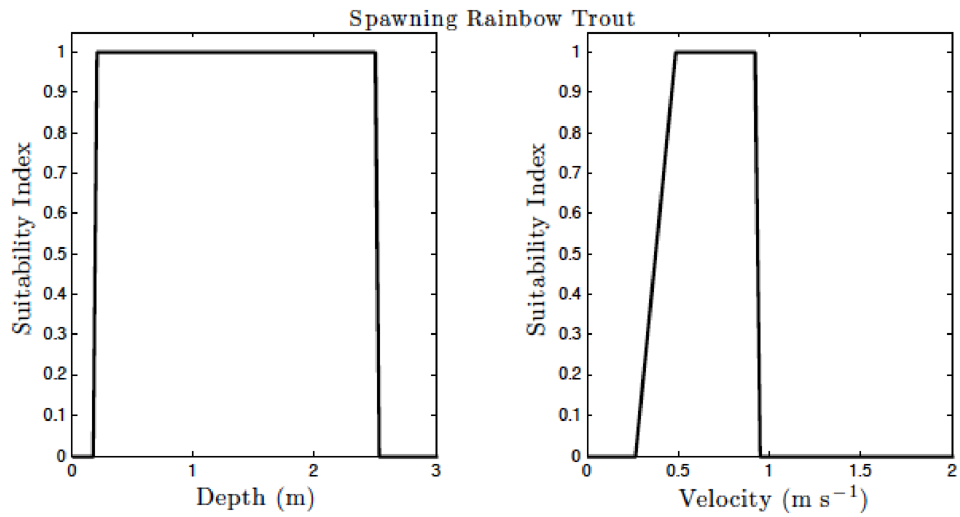

Figure A.3: USGS depth and velocity HSI for spawning rainbow trout

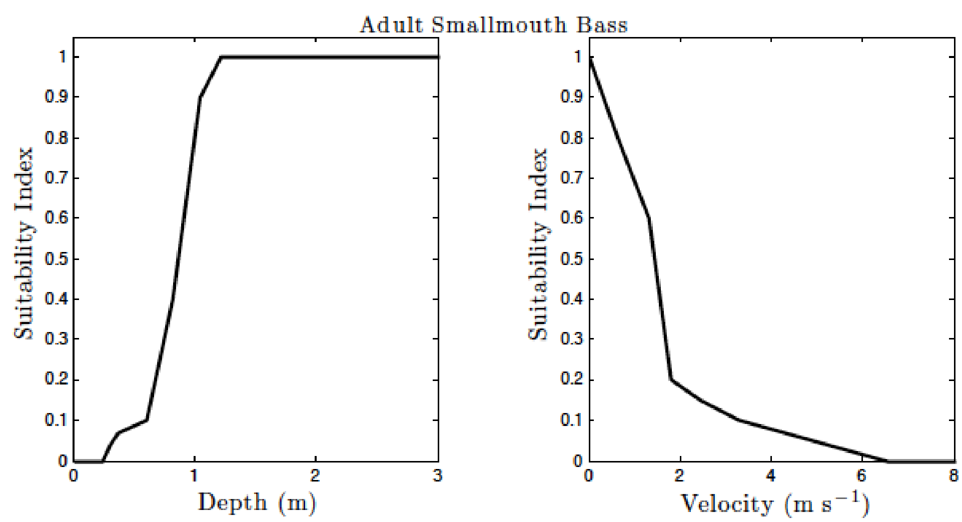

Figure A.4: USGS depth and velocity HSI for adult smallmouth bass

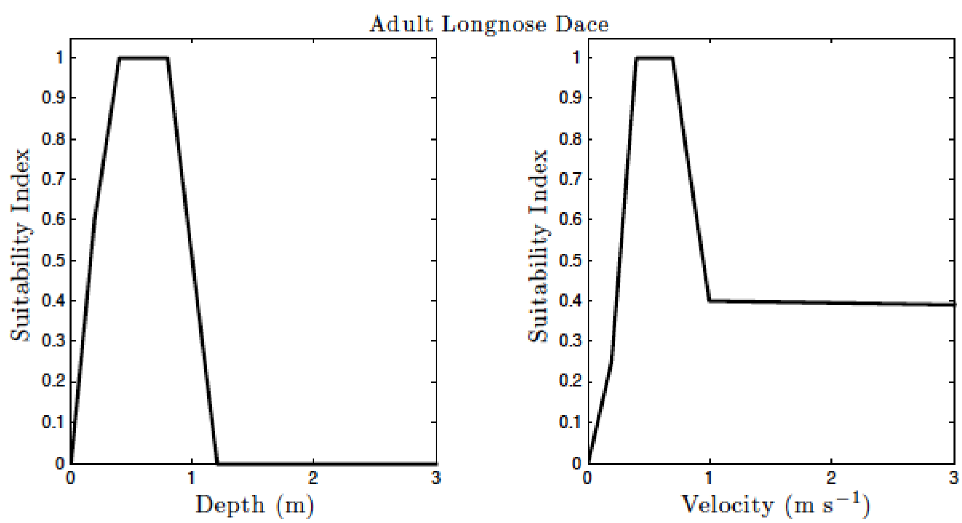

Figure A.5: USGS depth and velocity HSI for adult longnose dace

Appendix B

Relative depth and velocity distributions - Harris Creek

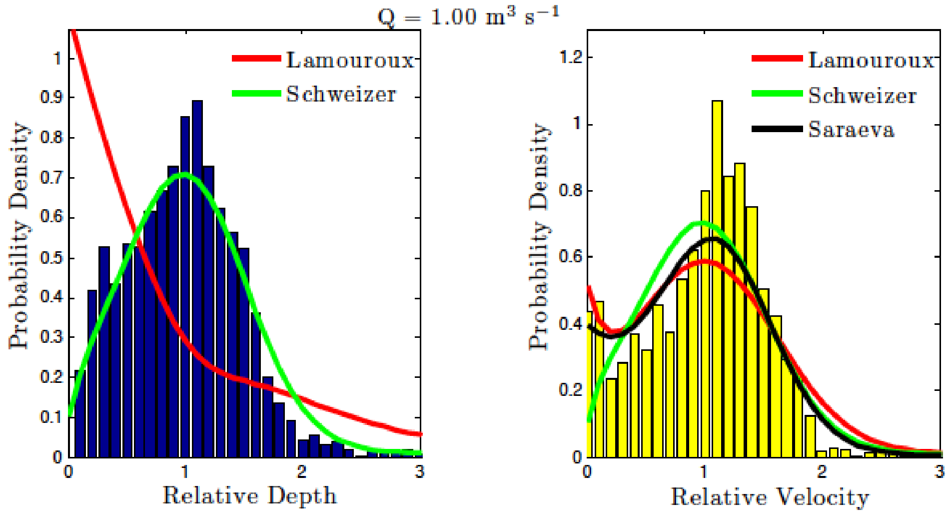

Figure B.1: Relative depth and velocity distributions for Harris Creek at Q = 1.00 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

