Low Stream Flows: Making Decisions in an Uncertain Climate

by

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Abstract

Water resource managers must make decisions regarding minimum instream flow requirements for rivers, despite many uncertainties. Two important uncertainties concern (1) estimates of usable fish habitat at different discharges, and (2) effects of climate change on future stream discharge. I examined the implications of these two uncertainties for the North Alouette River, British Columbia (BC). Using the British Columbia Instream Flow Methodology, which is an assessment method for water diversions needed by small-scale hydroelectric projects, I found that uncertainty in habitat preferences of rainbow trout (*Oncorhynchus mykiss*) fry generally dominated uncertainty in the results of the BCIFM when numerous transects were used. In contrast, for fewer than 15 transects, variation in physical habitat among sampled transects was the most important source of uncertainty. In addition, the increasing frequency of climate driven low-flow events suggests that operations of small-scale hydroelectric projects in BC may become more restricted in the future.

Keywords: Instream flow needs; low-flow period; fish habitat; run-of-river hydroelectric generation; climate change; small streams;

Dedication

To everyone who helped to motivate and support me

through the past two and a half years - you know who you are.

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List of Acronyms

AIC	Akaike Information Criterion
AIC_c	Akaike Information Criterion with small sample size correction
BC	British Columbia
BCIFM	British Columbia Insteam Flow Methodology
cHSI	Combined Habitat Suitability Index
CI	Confidence Interval
CV	Coefficient of Variation
ENSO	El Nino-Southern Oscillation
GCM	Global Circulation Model
HSI	Habitat Suitability Index
IFR	Instream Flow Requirement
MAD	Mean Annual Discharge
PDO	Pacific Decadal Oscillation
PHABSIM	Physical Habitat Simulation Model
PNW	Pacific Northwest
Q	Discharge
ROR	Run-Of-River
RVI	Relative Variable Importance
SD	Standard Deviation
SDU	Standard Deviation Unit
WUW	Weighted Usable Width

Chapter 1.

General Introduction

The growing competition for water resources, coupled with a greater awareness of the potential risks of discharge alterations to natural stream ecosystems, has placed pressure on resource managers to improve water management. Of particular concern to water resource managers are natural low-flow periods. During these critical periods, many components of the natural aquatic ecosystem within the stream may be stressed; hence, these periods are often assumed as limiting to productivity, especially for some fish species (Poff and Zimmerman 2010). Resource managers frequently face the difficult task of setting instream flow requirements (IFR) that allocate water during these low-flow periods to industry, agriculture, and/or development, while also meeting environmental objectives.

The stream discharge required to maintain aquatic ecosystem health has been a question of concern faced by researchers across the globe for several decades (Instream Flow Council 2002). As a result, many assessment methods have been developed to assist resource managers in determining the IFR of rivers, from simple desk-top based methods to more intensive field-based methods (Instream Flow Council 2002). However, not until recently has the uncertainty surrounding the results of any of these assessment methods been critically evaluated (e.g., Williams 1996, 2010; Ayllón et al. 2011). Understanding the uncertainty in the results of these assessment methods is important because it can help to inform decision makers about the risks associated with certain management actions. This type of informed decision making process has the potential to improve the quality of water management decisions over time (Reckhow 1994).

In Chapter 2, I explore a common water management problem in British Columbia (BC), Canada related to IRF. Management challenges related to IFR have been accentuated in recent years with the emergence of run-of-the river (ROR) hydroelectric project developments as a major component of BC's energy policy. During hydroelectric power generation, ROR facilities divert a portion of stream discharge out of a stream channel, resulting in reduced discharge in a section of the stream. During the permitting stages prior to construction of the facility, resource managers must make decisions regarding the quantity of discharge that can be diverted from the channel for hydroelectric power generation while minimizing impacts on fish and fish habitat. A common instream flow assessment method used to determine IFR for these ROR projects in BC is the British Columbia Instream Flow Methodology (BCIFM) (Lewis et al. 2004). The BCIFM is an empirical habitat-based assessment method that aims to determine IFR for aquatic biota by assessing the habitat value of a reach of stream as a function of discharge. Currently, however, decisions are often made regarding IFR by water resource managers without considering many of the uncertainties in the BCIFM.

I explored how some particularly important uncertainties in the BCIFM influence statistical confidence in the results, and how these uncertainties affect the chance of habitat loss at different discharges for rainbow trout/steelhead (*Oncorhynchus mykiss*) fry. I used a high-gradient reach of the North Alouette River, BC as a case study. I presented the uncertain results of the BCIFM in terms of probability of habitat loss for a given discharge, which can help managers set IFR based on their risk tolerance for fish-habitat loss. Finally, based on the probabilities of certain magnitudes of habitat loss, I inferred three potential IFR in the North Alouette River.

The projected rise in mean global temperature and changes in global weather patterns associated with climate change (Intergovernmental Panel on Climate Change 2007) present yet another uncertainty to water resource managers. For the Pacific Northwest of North America, global circulation models project changes in temperature, precipitation patterns and type, timing of snowmelt, quantity of snowpack and glacial runoff (Leith and Whitfield 1998; Morrison et al. 2002; Rodenuis et al. 2009; Elsner et al. 2010; Mote and Salathé 2010; Schnorbus and Rodenuis 2010; Schnorbus et al. 2011). These variables have all been linked to shifts in stream discharge hydrographs, including earlier spring runoff and prolonged summer low-flow periods (Leith and Whitfield 1998; Morrison et al. 2002; Rodenuis et al. 2009; Elsner et al. 2010; Mote and Salathé 2010; Schnorbus and Rodenuis 2010; Schnorbus et al. 2011). Anthropogenic water withdrawals during these low-flow periods may be limited in order to salvage discharge within the channel to maintain aquatic ecosystem health. Therefore, anticipating changes in stream discharge resulting from climate change will be essential for successful water resource management.

In chapter 3, I utilize a range of potential low-flow benchmarks that I identified in chapter 2 for the North Alouette River, for which there were various probabilities of *O. mykiss* fry habitat loss. I investigated how the number of days of low discharge in the North Alouette River, BC, has changed from 1970 to 2010. I analyzed trends in important weather variables including summer mean daily precipitation, summer mean daily temperature, and spring mountain snowpack during this same period. I used these three climate variables to model the number of days of low discharge each year using multiple linear regression. Finally, I used simple projections of climate variables based on historic rates of change to model trends in low discharge in the North Alouette River from 2011 to 2050 and to suggest potential implications for the feasibility of ROR hydroelectric generation as well as the health of natural stream ecosystems. These types of predictive tools should help water resource managers incorporate the potential effects of climate change into sustainable water management plans.

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Chapter 2.

Evaluating Uncertainty in the British Columbia Instream Flow Methodology in a High-Gradient Mountain Stream

Introduction

The increasing demand for water resources has resulted in alterations in the natural discharge of streams around the world, and the impacts of such discharge alterations on river biota are well documented (e.g., Richter et al., 1997; Wills et al., 2006; Dewson et al., 2007). Of particular importance is the human demand for diverted water during periods of naturally occurring low discharge. The low-flow state in streams is often recognized as a driver for changes in aquatic ecosystems (Bradford and Heinonen 2008). During low-flow periods, most stream-habitat types experience a reduction in habitat area, invertebrate production, and water quality, which can be stressful for fish and other biota (Poff and Zimmerman 2010). As a result, resource managers frequently face the difficult task of setting instream flow requirements (IFR) that meet the needs of industry, agriculture, or other human activities, while also meeting environmental objectives.

In British Columbia (BC), Canada, issues surrounding IFR were accentuated in recent years with the emergence of run-of-the river (ROR) hydroelectric project developments as a major component of British Columbia’s energy policy. ROR hydroelectric projects are unique in that they use the natural discharge and gradient of a stream to produce electricity without the construction of a major dam or reservoir (Paish 2002). A portion of the river’s discharge is diverted out-of-channel by an intake structure and into a penstock. The water is transported down-slope to a powerhouse, where the water turns turbines, generating electricity. The river water is subsequently returned to the channel downstream from the powerhouse via a tail-race, restoring natural stream discharge. Thus, the portion of the river channel between the intake structure and the tailrace, which can extend for several kilometres, experiences reduced discharge. During the permitting stages prior to construction of the facility, resource managers must make decisions regarding the quantity of discharge that can be diverted from the channel for hydroelectric power generation while minimizing impacts on fish and fish habitat.

The quantity of discharge required by aquatic biota has been a question of concern faced by researchers across the globe for several decades (Instream Flow Council 2002). As a result, many methods have been developed to assist resource managers with setting IFR. Early methods included simple desk-top exercises that based IFR on river characteristics, such as a percentage of the river's mean annual discharge (MAD) (e.g., Tennant's method - Tennant 1976). More recently, habitat-based methods, such as the physical habitat simulation model, PHABSIM (Bovee et al. 1998), or the British Columbia Instream Flow Methodology (BCIFM) (Lewis et al. 2004), have been used to assess the habitat value of a reach of stream as a function of discharge. In general, these models predict the available habitat for a species of interest within the stream from physical properties including water depth, velocity, bed material grain-size, and sometimes cover type and abundance, each of them collected at transects on the study stream. The transect data are weighted by biological models, or habitat suitability indices (HSI), which describe the preferences, between 0 and 1, of the fish in terms of the physical habitat variables (Williams 1996). Estimates of available habitat are either measured or predicted at various discharges; these estimates can be fit with a curve to characterize the change in available habitat with change in discharge, referred to here as the habitat-flow relation.

Although PHABSIM is one of the most widely used instream flow assessment methods (Ayllon et al, 2011), provincial instream flow guidelines in BC recommend the use of the BCIFM as a primary assessment method for water diversion projects such as small hydropower developments (Lewis et al. 2004). This empirical, habitat-based assessment method is similar to PHABSIM in that it uses physical habitat data from multiple transects to estimate a habitat-flow relation based on habitat preferences of target organisms. However, instead of using a hydraulic model to estimate the physical habitat conditions along a reach of a river, as in PHABSIM, the BCIFM requires field measurements of physical habitat variables from multiple transects at multiple discharges to produce an empirical estimate of a habitat-flow relation.

However, like PHABSIM, the BCIFM was developed without an explicit method for accounting for uncertainties in the analysis. It is now recognized that uncertainties in such habitat-based instream flow studies are large and ubiquitous (Williams 1996, 2010, Ayllón et al. 2011). Measurement error, variation in physical habitat variables among transects and different discharge levels, uncertainties in HSI curves of a given species, and inaccuracies in hydraulic models all contribute to uncertainty in the results of habitat-based instream flow assessment methods (Williams 1996). Using PHABSIM and variant models, researchers have begun to examine how incorporating uncertainty in HSI curves affects the resulting habitat-flow relation (Ahmadi-Nedushan et al. 2008; Mouton et al. 2008, 2011; Fukuda 2009, Ayllón et al. 2011). Others have explored how the variation among, and the number of, transects affects the uncertainty in the habitat-flow relation produced by PHABSIM (Williams 1996, 2010; Ayllón et al. 2011). However, these two important sources of uncertainty have yet to be rigorously explored using the BCIFM. This is the gap that my research aims to fill.

For many instream assessment projects, budgets or time may be limiting. Therefore, it is important to understand where the largest uncertainties lie in order to set priorities for sampling efforts. Efforts can be divided between the collection of HSI data and transect data. Often, these budget/time limitations may restrict the number of transects used in the analysis. Therefore, it is important to understand how the accuracy of estimates increases with the number of transects used in the analysis. In addition, data for developing HSI curves specific to individual streams may not be collected because of these budget/time limitations, forcing instream flow practitioners to choose between multiple pre-existing sets of HSI curves to conduct the analysis for a given species. Often there is considerable variation among these pre-existing sets of HSIs that potentially produce different outcomes in the habitat-flow relation (Williams et al. 1999). This uncertainty in the choice of HSI curves presents another unresolved uncertainty in habitat-based instream flow assessment methods that is important to consider when setting sampling effort priorities.