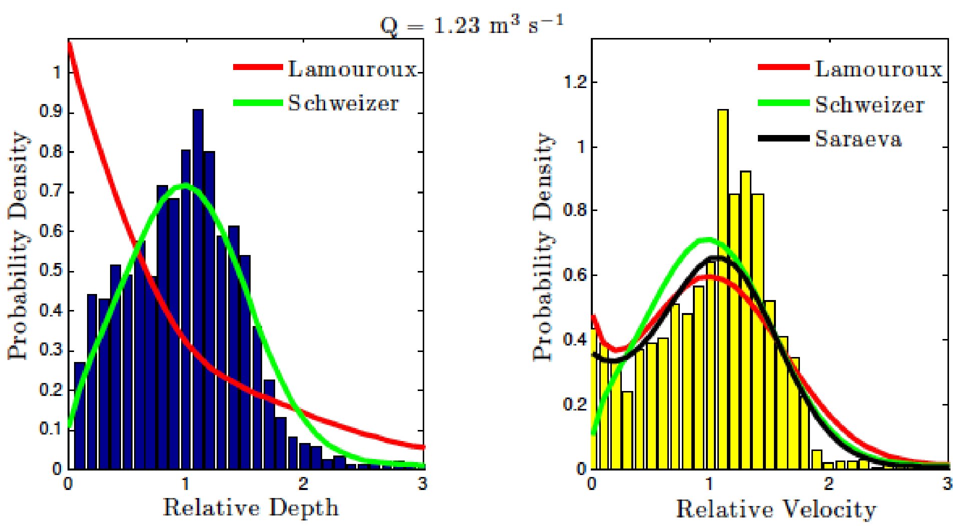

Figure B.2: Relative depth and velocity distributions for Harris Creek at Q = 1.23 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

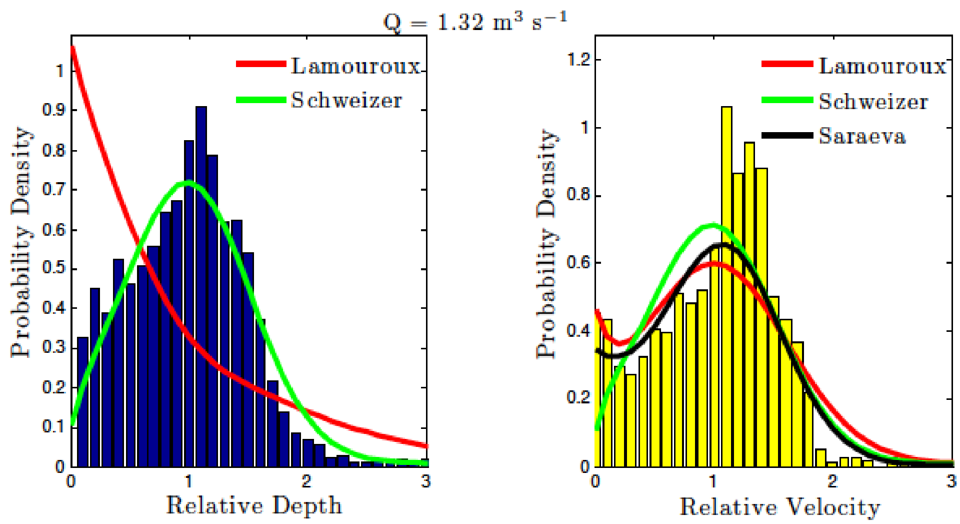

Figure B.3: Relative depth and velocity distributions for Harris Creek at Q = 1.32 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

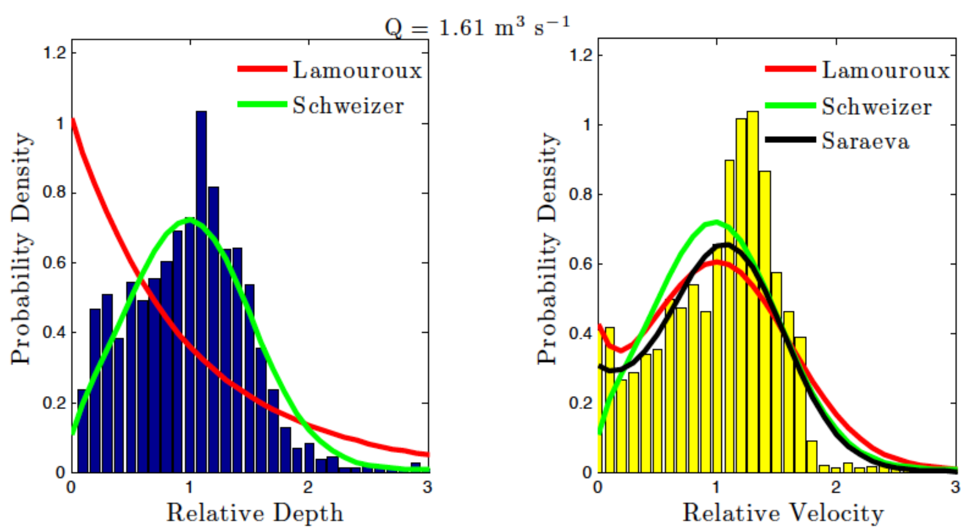

Figure B.4: Relative depth and velocity distributions for Harris Creek at Q = 1.61 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