Because habitat-flow relations are used directly by water resource managers to infer IFR of streams, both Williams (1996) and Hatfield et al. (2007) insist that statistical confidence intervals be presented on these habitat-flow relations. To aid in the interpretation of these confidence intervals, the uncertainty in the habitat-flow relation should be presented in a manner in which managers can choose IFR based on the probability of habitat loss. In doing so, managers can make decisions informed by their risk tolerance.

Therefore, I had four main research objectives: (1) explore how uncertainty in choice of fish HSI curves affects uncertainty in the resulting habitat-flow relation produced by the BCIFM; (2) examine how the level of uncertainty in the habitat-flow relation is affected by variation in physical habitat among the sampled transects, and how that variation changes with the number of transects; (3) demonstrate the relative contribution of each of these two sources of uncertainty to the total uncertainty in the habitat-flow relation; and (4) show how the uncertainty in the habitat-flow relation translates into uncertainty about habitat loss for a given discharge. These results can be used to explore, and communicate to managers, the uncertainty in the habitat-flow relation produced by the BCIFM.

Methods

Field Site

The North Alouette River (49°15’50”N, 122°34’00”W) flows out of the Golden Ears mountain range and drains into the Pitt River near the town of Maple Ridge, British Columbia, Canada (Figure 1.1). The watershed is located within the coastal temperate rainforest region, which is characterized by dry summers with low discharge and wet winters with heavy rainfall events that cause sporadic high discharge. My study site was located directly above a waterfall complex, within the University of British Columbia Malcolm Knapp Research Forest approximately 15 km upstream from the confluence with the Pitt River.

The North Alouette River has a total drainage area of 37.3 km^2 with a mean annual discharge of 2.8 m^3s^{-1} (Environment Canada 2011). The channel of the study reach was high-gradient (2.0-3.1%), with an average channel width of 18.6 m. The study reach was dominated by boulder, cobble, and gravel bed material with a D_{50} and D_{90} bed material grain size ranging from 130-180 mm and 400-430 mm respectively (obtained using Wolman pebble counts; Kondolf 1997). The study reach was exclusively composed of plane bed alluvial channel type (Montgomery and Buffington 1997) with riffle-run mesohabitat type (Maddock 1999). A waterfall complex downstream of the study site prevents the upstream migration of anadromous salmonids into the study reach. However, rainbow trout (*Oncorhynchus mykiss*) and cutthroat trout (*O. clarkii*) were introduced into the system in the mid-19th century and currently inhabit the reach (Mathes and Hinch 2009).

Physical Habitat Data

I collected physical habitat data from the North Alouette River on 5 dates during the summer and fall of 2010. I established two sets of 10 cross-stream transects (n=20). The first set of transects was systematically spaced 10 m apart from random starting points. The second set of transects was identical but was located approximately 250 m upstream from the first set. Transects were placed perpendicular to the stream flow and marked either with 1-m rebar stakes pounded into the river bed or 15-cm metal spikes tacked into trees adjacent to the stream bank. Measurements of river physical habitat (depth, velocity, width, and bed-material grain size) were collected at 0.5-m increments along each transect, as outlined in the BCIFM (Lewis et al. 2004). Depth and velocity measurements were collected using a wading rod and Marsh-McBirney Flo-Mate™. River discharge was calculated each day that physical data were collected from a designated transect as outlined in Resources Information Standards Committee (2009). The discharges sampled were: 0.13, 0.28, 0.55, 1.46, and 1.79 m^3s^{-1}. I calculated the mean annual discharge (MAD) from 40 years of mean daily discharge data from a Water Survey of Canada gauging station approximately 3 km downstream of the study reach (Environment Canada 2011).

Habitat Preference Data

In order to describe uncertainty in habitat preferences of an aquatic organism, I compiled results from several studies of habitat suitability indices (HSI) for *O. mykiss* fry in North America. In total, five sets of HSI curves for depth and velocity were gathered (Figure 1.2). To simplify the analysis, uncertainty in habitat preferences for bed-material grain size was not considered; instead I used a universal set of bed-material preferences for *O. mykiss* fry (Figure 1.3).

Habitat-Flow Relation

Physical habitat data and HSI information were combined to produce a metric of availability of habitat for *O. mykiss* fry, weighted usable width (WUW) (Lewis et al. 2004) at each transect at each discharge as:

$$WUW = \sum_{i=1}^{n} (w_i \times dHSI_i \times vHSI_i \times sHSI_i) \quad , \qquad (1)$$

where the WUW of each transect is the sum of the WUW of all *n* cells. The WUW of each cell, *i*, is calculated as its width *(w_i)* multiplied by its suitability of depth *($dHSI_i$)*, velocity *($vHSI_i$)*, and substrate size *($sHSI_i$)*.

The habitat-flow relation was estimated for the study reach by fitting a log-normal function with a multiplicative scalar to the WUW vs. discharge data. This log-normal form is typical of habitat-flow relations (Lewis et al. 2004). The reach average WUW was thus calculated as:

$$WUW = A \times \frac{1}{Q\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln Q - \mu)^2}{2\sigma^2}} \quad , \qquad (2)$$

where the WUW is a function of discharge (Q), a scalar (A), a location parameter (μ) and a scale parameter (*σ*). The log-normal function was fit to WUW-discharge data using a least-squares optimizing function in R (R Development Core Team 2008).

Fitting the habitat-flow relation with this log-normal function allowed me to solve for important management parameters in the study reach. These parameters were (1) the maximum WUW, which was the maximum amount of habitat available at the peak of the habitat-flow relation, (2) the optimal discharge, which is the discharge at which the maximum WUW occurs, and (3) the discharges at which different percentages of habitat loss occurred on the ascending limb of the habitat-flow relation relative to the maximum

WUW. All management parameters were calculated numerically using a maximum optimizing function in R (R Development Core Team 2008).

HSI Uncertainty

I first evaluated the effect of the choice of HSI set on the resulting habitat-flow relation from the BCIFM and the corresponding management parameters. Habitat-flow relations were generated and management parameters were calculated for each of the five different sets of HSI curves for depth and velocity using physical habitat data from the 20 transects at five discharge values.

As an alternative to selecting a single set of HSI depth and velocity curves, I combined the 5 sets of HSI curves into single curves for depth and velocity, under the assumption that each of the 5 sets of HSI curves (Figure 1.2) were equally likely. These combined HSI curves for depth and velocity, denoted as cHSI, were calculated by dividing the 5 individual curves into intervals of 0.01 $m \cdot s^{-1}$ for velocity and 0.01 m for depth. The habitat preference for depth and velocity at each interval was calculated by randomly sampling the five habitat preference values from my set of HSI curves with replacement and calculating the mean value of the sample. This process was repeated 1000 times. Uncertainty in cHSI curves was expressed as the median, 2.5 and 97.5% quantiles of the bootstrap samples for each interval. A sixth habitat-flow relation (cHSI) was generated from the resulting medians for each interval.

To evaluate the uncertainty in the habitat-flow relation resulting from uncertainty in the cHSI curves, I generated a habitat-flow relation from each bootstrap sample of the combined HSI curves for depth and velocity (Figure 1.4). This resulted in the generation of 1000 habitat-flow relations and corresponding management parameters for which the median, empirical 95% confidence interval (CI), and coefficient of variation (CV) were calculated.

Physical Habitat Uncertainty

As an indication of variability in physical habitat between sampled transects, I plotted the relation between river discharge and channel width, mean depth, and mean velocity among the 20 sampled transects in the North Alouette River. The relations for individual transects were fit with power functions according to rules of at-a-station hydraulic geometry (Leopold 1953).

I used a bootstrap analysis (Efron and Tibshirani 1993) to develop uncertainty bounds on the habitat-flow relation resulting from the variability in physical habitat among transects (Figure 1.4). I calculated available habitat at each transect at each discharge by fixing the HSI curves as the median of the cHSI curves for depth and velocity. I assumed that each transect could be treated as an independent sample of stream habitat. For each bootstrap iteration, 20 transects were randomly sampled with replacement. WUW was calculated for each of the bootstrap samples, a habitat-flow relation was generated, and management parameters were calculated. This process was repeated 1000 times. Again, the median, empirical 95% CI, and CV of the resulting management parameters from those 1000 bootstrap samples were calculated.

In addition, the uncertainty in the habitat-flow relation resulting from physical habitat variability among transects was assessed as a function of the number of transects used in the analysis. The sample size of the randomly drawn transects was reduced incrementally from 20 to 3 in separate analyses. For each sample size, transects were randomly sampled with replacement. WUW was calculated for each of the bootstrap samples, a habitat-flow relation was generated, and management parameters were calculated. This process was repeated 1000 times for each increment in transect sample size. The median, empirical 95% CI, and CV of the resulting management parameters were calculated.

Combined Uncertainty

I used another bootstrap analysis to develop uncertainty bounds on the habitat-flow relation resulting from the combination of uncertainty in the estimate of the cHSI curve and transect variability (Figure 1.4). For each bootstrap sample, 20 transects were randomly sampled with replacement. For each of those 20 transects, WUW was calculated at each discharge level using a set of HSI curves randomly sampled from the cHSI curves. A habitat-flow relation was generated and management parameters were calculated. This entire process was repeated 1000 times and the median, empirical 95% CI, and CVs of the resulting management parameters were calculated.

Habitat Loss

Using the habitat-flow relations produced from the analysis that incorporated the combination of uncertainty in the estimate of the cHSI curve and variability in physical habitat among transect, I calculated both the percent habitat loss (median and 95% CI) and the probability of a particular magnitude (0, 5, 10, and 25%) of habitat loss occurring as a function of discharge. I defined habitat loss as the percent decrease in WUW relative to the maximum WUW. Habitat loss was only considered on the ascending limb of the habitat-flow relation because habitat losses occurring from high discharges were of little concern when considering minimum discharge requirements for a stream.

Results

HSI Uncertainty

In the study reach of the North Alouette River, the use of different sets of HSI curves for depth and velocity for *O. mykiss* fry (Figure 1.2) produced substantially different habitat-flow relations (Figure 1.5). Management parameters calculated from each of the habitat-flow relations reflected those differences (Table 1.1).

Uncertainty in habitat preferences by *O. mykiss* fry, as reflected by uncertainty in the estimate of the cHSI curve (Figure 1.6), resulted in substantial uncertainty in the habitat-flow relation (Figure 1.7A). This uncertainty was reflected in both the maximum weighted useable width (WUW) and the optimal discharge (Table 1.2).

Physical Habitat Uncertainty

Variability in the relation between river discharge and channel width, mean depth, and mean velocity among the 20 sampled transects in the North Alouette River is shown in Figure 1.8. Although substantial, variation among sampled transects through the BCIFM generated less uncertainty about the shape of the habitat-flow relation than did the choice of HSI curve (Figure 1.7B). For this effect of transect alone, uncertainty was greater for the optimal discharge parameter than the maximum WUW parameter (Table 1.2). However, when the number of transects used in the analysis was reduced from 20, the magnitude of uncertainty about both parameters increased at an accelerating rate

(Table 1.3). In particular, when small numbers of transects were used in the analysis (<15), variability among those transects resulted in substantial uncertainty in estimates of the optimal discharge parameter.

Combined uncertainty

When both variability in physical habitat among sampled transects and uncertainty in the estimated cHSI curves were combined, the uncertainty in the habitat-flow relation increased in an additive manner compared to when either source of variability was incorporated independently (Figure 1.7C). This additive increase in uncertainty about the habitat-flow relation was reflected in the CVs of management parameters (Table 1.2).

Habitat Loss

Habitat loss, as calculated from the habitat-flow relation that incorporated the combination of both variability in physical habitat among sampled transects and uncertainty in the estimated cHSI curves, increased non-linearly with decreasing discharge values (Figure 1.9). At discharge values of below approximately 0.45 m^3s^{-1}, it was highly likely that at least some habitat loss will occur for *O. mykiss* fry, and the percent habitat loss increased at an accelerating rate with decreasing discharge.