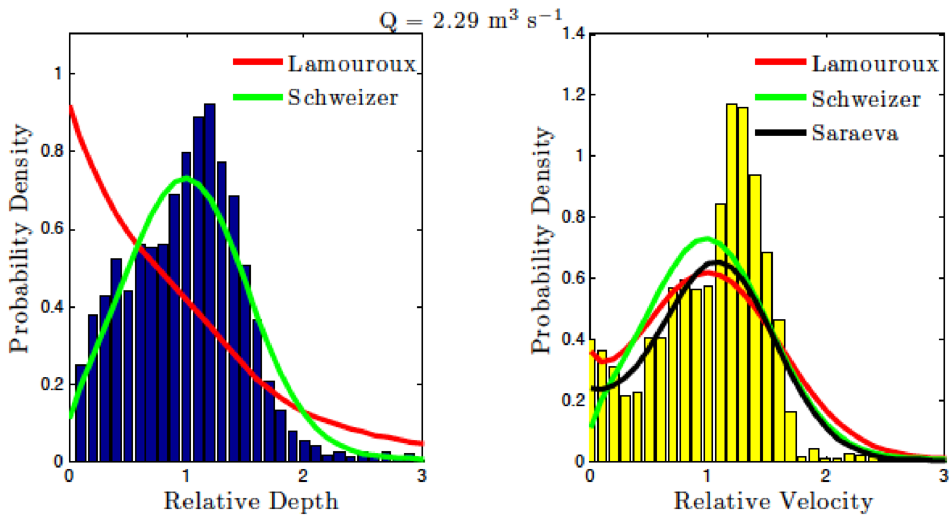

Figure B.5: Relative depth and velocity distributions for Harris Creek at Q = 2.29 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

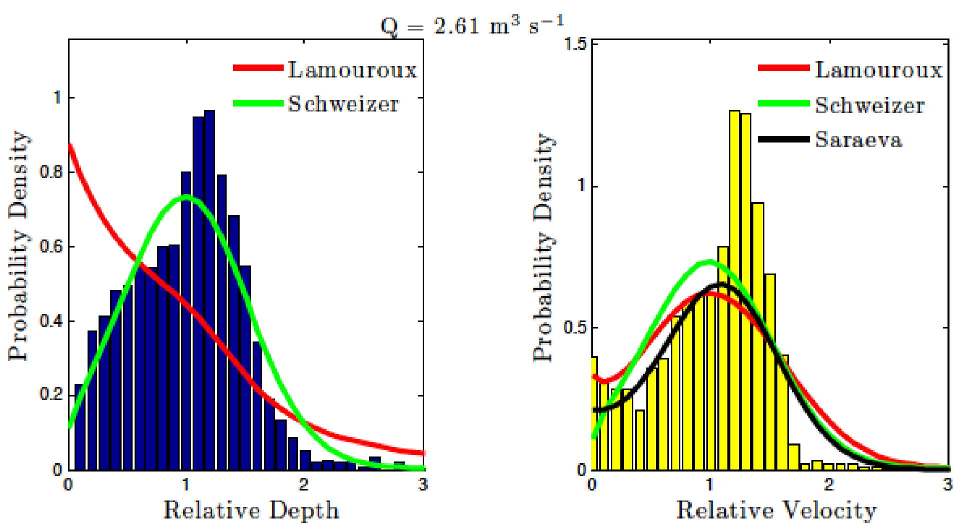

Figure B.6: Relative depth and velocity distributions for Harris Creek at Q = 2.61 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

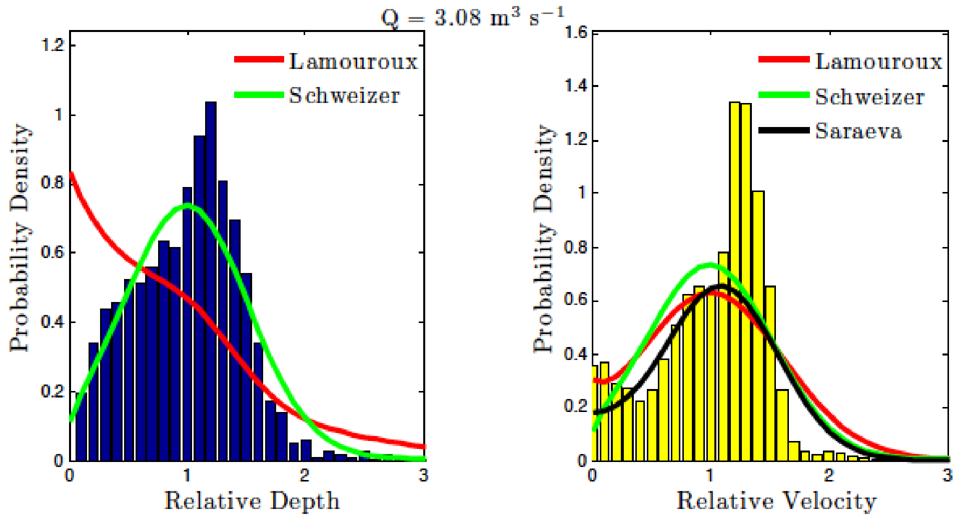

Figure B.7: Relative depth and velocity distributions for Harris Creek at Q = 3.08 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

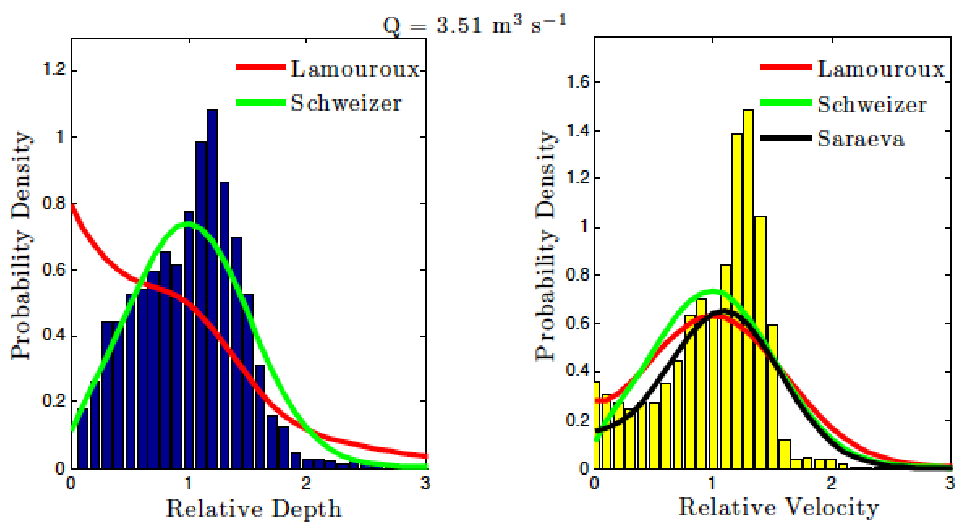

Figure B.8: Relative depth and velocity distributions for Harris Creek at Q = 3.51 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

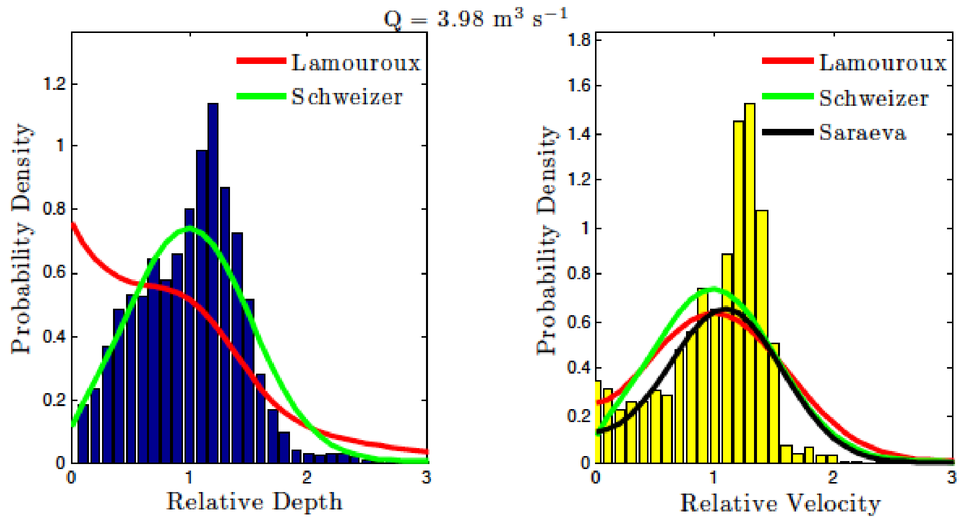

Figure B.9: Relative depth and velocity distributions for Harris Creek at Q = 3.98 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

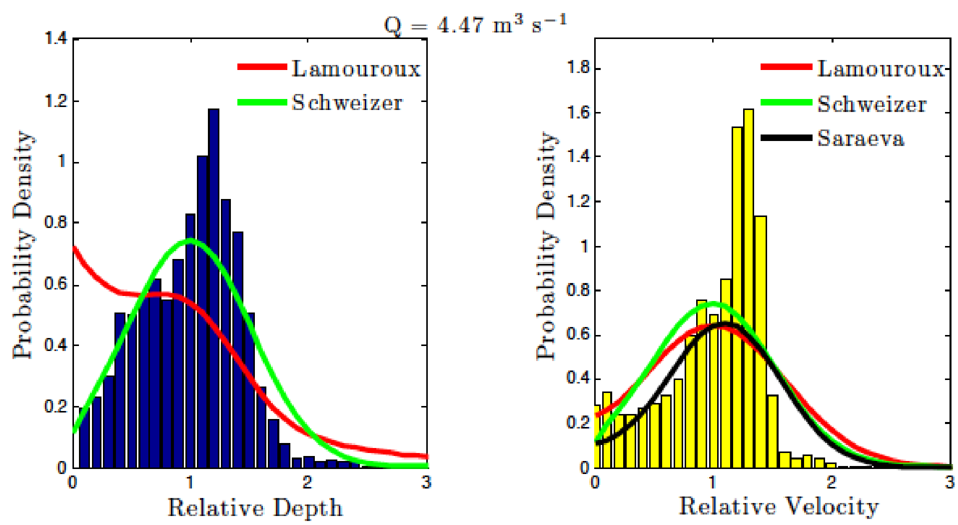

Figure B.10: Relative depth and velocity distributions for Harris Creek at Q = 4.47 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

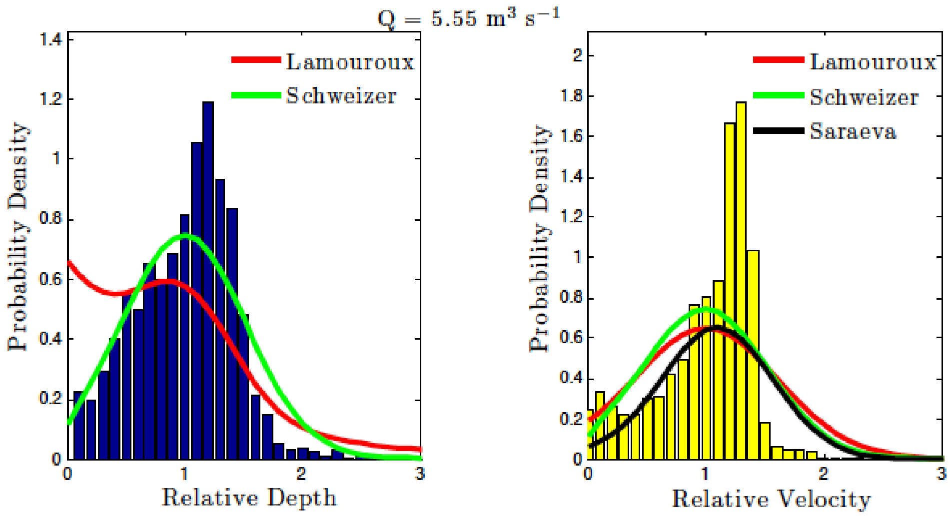

Figure B.11: Relative depth and velocity distributions for Harris Creek at Q = 5.55 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