In addition, I calculated the probability of different magnitudes of habitat loss as a function of discharge (Figure 1.10). The probability of a given magnitude of habitat loss increased nonlinearly with decreasing discharge values. This nonlinear increase resulted in threshold discharge values for each magnitude of habitat loss at which the probability of that habitat loss began to increase dramatically as discharge decreased. A 0% habitat loss is equivalent to the optimal discharge from the habitat-flow relation; therefore, this line in Figure 1.10 can be interpreted as the probability that *any* habitat loss will occur. For example, at a discharge of 0.45 m^3s^{-1}, there is a probability of approximately 0.95 that less than 5% habitat loss will occur. For larger magnitude losses (5-25%), the figure can be interpreted as the probability that the given magnitude of habitat loss will occur. For example, at a discharge of 0.25 m^3s^{-1}, there is a probability of approximately 0.05 that a 25% habitat loss will occur but >95% chance that a 10% loss will occur.

Discussion

Evaluating Uncertainty

I found that both variability among transect samples and uncertainty in habitat preference data were important when generating a habitat-flow relation using the British Columbia Instream Flow Methodology (BCIFM). Further, I estimated the relative importance of each source of uncertainty. The uncertainty from the HSI curves is very important when large numbers of transects are used in the analysis; however, when small numbers of transect are used (<15), the variation in physical habitat among transects becomes a dominant source of uncertainty in the analysis, particularly in estimates of the optimal discharge. This information is important to instream flow practitioners who are limited by budget/time constraints and who must strategically focus sampling efforts. One novel aspect of this work is how I interpret uncertainty in the habitat-flow relation. Specifically, I express results of the BCIFM in terms of probability of different magnitudes of habitat loss. Such probabilities can be used by decision makers to set instream flow requirements (IFR) based on their individual risk tolerance for habitat loss.

In this study, I simulated a scenario in which instream flow practitioners may be forced to choose among multiple pre-existing sets of HSI curves because budget or time limitations do not allow them to develop location-specific curves. As an example, I collected five sets of curves describing *O. mykiss* fry depth and velocity preferences that contained considerable variation among results (Figure 1.2). In general, the most pronounced differences in the HSI curves were habitat preferences for higher velocities. Some curves suggest that fry begin to lose preference for water velocities greater than 0.1 $m \cdot s^{-1}$ (e.g., HSI curve-B and C), whereas other curves suggest preferences do not drop until water velocities reach greater than 0.45 $m \cdot s^{-1}$ (e.g., HSI curve-C). In addition, curves varied greatly in preferences of fry for different water depths. Some curves show substantially higher preferences for deeper water (e.g., HSI curves C and D), whereas others show higher preferences for shallow water (e.g., HSI curves A and D).

This variation among sets of HSI curves for *O. mykiss* fry may be attributed to several factors. The methods used to generate the HSI curves vary between studies, from field data collection to expert-opinion-driven processes. In addition, variation among HSI curves can result from natural variability in habitat preferences of *O. mykiss* fry (Williams et al. 1999). Genetic variability among isolated populations of the same species may result in variability in habitat-preferences because of behavioural adaptation to local conditions. Alternatively, variability in habitat preferences for depth and velocity can result from fluctuations in other physical variables such as discharge (Beecher et al. 1995), season (Yu and Peters 2002), light intensity (Rowe and Chisnall 1995, Metcalfe et al. 1997), temperature (Rowe and Chisnall 1995), and dissolved oxygen (Kramer 1987, Rowe and Chisnall 1995).

Regardless of the source of variation among the different sets of depth and velocity HSI curves, I found that the use of these different sets of HSI curves had a large influence on the habitat-flow relation, which could have serious management implications. In general, velocity preferences of *O. mykiss* fry played a more pronounced role in determining the maximum WUW and optimal discharge than did depth preferences in the North Alouette River because water velocities often exceeded preferences, whereas water depths did not (Figure 1.2 and 1.8). As a result, those sets of HSI curves that contained higher habitat preferences for low water velocities tended to produce habitat-flow relations with a lower maximum WUW and optimal discharge. Such sets of HSI curves will result in IFR curves biased towards lower discharge values, which could potentially put fish habitat at risk of loss if the HSI curves were incorrect. It is important to note, however, that in slower moving, deeper rivers, depth preferences may be more important than velocity preferences. In such rivers, HSI curves with higher preferences for low water depths may result in IFR choices biased towards lower-than-ideal discharge values for the protection of aquatic habitat.

As an alternative to choosing a single set of HSI curves and producing potentially biased results, I explored a method that produced combined HSI (cHSI) curves for depth and velocity. This method allowed me to incorporate variation among the pre-existing sets of HSI curves into the estimates of the habitat-flow relation through the BCIFM. In this example, because I had no basis to prefer one curve over another, I assumed each competing curve was equally likely. Other weighting schemes could be used if there was reason to choose or prefer one or some over others. In addition, other methods exist to quantify the uncertainty in habitat preferences of organisms on a regional or local scale, such as uncertainty bounds of univariate resource selection functions (Ayllón et al.(2011), expert opinion (Johnson and Gillingham 2004), and fuzzy logic (Burgman 2001; Ahmadi-Nedushan et al. 2008; Mouton et al. 2008 and 2011; Fukuda 2009).

Incorporation of the uncertainty in the estimated cHSI curves alone through the BCIFM resulted in considerable uncertainty in the habitat-flow relation, which translated into substantial uncertainty in estimates of the management parameters, particularly in the maximum WUW parameter. The large amount of uncertainty about the upper tolerance limits of the cHSI curves for depth and velocity (e.g., where habitat preference scores fall below 0.5) likely resulted in the large uncertainty in the habitat-flow relation. Small differences in depth and velocity preferences around these upper tolerance limits substantially changed the amount of available habitat in the study reach because those upper tolerances for both depth and velocity were often exceeded in some portions of the river, even at low discharges.

When the full set of 20 transects was used in the analysis, variability in physical habitat among transects translated into relatively little uncertainty in the maximum WUW parameter and roughly equal uncertainty in the optimal discharge compared to that arising from the uncertainty in the estimated cHSI curves. The manner in which the physical habitat (depth, velocity, and width) of a transect changes with discharge, also known as the at-a-station hydraulic geometry (Leopold 1953), governs the shape of the habitat-flow relation in conjunction with the habitat preferences of the organism. Because of the relatively homogenous river morphology over the study reach of the North Alouette River, the at-a-station hydraulic geometry remained fairly constant among transects. Rivers with more variable morphology (i.e., riffle-pool sequences) and bed-material grain size will have more variable at-a-station hydraulic geometry and thus transect data will be more variable. This increased variability will result in more uncertainty in the habitat-flow relations, especially in optimal discharge estimates.

Variability in management parameters from the habitat-flow relation increased nonlinearly as the number of transects used in the analysis decreased (Table 1.3). Both variability in the maximum WUW and the optimal discharge did not increase dramatically when reducing the number of transects from 20 to 15. However, for fewer transects than 15, uncertainty increased substantially and was a dominant source of uncertainty in the analysis, particularly in the estimates of optimal discharge. This result suggests that, for streams with similar characteristics to the North Alouette River, a minimum of 15 transects should be used to minimize variability in transect data when conducting a BCIFM analysis. However, for more than 15 transects, the increase in information (decrease in variability) is not likely worth the effort of collecting the physical habitat data in reaches with homogeneous morphology and bed material grain-size. This number is on the lower end of the 15-20 transects suggested in the literature to be used to capture the full variability of rivers and produce a meaningful habitat-flow relation using PHABSIM (Williams 1996; Thomas et al. 2004). It is likely that because of the lack of heterogeneity in the river morphology of the North Alouette River, a smaller number of transects was needed to sufficiently capture the variability in physical habitat.

Habitat Loss

Uncertainty in the habitat-flow relation can be interpreted by investigating the percent habitat-loss and the probability of certain magnitudes of habitat-loss occurring as a function of discharge. Calculating the percent habitat loss (with 95% empirical confidence intervals) will allow managers to analyse where habitat loss is likely to occur. In the North Alouette River, discharge levels below 0.45 m^3s^{-1} likely result in loss of habitat to *O. mykiss* fry relative to the optimal discharge, and the percent habitat loss increases at an accelerating rate with decreasing discharges below that value (Figure 1.9). Calculating the probability of different magnitudes of habitat loss as a function of discharge allows managers to target a specific discharge value based on an acceptable probability for a given magnitude of habitat loss occurring (Figure 1.10). In addition, threshold discharge values become evident where the probability of a particular magnitude of habitat loss increases rapidly with decreasing discharge values. These threshold discharge values could be relevant because water resource managers could use them as cut-off points to define discharge levels to be avoided because of their undesirable magnitudes of habitat loss. For example, if a manager desired to have less than a 5% loss of *O. mykiss* fry habitat in the North Alouette River, he or she would recommend an instream flow requirement of at least 0.45 m^3s^{-1}, at which there is a probability of 0.95 of having less than 5% habitat loss. In contrast, if a manager was willing to take a chance of losing some habitat but wanted to avoid large magnitudes of habitat loss to *O. mykiss* fry habitat, an instream flow requirement of at least 0.25 m^3s^{-1}

would be advised, where there is a probability of approximately 0.05 that a 25% habitat loss will occur.

Conclusion

Understanding the relative contributions of uncertainty to the results of the BCIFM is important in order to set priorities for sampling efforts. If budgets/time are limiting, my results suggested that priority should be taken to collect physical habitat data from at least 15 transects in order to capture adequate variability of stream morphology, providing the river has similar morphology and bed material grain-size throughout the reach of interest. Regardless of the transect-based instream flow assessment method used by practitioners (e.g., PHABSIM or BCIFM), this finding should hold true, because the aim of transect sampling is to capture sufficient variability of the physical environment within a river.

My results demonstrated the importance of including uncertainty in habitat preferences of an organism when developing a habitat-flow relation. I showed that instead of developing data-intensive, stream-specific habitat preferences for a species of interest, composites of pre-existing HSI curves could be used to estimate uncertainty in habitat preferences of that organism. This method would be especially advantageous if budgets or time are very limiting. However, if funds and time were available, generation of a stream- and species-specific HSI may reduce uncertainty in the recommended instream flow requirements (IFR).

Finally, my results showed that when uncertainty is incorporated in the habitat-flow relation, calculating the probability of different magnitudes of habitat loss permitted clear and concise interpretation and communication of this uncertainty. This information is important because it allows managers to develop IFR based on their risk tolerance for habitat loss. Without this sort of information, managers are left to set IFR based on best point estimates of available habitat as a function of discharge, with little knowledge of the certainty of maintaining the aquatic ecosystem's health.

However, one should also be cautious when extrapolating the results of this study to other river systems or other species. Because the current findings are limited to the river, reach, and species of study, generalizations of these findings must be checked by repeating similar sampling and statistical analysis on rivers of different scales, slopes, and morphologies, and with species with different habitat preferences. In addition, many uncertainties and assumptions of habitat-based assessment methods were not considered in this study. For example, I collected physical habitat data from the North Alouette River at five different discharge levels. Although it was not considered in this study, the ideal number of sample discharge values across which these physical habitat conditions should be collected needs to be explored in order to further set priorities for sampling efforts.

Tables

Table 1.1. Estimated maximum weighted usable width (WUW) and optimal discharge from the habitat-flow relation produced by each of the five habitat preference curves (A-E) and the combined HSI (F). Habitat-flow relations shown in Figure 1.5. Letter correspond to the habitat preference curves from Figure 1.2.

HSI curve set	Maximum WUW (m)	Optimal Discharge (m^3s^{-1})
A	6.3	0.4
B	1.5	0.8
C	8.7	1.1
D	3.3	1.0
E	3.3	0.4
F	4.3	0.7

Table 1.2. Median, empirical 95% confidence interval (CI), and coefficient of variation (CV) of the estimated maximum weighted usable width (WUW) and optimal discharge from the habitat-flow relations produced when incorporating (1) uncertainty from the combined habitat suitability indices (cHSI) with the transects fixed, (2) variability among transects but using a constant cHSI, and (3) both sources of uncertainty. Habitat-flow relations shown in Figure 1.7.

Source of Uncertainty	Maximum WUW (m)			Optimal Discharge (m^3s^{-1})		
	Median	95% CI	CV	Median	95% CI	CV
cHSI	4.3	2.5 - 6.8	25%	0.7	0.5 - 1.0	21%
Transect	4.2	3.5 - 4.9	8%	0.7	0.5 - 1.1	21%
cHSI & Transect	4.3	2.3 - 6.8	27%	0.7	0.4 - 1.3	34%

Table 1.3. Median, empirical 95% confidence interval (CI), and coefficient of variation (CV) of the estimated maximum weighted usable width (WUW) and optimal discharge from the habitat-flow relations produced when bootstrapping the variability among transects for a range of numbers of transects sampled. Habitat-flow relations were generated with constant combined habitat suitability indices (cHSI) curves.

Number of transects	Maximum WUW (m)			Optimal Discharge (m^3s^{-1})		
	Median	95% CI	CV	Median	95% CI	CV
20	4.2	3.5 - 4.9	8%	0.7	0.5 - 1.1	21%
15	4.3	3.4 - 5.1	10%	0.7	0.5 - 1.1	23%
10	4.3	3.3 - 5.4	13%	0.7	0.5 - 1.3	31%
5	4.2	2.9 - 5.7	17%	0.7	0.4 - 2.1	52%
3	4.4	2.7 - 6.2	22%	0.7	0.3 - 2.7	75%

Figures

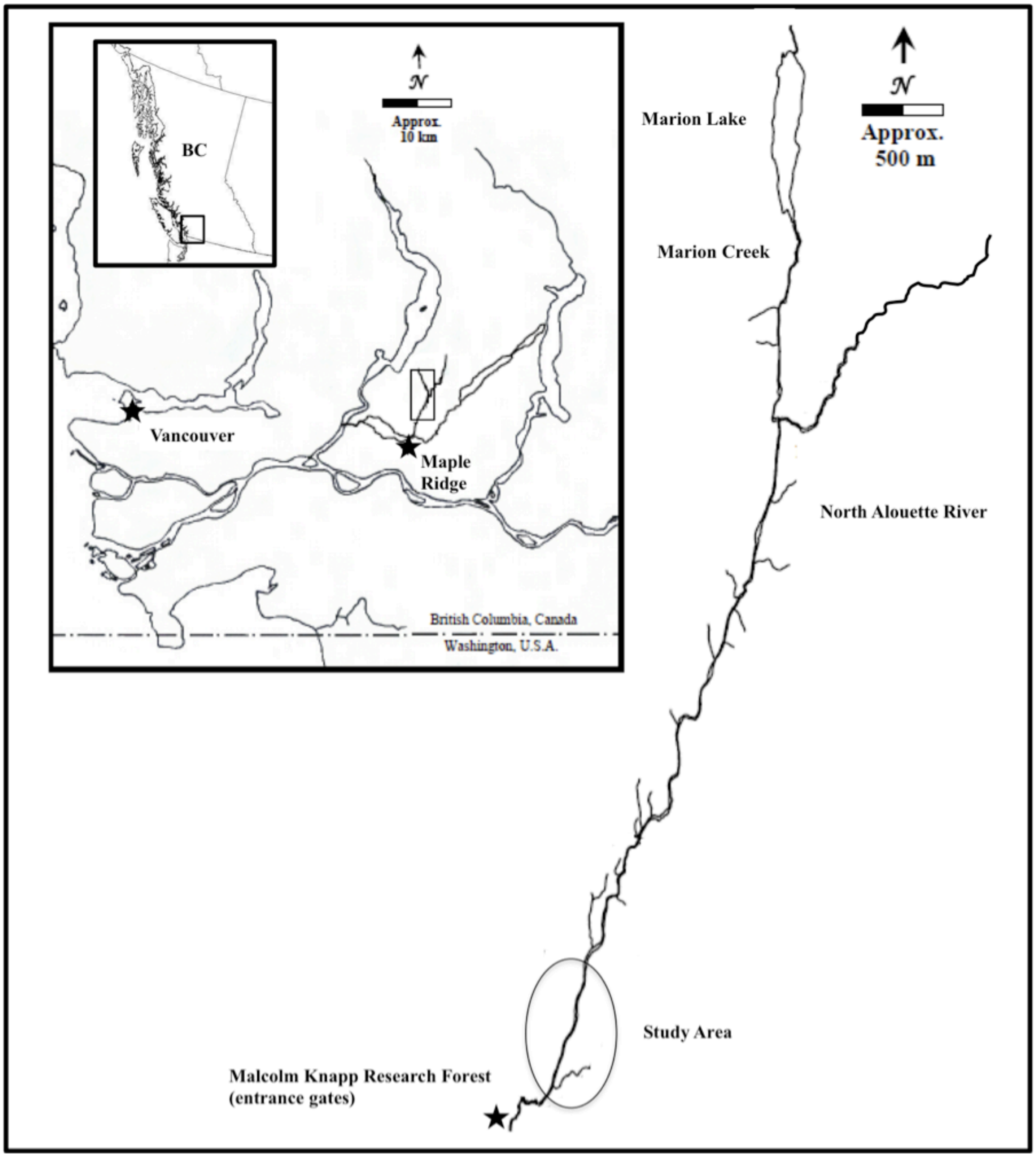

Figure 1.1. Study area (oval) on the North Alouette River, BC (Modified from Mathes and Hinch 2009).

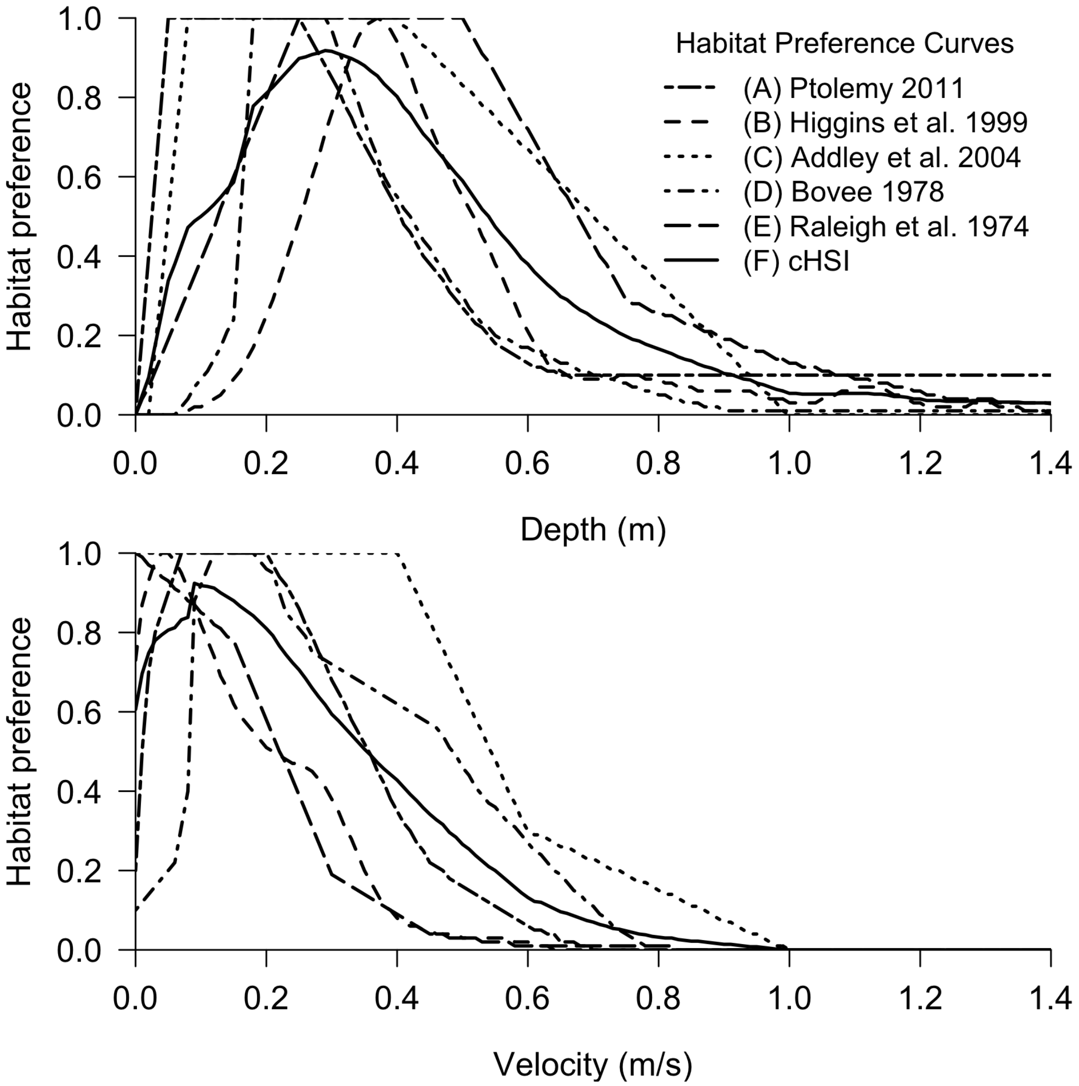

Figure 1.2. Functions for habitat preference for *O. mykiss* fry for depth (top panel) and velocity (bottom panel). Data were drawn from five studies as indicated in the legend, except (F) cHSI, which is the median of the bootstrapped mean of the 5 habitat preference curves (A-E).

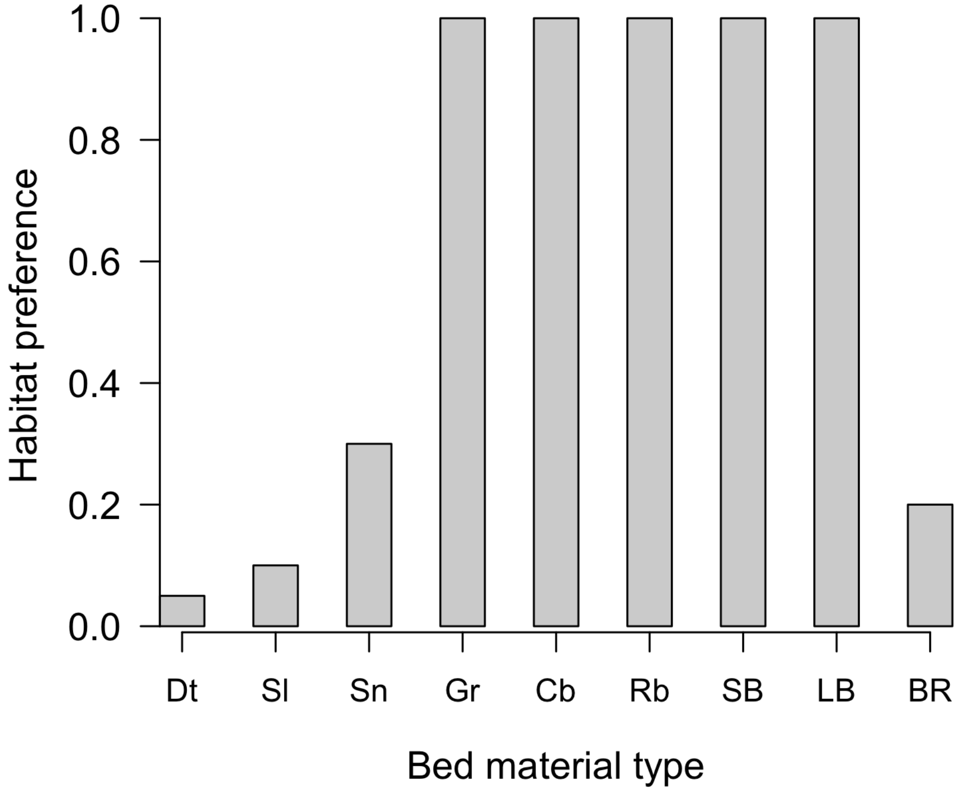

Figure 1.3. Functions for habitat preferences for *O. mykiss* fry for bed-material type used across all analyses. Substrate categories refer to detritus (Dt), silt (Sl), sand (Sn), gravel (Gr), cobble (Cb), rubble (Rb), small boulders (SB), large boulders (LB), and bedrock (BR). From Ptolemy, R., pers. comm., 2011, Rivers Biologist, Fisheries Science Section, Ecosystems Branch, Ministry of Environment, Victoria, BC.