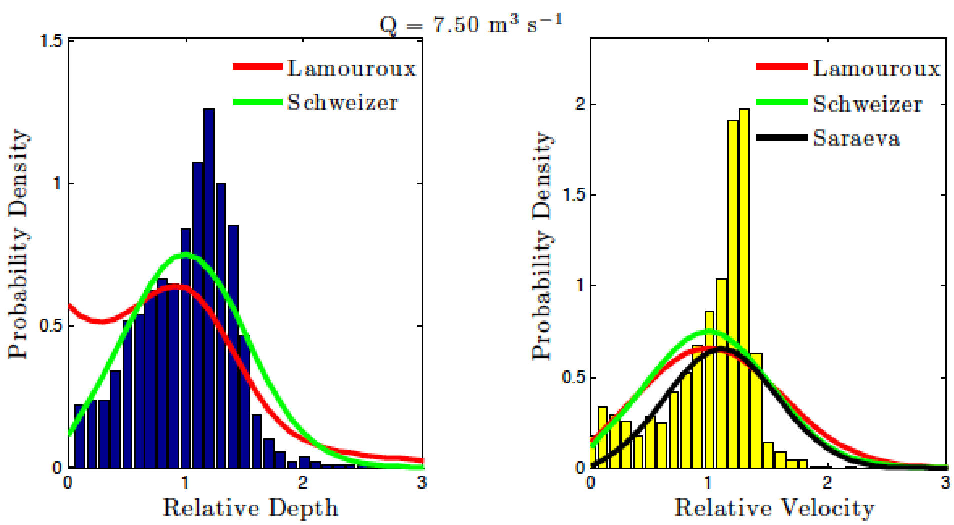

Figure B.12: Relative depth and velocity distributions for Harris Creek at Q = 7.50 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

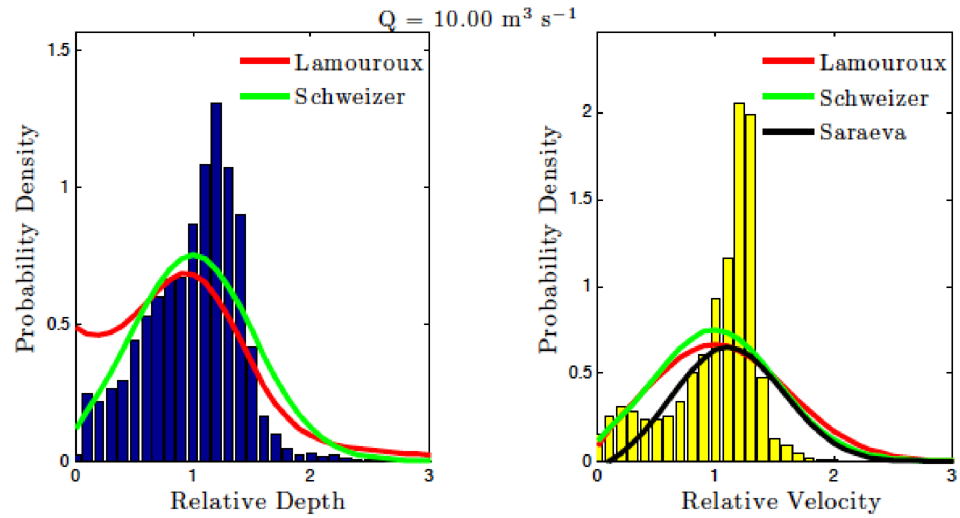

Figure B.13: Relative depth and velocity distributions for Harris Creek at Q = 10.00 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

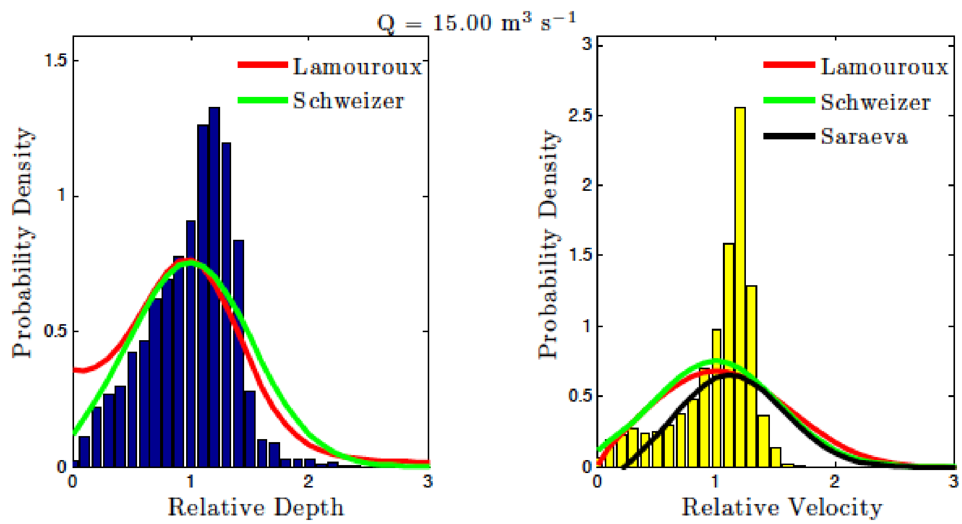

Figure B.14: Relative depth and velocity distributions for Harris Creek at Q = 15.00 m^3 s^{-1}. The bars represent distributions produced by River2D. The lines are proposed statistical distributions.