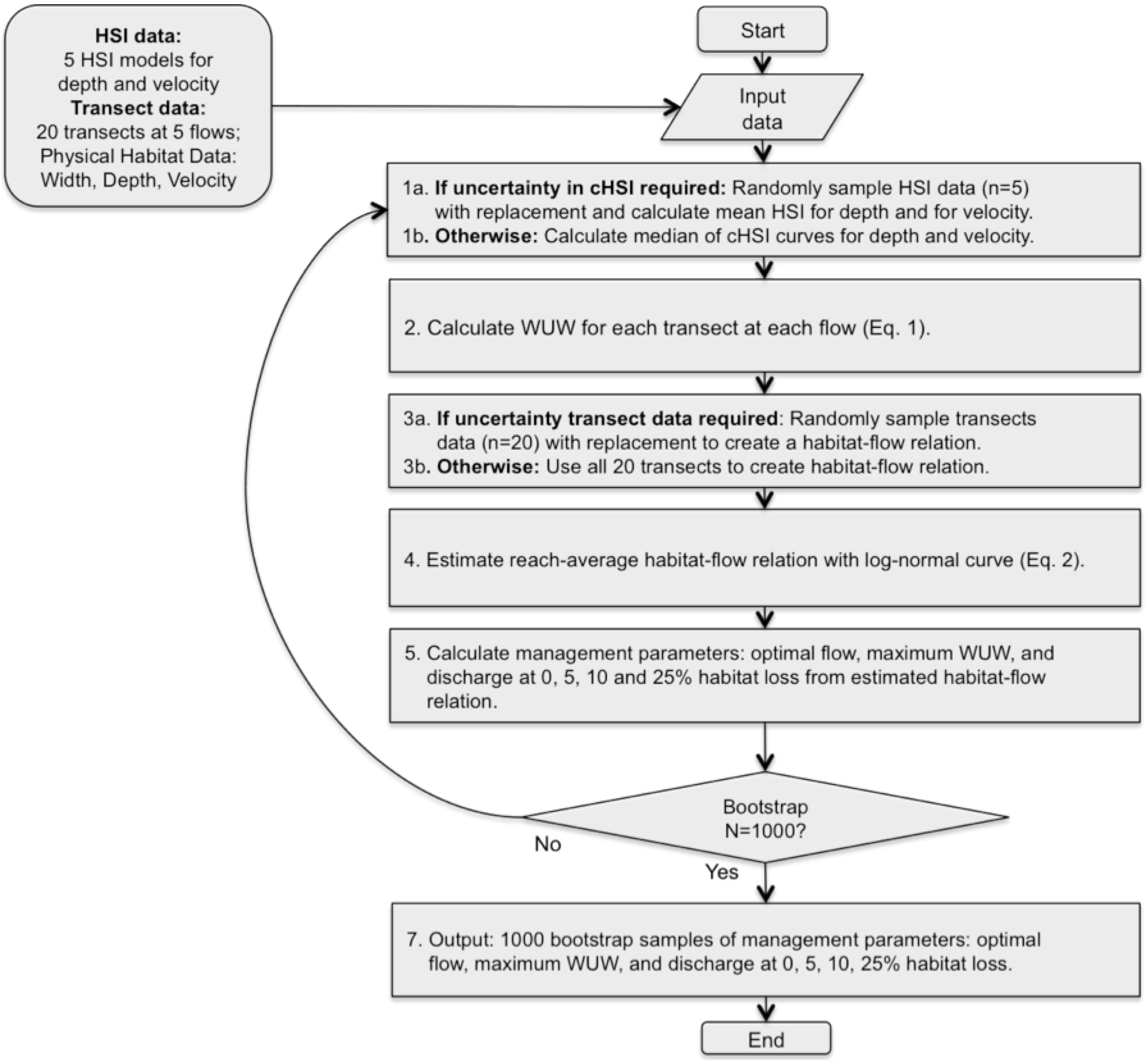

Figure 1.4. Flow diagram of the method used to incorporate the uncertainties of the habitat suitability indices (HSI) and transect data into the habitat-flow relation produced by the British Columbia Instream Flow Methodology (BCIFM).

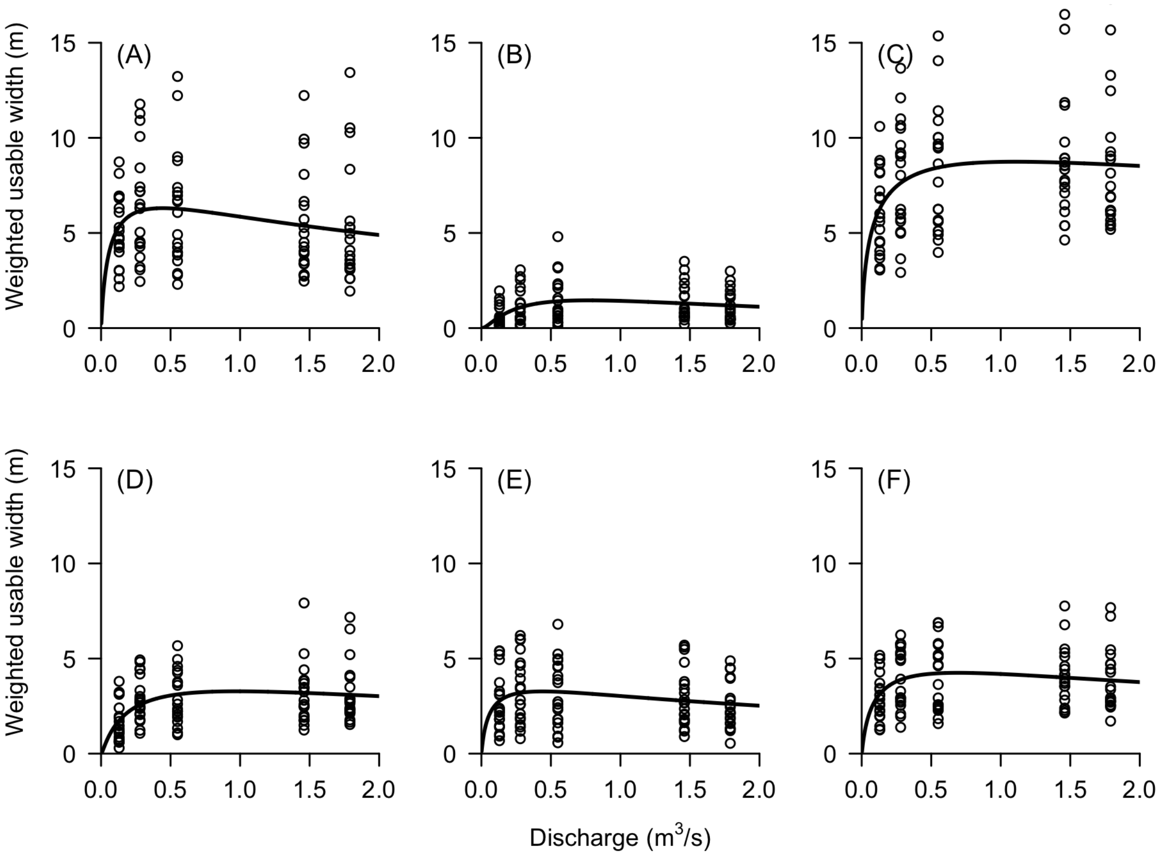

Figure 1.5. Results of the sensitivity analysis showing the estimated habitat-flow relations for *O. mykiss* fry in the North Alouette River for the six sets of habitat preference curves for depth and velocity presented in Figure 1.2. Letters correspond to habitat preference curves A-F in Figure 1.2. Open circles are weighted usable width calculations for each of the 20 transects at the five discharge levels. The solid line is the fit of the log-normal function (equation 2).

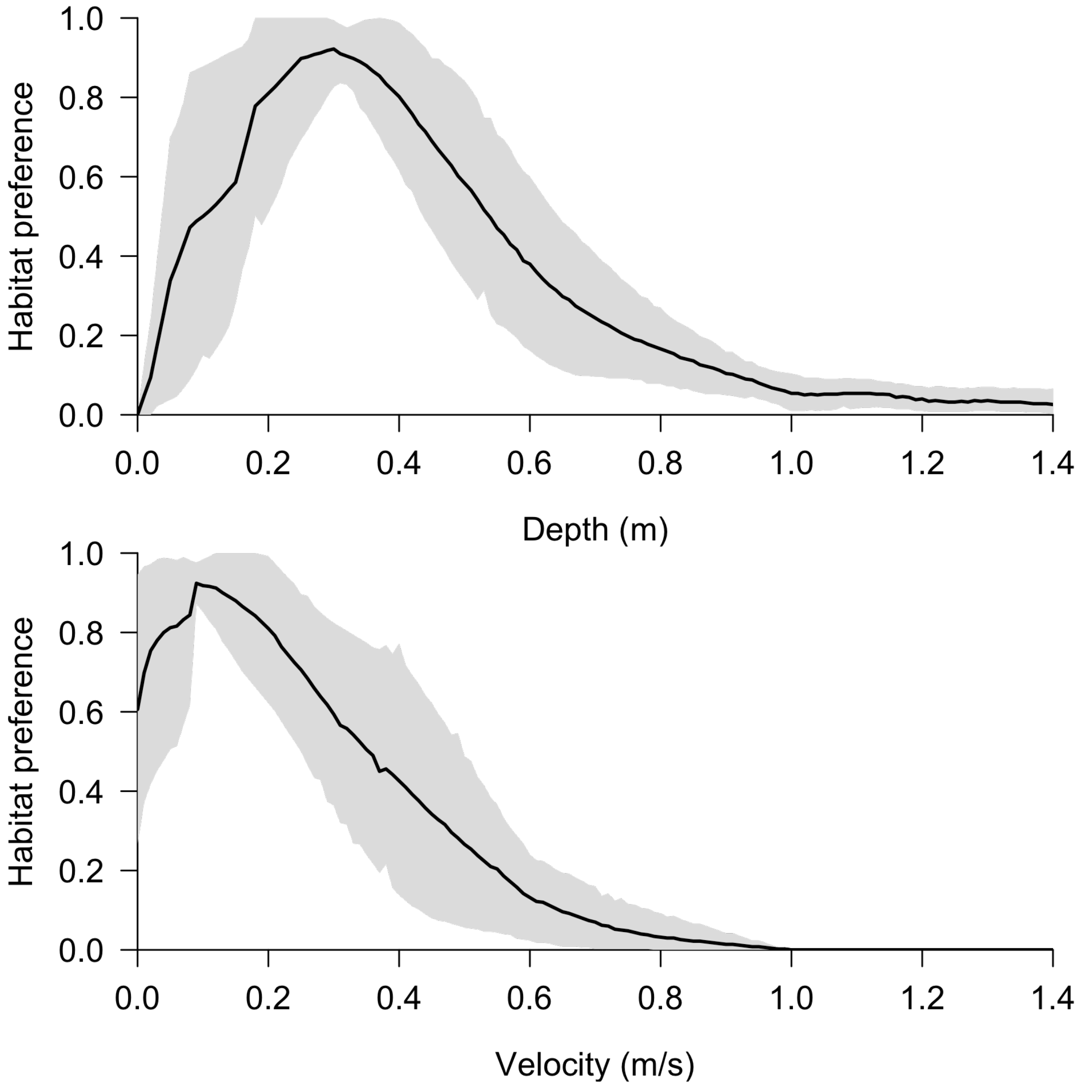

Figure 1.6. Combined habitat suitability indices (cHSI) for *O. mykiss* fry for depth (top panel) and velocity (bottom panel). The solid line is the median and grey band is the empirical 2.5 and 97.5% confidence interval from bootstrapping the mean of five habitat suitability indices in Figure 1.2. Bootstrapped means were generated at 0.01 intervals along the x axis.

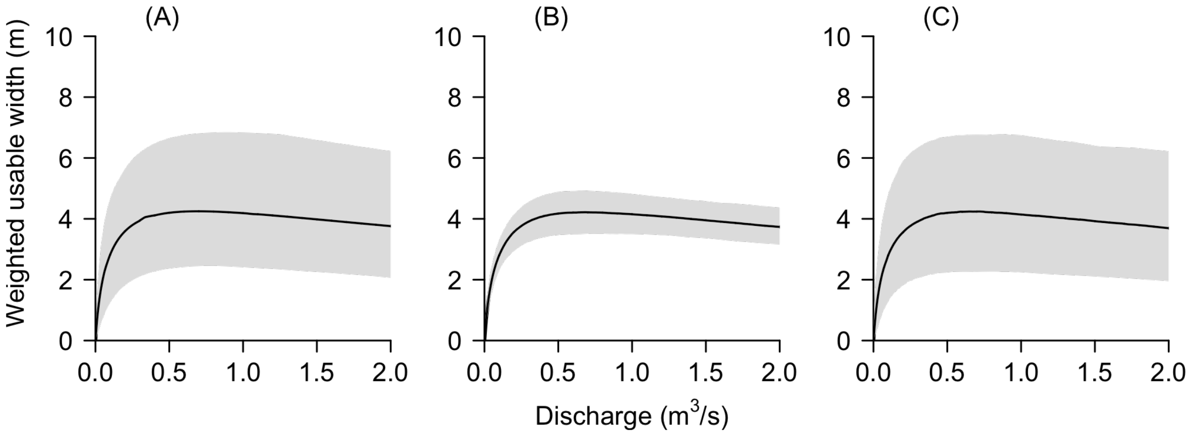

Figure 1.7. Estimated habitat-flow relations produced by the BCIFM when integrating the uncertainty from (A) the combined habitat suitability indices (cHSI) (Figure 1.6), (B) the variability among transects while using a constant cHSI for depth and velocity, and (C) both sources combined. Solid line is the median weighted usable width; grey band is the empirical 2.5 and 97.5% confidence interval from a bootstrap analysis.

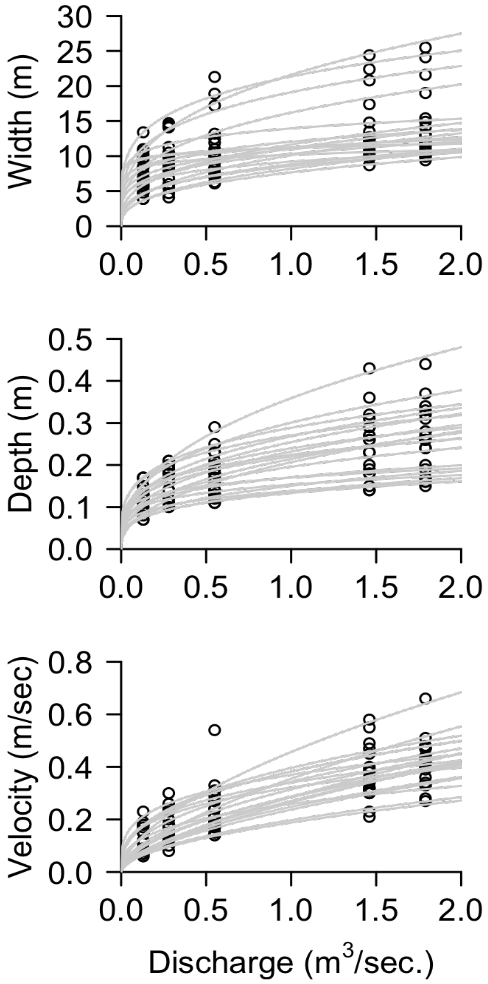

Figure 1.8. Variability in the relation between river discharge and width, mean depth, and mean velocity among the 20 sampled transects in the North Alouette River (open circles). The relations for individual transects were fit with a power function (grey line) according to rules of at-a-station hydraulic geometry (Leopold 1953).

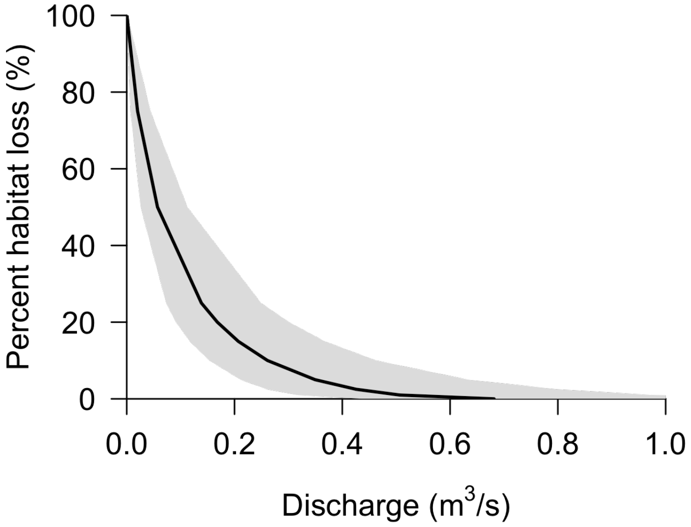

Figure 1.9. Estimated habitat loss from the maximum for *O. mykiss* fry in the North Alouette River as a function of discharge. The solid line is the median value; grey band is the empirical 95% confidence interval from a bootstrap analysis. Uncertainty in both combined habitat suitability indices (cHSI) and transect data were included. The figure presents habitat losses occurring only on the ascending limb of the habitat-flow relation.

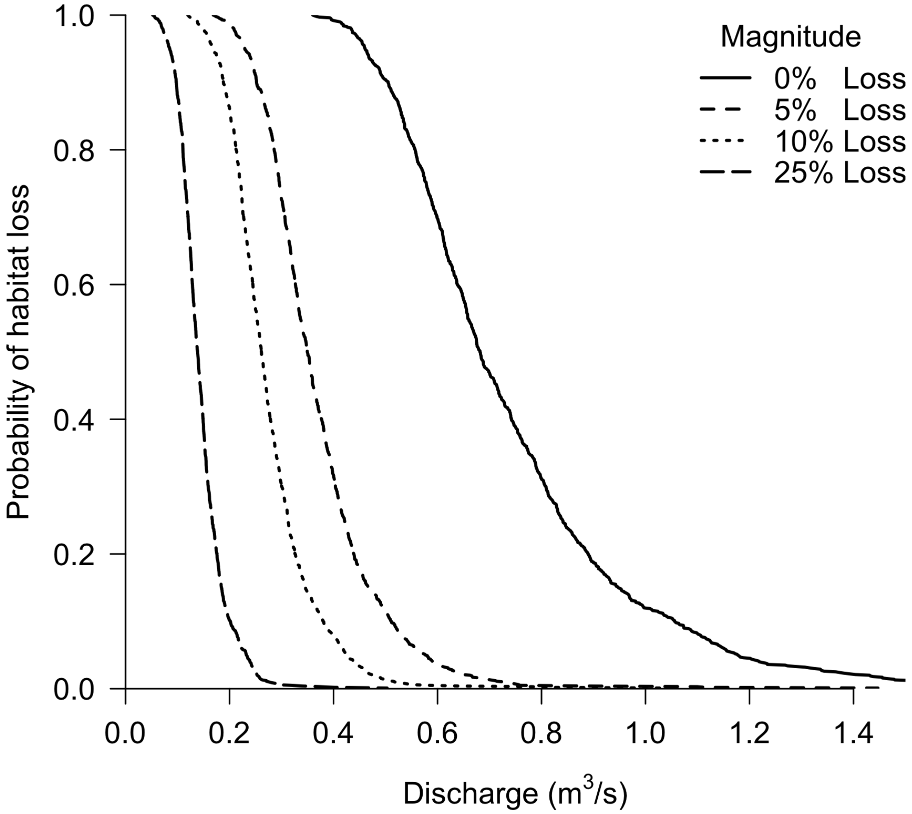

Figure 1.10. Estimated probability of habitat loss for *O. mykiss* fry in the North Alouette River as a function of discharge. Magnitude of habitat loss (0, 5, 10, and 25%) are presented as different line types. The habitat-flow relations that data were drawn from incorporated both uncertainty in (combined habitat suitability indices) cHSI and transect data (Figure 1.7C). This figure presents results from the analysis of habitat loss only on the ascending limb of the habitat-flow relation.

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Chapter 3.

Modeling the Relationship Between Climate and the Natural Low-Flow Period in the North Aloutte River, BC

Introduction

It is well recognized that climate is a key driver of stream discharge (Leith and Whitfield 1998; Morrison et al. 2002; Rodenuis et al. 2009; Elsner et al. 2010; Mote and Salathé 2010; Schnorbus and Rodenuis 2010; Schnorbus et al. 2011). Changes in temperature, precipitation patterns, timing of snowmelt, quantity of snowpack, and glacial runoff have all been linked to shifts in stream discharge hydrographs (Schnorbus and Rodenuis, 2010). Consequently, future changes in climatic conditions will undoubtedly result in alterations in the characteristics of natural stream discharge.

Global climate change is a well-documented phenomenon that has been associated with a rise in mean global temperature and changes in global weather patterns (Intergovernmental Panel on Climate Change 2007). However, the precise effect of climate change varies by region and is highly uncertain. In the Pacific Northwest (PNW) of North America, projected increases in temperature and changes in precipitation patterns are expected to have large effects on regional hydrology (Leith and Whitfield 1998; Morrison et al. 2002; Rodenuis et al. 2009; Elsner et al. 2010; Mote and Salathé 2010; Schnorbus and Rodenuis 2010; Schnorbus et al. 2011).

Of particular concern to water resource managers are low-flow periods during summer months. Changes in summer low-flow periods will have serious implications for both anthropogenic uses and natural stream ecosystems. During these critical low-flow periods, many components of the natural aquatic ecosystem within the stream may be stressed; hence, this period is often assumed to be a productivity-limiting period, especially for some fish species (Poff and Zimmerman 2010). Anthropogenic water withdrawals may need to be limited in order to maintain instream discharge to protect aquatic ecosystem health. Therefore, anticipating changes in stream discharge resulting from climate change will be an essential step for successful water resource management.

With projected human population growth, the demand for out-of-channel water uses will continue to increase throughout British Columbia (BC) in all sectors, whether it be for residential, agricultural, industrial, or hydroelectricity generation uses. In particular, the emergence of Run-of-River hydroelectric generation as a major component of BC's clean energy policy has increased demand for out-of-channel water uses from small high-gradient, mountain streams. These small-scale hydroelectric generation facilities divert a portion of the rivers discharge out-of-channel. The water is transported down-slope to a powerhouse, where it turns turbines, generating electricity. The river water is subsequently returned to the channel downstream from the powerhouse, restoring natural stream discharge. Thus, the portion of the river channel, often extending several kilometres, experiences reduced discharge. The amount of water that can be diverted from the river is regulated based on a minimum instream flow requirement (IFR) that attempts to maintain the ecological integrity of the stream. During natural low-flow periods, out-of-channel water diversion for hydroelectric generation is terminated in order to preserve the discharge necessary to sustain the aquatic ecosystem.

Several studies have projected future patterns of natural low-flow periods in BC (Whitfield et al. 2003, Whitfield 2004, Morrison et al. 2002, Rodenuis et al. 2009). These and other regional studies of the PNW suggest that in general, increases in temperature in the winter months will lead to decreased snowpack, resulting in earlier spring runoff and reduced summer stream discharge (Rodenhuis et al. 2009, Elsner et al. 2010; Mantua 2010; Mote and Salathé 2010). In addition, changes in summer temperature and precipitation patterns may further alter summer stream discharge (Morrison et al. 2002, Whitfield 2004). However, the relative importance of each of these climate variables in predicting the frequency of low-flow events has yet to be investigated. Whitfield (2004) stressed the importance of understanding the control mechanisms governing low discharge in order to make confident predictions to aid in adaptation to future climate conditions.