Appendix C

ASHGS habitat indices and sensitivity analyses

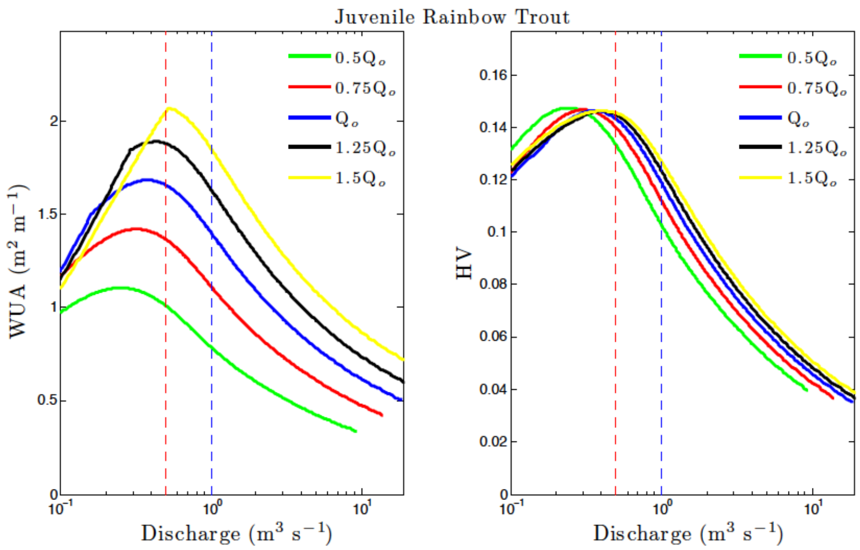

Figure C.1: Juvenile rainbow trout WUA and HV at Harris Creek across a range of potential Q_b. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

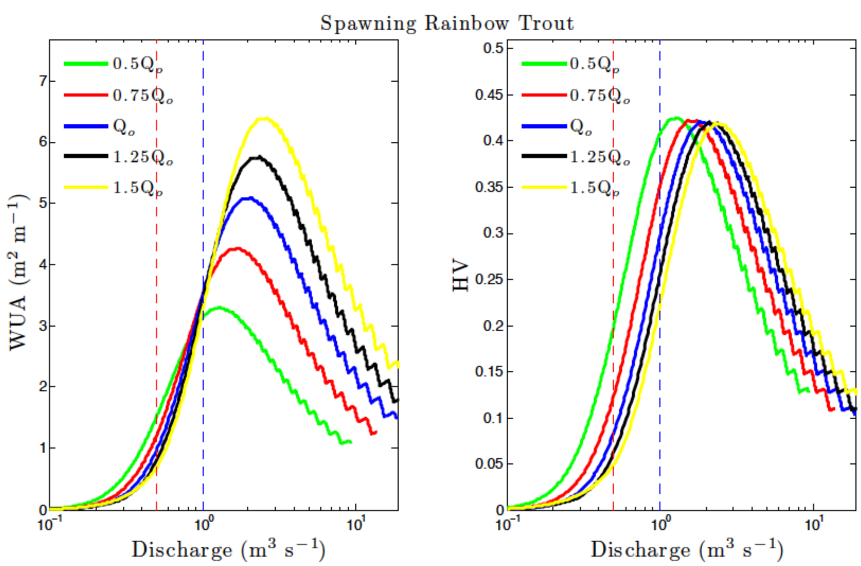

Figure C.2: Spawning rainbow trout WUA and HV at Harris Creek across a range of potential Q_b. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

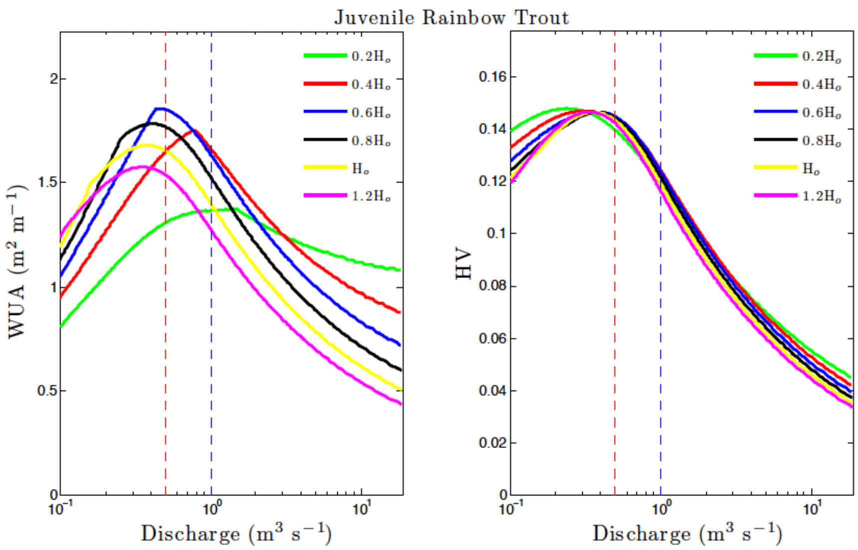

Figure C.3: Juvenile rainbow trout WUA and HV at Harris Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

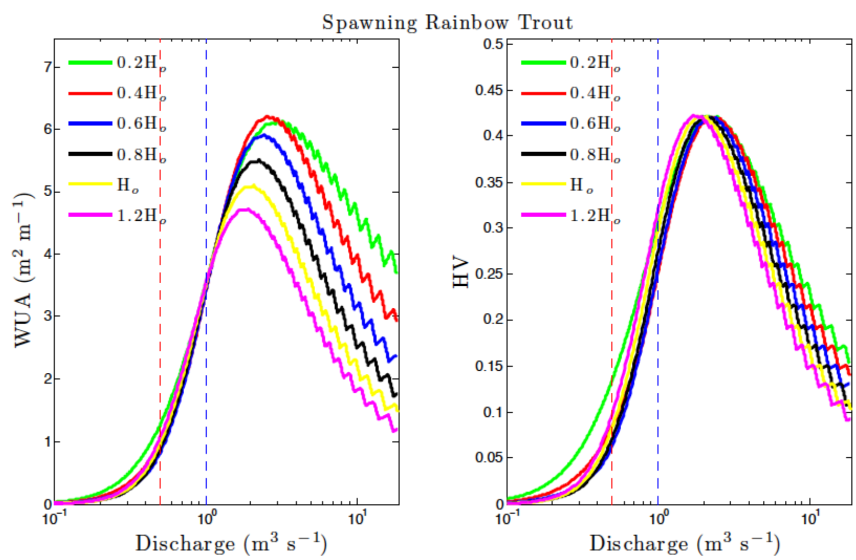

Figure C.4: Spawning rainbow trout WUA and HV at Harris Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

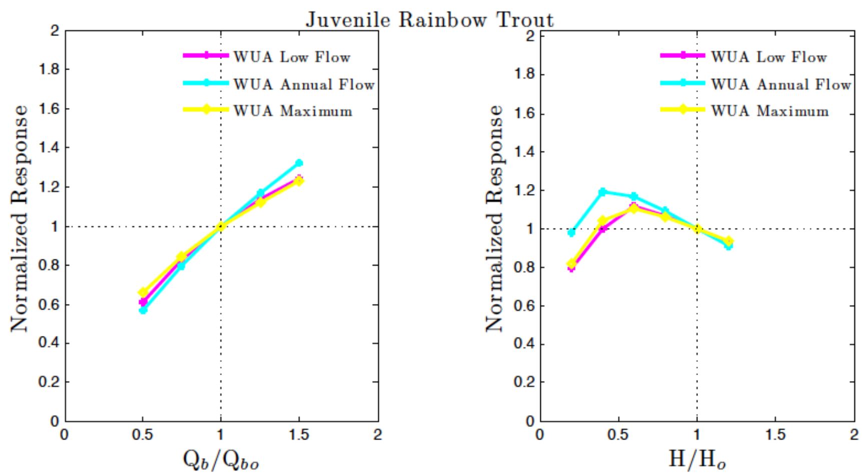

Figure C.5: Sensitivity of juvenile rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of Q_b and H.

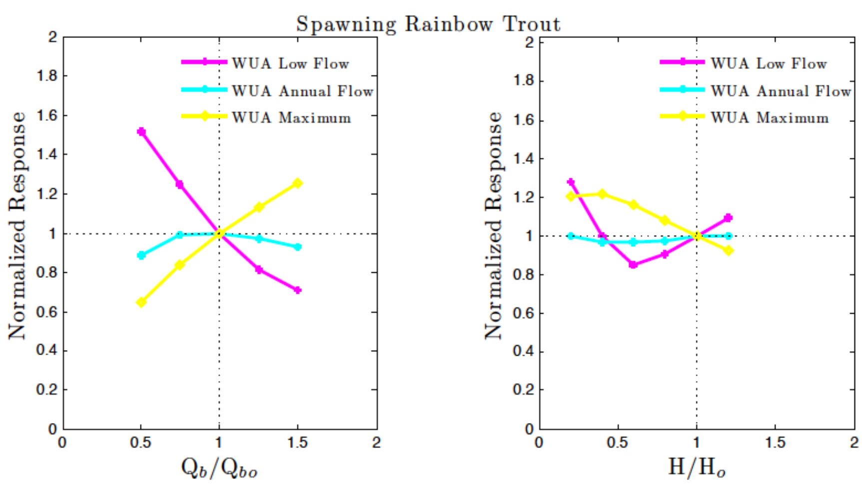

Figure C.6: Sensitivity of spawning rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of Q_b and H.

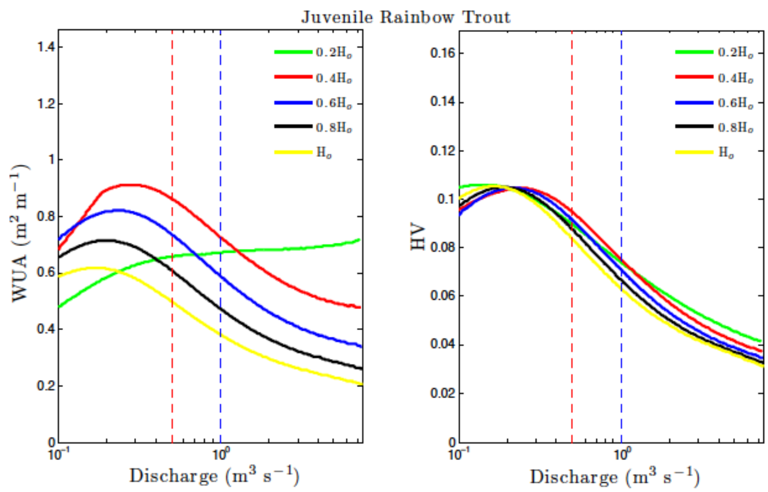

Figure C.7: Juvenile rainbow trout WUA and HV at Fishtrap Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

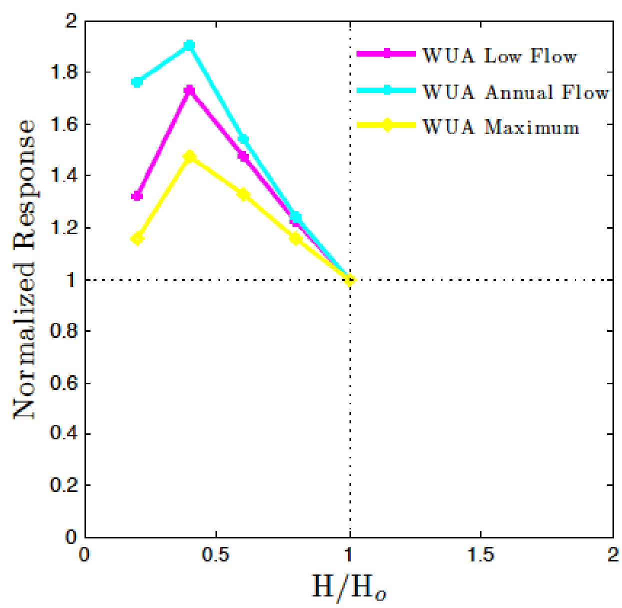

Figure C.8: Sensitivity of juvenile rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of H at Fishtrap Creek.