In this study, I examined how the number of days of low discharge in the North Alouette River, BC, based on instream flow requirements as defined in Chapter 2, has changed from 1970 to 2010. I selected a suite of climate variables that were likely to explain summer stream discharge levels in the North Alouette River based on the general principals of the UBC Watershed Model (Quick and Pipes 1977). The UBC Watershed Model estimates snowpack accumulation and depletion and operates entirely from meteorological inputs of daily maximum and minimum temperatures and precipitation to forecast daily discharge in the Fraser River system in BC. The climate variables chosen to explain summer stream discharge levels in the North Alouette River included summer mean daily precipitation, summer mean daily temperature, and spring mountain snowpack. I analyzed historical trends in these climate variables from 1970 to 2010, and used these variables to model the number of days of low discharge each year. Finally, I used a simple projection of climate variables based on historical rates of change to provide a first order estimate of changes in the occurrence of low discharge in the North Alouette River from 2011 to 2050.

Methods

Study Stream

The North Alouette River (49°14’34”N, 122°34’42”W) is an unregulated river that flows out of the Golden Ears mountain range (maximum watershed elevation 1716 m) and drains into the Pitt River near the town of Maple Ridge, British Columbia, Canada (Figure 1.1). The total drainage is 37.3 km^2 and the mean annual discharge is 2.8 m^{3}s^{-1}, with average annual peak discharge reaching 45.6 m^{3}s^{-1}, and average annual minimum discharge falling to 0.13 m^{3}s^{-1} (Environment Canada 2011a). The study reach was located within the University of British Columbia Malcolm Knapp Research Forest, approximately 15 km upstream from the confluence with the Pitt River. The study reach channel was high-gradient (2.0-3.1%) with an average channel width of 18.6 m. The river bed material was dominated by boulder, cobble, and gravel bed material type, with a D_{50} and D_{90} bed material grain size ranging from 130-180 mm and 400-430 mm respectively (obtained using Wolman pebble counts; Kondolf 1997). The study reach was a plane-bed alluvial channel type (Montgomery and Buffington 1997) with riffle-run mesohabitat type (Maddock 1999). A waterfall complex downstream of the study site prevents the up-stream migration of anadromous salmonids into the study reach. However, rainbow trout (*Oncorhynchus mykiss*) and cutthroat trout (*O. clarkii*) were introduced into the system in the mid-19th century and currently inhabit the reach (Mathes and Hinch 2009).

The watershed is located within the coastal temperate rainforest region, which is characterized by dry summers with low discharge and wet winters with heavy rainfall events that cause sporadic high discharge. Watersheds can be classified based on characteristics of their flow regime as snowmelt-dominant, transient, or rainfall-dominant. Wade et al. (2001) identify the North Alouette River watershed as transient flow regime type that has both winter rain-driven spates and a spring snowmelt freshet (Figure 2.1). The North Alouette River has no glacial influence, however, a major tributary, Marion Creek, contains several small lakes within its headwaters (Figure 1.1), which may moderate discharge.

Streamflow data

Mean daily discharge measurements from 1970-2010 in the North Alouette River were collected from a Water Survey of Canada gauging station near the 232nd St. Bridge in the town of Maple Ridge (Environment Canada 2011a) approximately 2.9 km downstream from the study reach. Low-flow benchmarks for the North Alouette River were derived from an instream flow habitat assessment (Chapter 2), which denoted variable levels of risk of habitat loss for rainbow trout/steelhead (*Oncorhynchus mykiss*) fry. These low-flow benchmarks were chosen to represent a range of tolerances by water managers for the chance of a given habitat loss occurring, ranging from a 95% chance that discharge was at the level at which less than 5% loss of fish habitat would occur (0.45 m^3s^{-1}), to the discharge that gave a 5% chance that a 25% habitat loss would occur (0.25 m^3s^{-1}). In total, I explored three potential low-flow benchmarks (0.25, 0.35, and 0.45 m^3s^{-1}), which corresponded to approximately 9, 13, and 16% of mean annual discharge (Figure 2.1). I calculated the number of days each year from 1970-2010 that the mean daily discharge receded below each low-flow benchmark. Then, for each of the low-flow benchmarks, I fit a linear regression to the number of days of low discharge as a function of the historical year.

Climate data

Low discharge in the North Alouette River predominantly occurred in the late summer months (Figure 2.1); consequently, I considered only those climatic variables that were expected to exert a first-order control on stream discharge during summer months based on those variables used in the UBC Watershed Model (Quick and Pipes 1977). These variables included summer mean daily temperature, summer mean daily precipitation, and a proxy of winter/spring climatic conditions, i.e., spring snowpack.

Mean daily temperature and precipitation data from 1970-2010 were collected from an Environment Canada weather station at the UBC Malcolm Knapp Research Forest (Environment Canada 2011c). Both temperature and precipitation data were divided into season by day of year: Winter (days 1-92); Spring (days 93-183); Summer (days 184-274); Fall (days 275-366). The average mean daily temperature and precipitation were calculated for each season from 1970-2010. No spring snow pack data were available for the headwaters of the North Alouette River in the Golden Ears mountain range from 1970-2010. Instead, I used spring snowpack levels from April 1st manual snow survey data collected from Cairn W4 mountain (49°49'N, 122°03'W) in the headwaters of the Nahatlatch River (British Columbia Ministry of Forests, Lands, and Natural Resource Operations 2011), at similar elevations to (1530 m), and approximately 60 km northeast of the Golden Ears mountain range. I used ordinary least squares regression to fit linear time trends in summer daily average temperature, summer daily average precipitation, and spring snowpack levels from 1970-2010.

Linear regression models and model selection

I used multiple linear regression models to investigate the relations between the number of days of low discharge and summer mean daily temperature, summer mean daily precipitation, and spring snowpack (Zar 1999). To facilitate interpretation of the relative importance of each of the independent variables in predicting the number of days of low discharge, both independent and dependent variables were converted into standard deviation units (SDUs) for the linear regression analysis by subtracting the mean from each observed data point and then dividing by the standard deviation (SD) of the data series. The full model was as follows:

$$D = a + b_1 P + b_2 S + b_3 T + b_4 PT + b_5 PS + b_6 ST + v \quad , \tag{1}$$

where D is the average number of days of low discharge for a given low-flow benchmark (0.25, 0.35, and 0.45 $m^3 s^{-1}$), a is the intercept, b_i are parameters, P is summer mean daily precipitation, T is summer mean daily temperature, S is spring snowpack depth, and v is the error term, which was assumed to be normally distributed and serially independent.

I evaluated 18 different models, which were subsets of the full model (eqtn. *1*) based on additive and multiplicative interactions of the three independent variables (Table 2.1). The most parsimonious models for each low-flow benchmark were determined using the Akaike Information Criterion with a correction factor for small sample sizes (AIC_c; Burnham and Anderson 2002). The AIC_c was calculated as:

$$AIC_c = -2\log L + (2kn/(n-k-1)] \quad , \tag{2}$$

where L is the likelihood of the model, n is the sample size, and k is the number of parameters in the model. The model with the lowest AIC_c value was defined as being the most parsimonious. The difference in AIC_c values between the most parsimonious model and each other model i was calculated (ΔAIC_c):

$$\Delta AIC_{c,i} = AIC_{c,i} - \min(AIC_c) \quad . \tag{3}$$

If a ΔAIC_c value for a model is between 0 and 2 the level of empirical support for that model is substantial, between 2 and 4 the model has considerable support, between 4 and 7 the model has considerably less support, and greater than 10 the model has essentially no support (Burnham and Anderson 2002).

Model averaging

For each low-flow benchmark, I selected a subset, R, of all candidate models that contained considerable support (ΔAIC_c <4) (Table 2.2). For each subset R of candidate models, re-scaled Akaike weights (w_i) were calculated as:

$$w_i = \frac{\exp(-\Delta AIC_{c,i}/2)}{\sum_{i=1}^{N}\exp(-\Delta AIC_{c,i}/2)} \quad . \tag{4}$$

The weight for a model, w_i, represents the relative support for model *i*. In addition, the relative variable importance (RVI) for each independent variable was also calculated for each low-flow benchmark. This was done by summing the w_i values of all models in the subset *R* that included a particular variable (Burnham and Anderson 2002).

Finally, using the top model subset, *R*, model-averaged parameters coefficients and errors were estimated for each model variable using the zero method (Burnham and Anderson, 2002). In this method, a parameter estimate and an error of zero is substituted into those models where the given parameter is absent, and the model-averaged parameter estimates are obtained by averaging over all models in the top model set (in contrast to the natural average method, which averages model coefficients from only models that contain the variable). Thus, the zero method decreases the effect sizes and errors of predictors that only appear in models with small model weights, thereby diluting the parameter estimates of these predictors (Grueber et al. 2011). All calculations were performed in R (R Development Core Team 2008).

Climate projections

Summer mean daily precipitation, summer mean daily rainfall, and spring snowpack levels were projected forward with uncertainty from 2011-2050 based on historical rates of change and inter-annual variability. For each climate variable, future trends were assumed to be linear. Projections of each climate variable, *X*, were calculated as:

$$X_{k=1}^{K} = a + b_k Year \quad , \tag{5}$$

where the intercept of the linear projection, *a*, was assumed to be the 2010 mean value from the historical regression of the corresponding climate variable. The slope of the projected linear trend, b_k, was assumed to have a normal distribution, with a mean and standard deviation equivalent to that of the historical regression (1970-2010) of the time series of the corresponding climate variable. Bootstrap techniques (Efron and Tibshirani 1993) were used to estimate uncertainty in each projected climate variable, whereby, the slopes, b_k, of the future projection of each climate variable were randomly sampled with replacement K=2000 times from the normal distribution, resulting in 2000 sample projections of each climate variable. The median and 95% empirical confidence intervals were calculated from those 2000 samples.

Low-flow projections

For each low-flow benchmark (0.25, 0.35, and 0.45 m^3s^{-1}), I projected the number of days of low discharge each year in the North Alouette River from 2011-2050 based on the projections of each climate variable (summer mean daily precipitation, summer mean daily rainfall, and spring snowpack). Climate variables were assumed to be independent of each other. Model predictions for the number of days of low discharge were made using the multi-model averaged model for each low-flow benchmark:

$$D_{k=1}^{K} = a + b_1P_k + b_2S_k + b_3T_k + b_4P_kT_k + b_5P_kS_k + b_6S_kT_k \quad , \qquad (6)$$

where, for each set of sample climate variable projections, k, the average number of days of low discharge, D_k, was predicted. In total, K=2000 predictions of the average number of days of low discharge were made for each low-flow benchmark, based on the 2000 sample sets of projections for the climate variables. The median and 95% empirical confidence intervals were calculated from the 2000 samples of the number of days of low discharge for each low-flow benchmark.

Results

Historical trends in the low-flow period

I found statistically significant ($p<0.05$) positive time trends in the number of days that the discharge in the North Alouette River fell below each low-flow benchmark (0.25, 0.35, and 0.45 m^3s^{-1}) from 1970 to 2010 (Table 2.3; Figure 2.2).

Historical trends in climate

A statistically significant trend in summer mean daily temperature was detected from 1970-2010 ($p<0.001$), however, neither summer mean daily precipitation nor spring snowpack show statistically significant time trends ($p>0.09$) (Table 2.4; Figure 2.3). Summer mean daily temperature and summer mean daily precipitation were inversely correlated (r = -0.33, p = 0.035). Neither summer mean daily temperature and spring snowpack (r = *-0.30* , p = 0.055) nor summer mean daily precipitation and spring snowpack (r = *0.14* , p = 0.371) were significantly correlated with year.