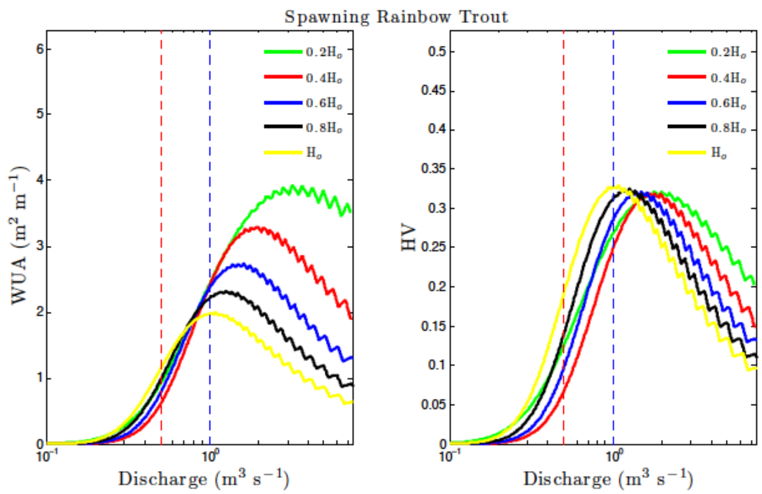

Figure C.9: Spawning rainbow trout WUA and HV at Fishtrap Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

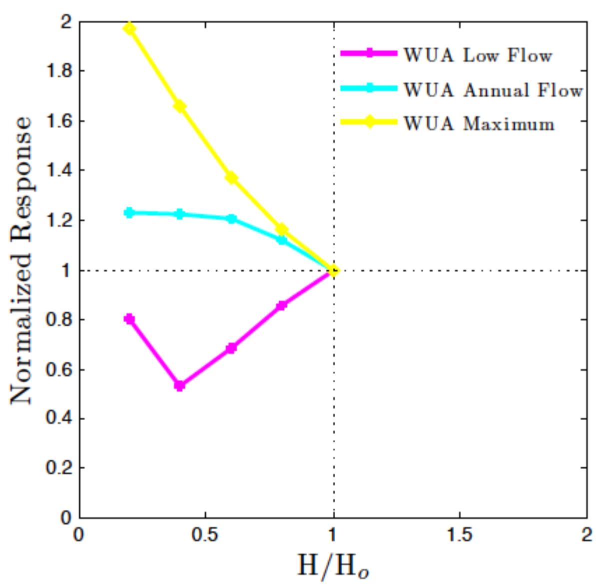

Figure C.10: Sensitivity of spawning rainbow trout WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of H at Fishtrap Creek.

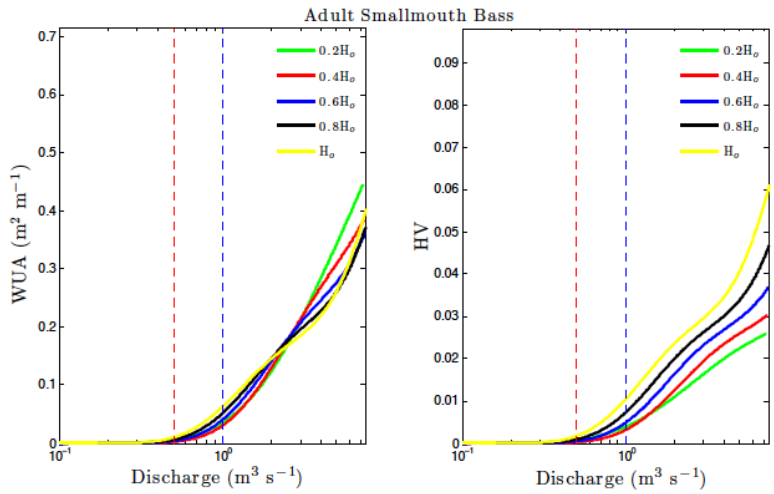

Figure C.11: Adult smallmouth bass WUA and HV at Fishtrap Creek across a range of potential H. The red and blue dash vertical lines represent minimum mean monthly flow and mean annual flow respectively.

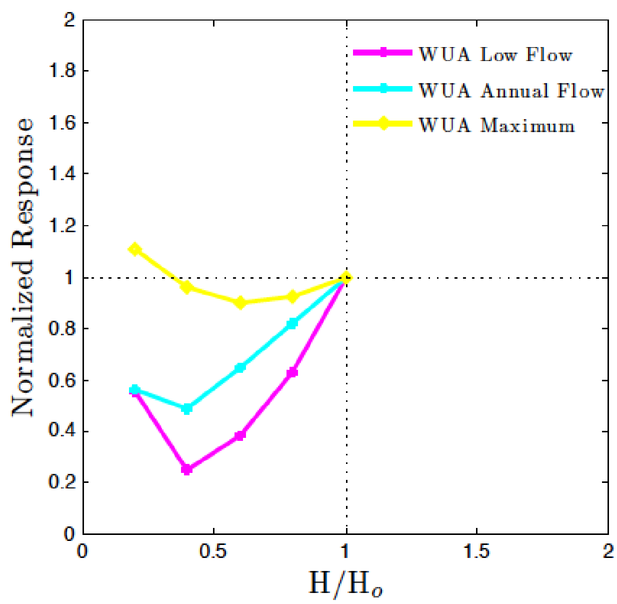

Figure C.12: Sensitivity of adult smallmouth bass WUA at minimum mean monthly flow (low flow) and mean annual flow as well as the maximum WUA for a range of H at Fishtrap Creek.