Multi-model averaged linear regression

In general, summer average daily precipitation, summer average daily temperature, and April 1st snowpack levels were all important variables in explaining the number of days that discharge in the North Alouette River fell below each low-flow benchmark; however, the relative magnitude of effect of each of the variables changed, depending on the low-flow benchmark (Table 2.5; Figure 2.4). Based on coefficient values in standard deviation units, both spring snowpack and summer mean daily precipitation had a similar negative effect, and it was greater than the effect of summer temperature for predicting the number of days that discharge fell below 0.45 m^3s^{-1}. However, the relative effect size of spring snowpack decreased substantially for smaller low-flow benchmarks (0.25 and 0.35 m^3s^{-1}), in which cases, the effect size of summer precipitation became the most important of the variables. Summer temperature was positively associated with the number of days of low discharge. The effect size of summer temperature increased substantially relative to other variables when explaining smaller low-flow benchmark levels. In general, the effect sizes of all interactions between variables were relatively unimportant (<5% of the largest effect size) (Table 2.5; Figure 2.4).

Climate projections

Extrapolations of the historical trend in summer mean daily temperature into the future suggested that there was a high probability that temperatures will continue to increase by the year 2050 from 2010 values. Extrapolations of the historical trend in summer mean daily precipitation were highly uncertain; however, on average, they suggested minor decreases in precipitation from 2010 to 2050. Finally, decreases in spring snowpack were highly probable from 2010 to 2050 based on extrapolations of the historical trend (Table 2.6; Figure 2.3).

Low-flow projections

Multi-model average model predictions based on projected climate scenarios suggested that there was a high probability that the number of days of low discharge in the North Alouette River will increase from 2011-2050, with the greatest increase for the lowest benchmark (Table 2.7; Figure 2.2).

Discussion

If past trends in climate continue into the future, the resulting increased frequency of climate driven low-flow events will likely have serious implications for water management in BC. Extended durations of natural low-flow periods will have consequences for both natural stream ecosystems and anthropogenic water users. As a result, it is important to be able to predict the effects of climate change on stream discharge on a watershed level in order to properly manage water resources within those watersheds in the future.

Historical trends in climate

Historical trends in climate in the North Alouette River watershed were generally consistent with other findings from historical weather analyses across BC (Rodenhuis et al. 2009, Schnorbus and Rodenhuis 2010). Over the past century, statistically significant positive time trends have occurred in annual daily mean air temperature at a rate of +0.12°C (95% confidence interval (CI) of +0.05°C to +0.15°C) per decade, although trends varied seasonally and spatially across the province (Rodenhuis et al. 2009). Seasonally, mean daily temperatures increased during winter (+0.22° C per decade) and spring (+0.15° C per decade), however, summer temperature changes were negligible, and autumn mean temperatures appear to have gotten cooler in northern regions of BC (Schnorbus and Rodenhuis 2010). Further analysis of trends over shorter periods showed that trends for BC average temperature increases have been accelerating, especially in winter (Schnorbus and Rodenhuis 2010). My analysis showed that summer daily mean temperatures have increased significantly at a rate of +0.4°C (95% CI of +0.2°C to +0.6°C) per decade. This finding suggests that the rate of warming during the summer months over the past 40 years in the North Alouette River watershed has been 2-3 times the average rate across the province over the past century.

In their historical analysis, Rodenhuis et al. (2009) found positive trends in average annual precipitation (+2.4% per decade) across BC over the past century, with the greatest increases occurring in winter and across drier areas of the province. However, although not statistically significant, decreasing trends in annual precipitation were identified both in southwest BC and over shorter time periods (30 - 50 years) (Rodenhuis et al. 2009). My results were consistent with the latter, where, although not statistically significant, on average, summer mean daily precipitation appeared to decrease slightly by -2.0% (95% CI of -11.0% to +6.3%) per decade from 1970-2010 in the North Alouette River watershed.

Finally, over the past 50 years, Rodenhuis et al. (2009) found that April snowpack was decreasing on average at a rate of -5% per decade across BC, and as much as -10% per decade at particular sites. Similar trends were evident in spring snowpack levels on Cairn W4 mountain (used as a proxy of snowpack conditions in the North Alouette River watershed), where, although not statistically significant, spring snowpack decreased on average by -5% (95% CI of -12% to +1%) per decade from 1970-2010. These decreased snowpack levels are likely a direct result of the increasing winter and spring temperatures across BC (Elsner et al. 2010).

High inter-annual variability in both summer daily average precipitation and spring snowpack in the North Alouette River watershed likely precluded the detection of any significant trends in these variables from 1970-2010, even if such trends existed. Natural variability in climate across years is influenced in BC by major climatic events such as the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Barlow et al. 2001; Rodenhuis et al. 2009; Schnorbus and Rodenhuis 2010). Had these natural climatic events been accounted for in the historical analysis, more pronounced trends in precipitation and snowpack might have been evident.

Historical trends in the low-flow period

Reduced summer stream discharge was evident in the North Alouette River from 1970 to 2010. Although there was substantial inter-annual variability during this period, the number of days that the discharge fell below all low-flow benchmark levels increased significantly. Although variable throughout BC, similar shifts in stream hydrographs were evident over the past century. In particular, earlier spring freshets and lower summer stream discharge have occurred (Leith and Whitfield 1998; Schnorbus and Rodenuis 2010). In snowpack-dominated systems, the timing of the spring freshet has advanced by 10 - 30 days, and in low-elevation, southern latitude streams, both the mean annual discharge and the minimum daily average discharge have decreased (Rodenhuis et al. 2009). These shifts in stream discharge hydrographs have been attributed to changes in temperature, precipitation patterns and type (snow or rain), timing of snowmelt, quantity of snowpack, and glacial runoff (Schnorbus and Rodenuis, 2010). In coastal streams similar to the North Alouette River, these shifts in snowpack and precipitation have resulted in streams transitioning from snowpack to rainfall-dominated regimes (Schnorbus and Rodenhuis 2010).

Effects of climate variables on the low-flow period

Both summer mean daily precipitation and spring snowpack levels are important drivers of low discharge in the North Alouette River, however, summer mean daily temperature became increasingly important in driving the low-flow events as the low-flow benchmark decreased from 0.45 to 0.25 m^3s^{-1}. In late summer months, once the snowpack has dissipated at high elevations in the watershed, base-flows in the North Alouette River are reached. During this period of base-flow, it appears that high summer temperatures result in additional water loss from the river, likely from increased evaporation and evapotranspiration through vegetation. Many studies cite spring snowpack and precipitation as major drivers of summer low discharge (Schnorbus and Rodenuis, 2010; Elsner et al. 2010; Mantua 2010); however, this study directly links the increasing importance of high summer temperature, relative to other variables, to extreme low-flow events. Identification of such relative importance of predictor variables will be necessary to correctly anticipate future trends in low-flow events.

Although the three easily obtainable climate variables included in the analysis (i.e., summer daily mean precipitation, summer daily mean temperature, and spring snowpack level) explained a substantial amount of the variability in the frequency of low-flow events, the multi-model averaged model tended to have a narrower range of predictions. Specifically, the model tended to underestimate the frequency of low-discharge days in years of historically high number of observations of low-flow events, and overestimate the frequency of low-discharge days in years of historically few observations of low-flow events (Figure 2.2). Other variables could have been included into the model in an attempt to increase model fit. For example, large-scale temporal patterns in climatic variation, El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), are known to have important implications for water resources in western North America (Barlow et al. 2001; Whitfield et al. 2010). In addition, Smakhtin (2001) conducted a review of low-flow hydrology and listed a number of natural factors, in addition to climate, that influence various aspects of the low-flow regime of rivers. These factors included aspects of subsurface groundwater movement, changes in vegetation, and topography. However, reliably including this complexity into the model used here is beyond the scope of this work.

Climate projections

My projections for summer precipitation, summer rainfall, and spring snowpack levels in the North Alouette River watershed by 2050 were generally consistent with, although more uncertain than, projections for BC (Rodenhuis et al. 2009) and for the Pacific Northwest (PNW) (Elsner et al. 2010; Mote and Salathé 2010).

By the year 2050, my results suggested that summer mean daily temperature in the North Alouette River watershed would increase on average by +1.6 °C (95% CI of +0.8°C to +2.3°C) from 2010 levels. These results generally concur with those of Rodenhuis et al. (2009), who found that by the 2050s, the average annual temperature in BC was projected to increase by +1.7°C (+1.2°C to +2.5°C) compared to the GCM baseline (1961-1990) climate. In addition, the greatest increases in temperature were projected in the summer and winter seasons, with increases of +1.9°C (+0.5°C to +2.7°C), and +1.8°C (+1.2°C to +2.7°C) respectively. My results are also consistent with the projected +1.8°C increased average annual temperature for the PNW over a similar time period (Mote and Salathé 2010).

Rodenhuis et al. (2009) projected that across BC, average annual precipitation will increase by +6% (+3% to +11%) by 2050. Winter season precipitation was projected to increase by +7% (-2% drier to +15% wetter) across BC, however, summer precipitation was expected to decrease -3% drier (-9% drier to +2% wetter). The decreases in projected precipitation were mainly in southern and coastal regions of BC. Projections for annual mean precipitation in the PNW suggest increases of +1 to +2% by the 2040s, however, some models projected an enhanced seasonal cycle with changes toward wetter autumns and winters and drier summers (Mote and Salathé 2010). Other studies project a wide range of possible changes in annual precipitation in the PNW by the 2040s, from -11% to +12% (Elsner et al. 2010). Although my projections were more uncertain, they generally fall within the range of projections for summer precipitation across BC and the PNW, where summer mean daily precipitation in the North Alouette River watershed is projected to decrease by -9% (95% CI of -47% to +27%) by 2050 compared to 2010 levels.

Finally, declines in snowpack are predicted to be significant across BC by 2050, with the most dramatic decreases of up to -55% occurring in the coastal mountains (Rodenhuis et al. 2009). In the PNW, April 1 snow-water equivalent is projected to decrease by approximately -38% to -46% by the 2040s (Elsner et al. 2010). Although they are more uncertain, my projections concur; by the year 2050, spring snowpack at my index site for the North Alouette River watershed was projected to decrease by -27% (95% CI of -69% to +4%) from 2010 levels.

Although similar to other studies, in general my results suggest a larger magnitude of uncertainty in climate variable projections than other climate projections for BC and the PNW. Other researchers produced estimates of uncertainty by simply using the variation in results from a suite of different GCMs forced by multiple CO_2 emission scenarios (Whitfield 2003; Rodenhuis et al. 2009, Elsner et al. 2010; Mote and Salathé 2010), whereas I used uncertainty in the historical rate of change of the climate variables from a 40 year record. To make projections, I assumed that climate variables were changing in a linear manner, and will continue to change in the same linear manner over the next 40 years. As a result, my projections of climate are not empirically associated with a causal mechanism nor do they incorporate large-scale climatic events (i.e., PDO or ENSO). However, the purpose of this exercise was to illustrate a hypothetical scenario. Specifically, if the past rate of change in climate variables continues into the future, how will climate conditions change, and what will be the effect on the natural stream discharge?

Low-flow projections

Based on my projected trends for summer precipitation, summer rainfall, and spring snowpack levels, which generally correspond with other predictions in BC and the PNW, there is a high probability that the number of days of low discharge in the North Alouette River will increase by the year 2050 for all low-flow benchmark levels. These projected increases in the duration of low-flow period correspond with the projected drier, hotter summers in conjunction with decreased spring snowpack in the North Alouette River watershed. However, when analysing the more severe low-flow benchmarks, increases in both certainty and magnitude of low-flow events were evident. This is a result of the highly significant increasing historical trend in summer temperature assumed to continue into the future, in combination with the high relative importance of summer temperature in predicting these extreme low-flow events.

Other studies have investigated the potential effects of climate change on stream discharge in BC (Morrison et al. 2002; Whitfield et al 2003; Rodenhuis et al. 2009) and across the PNW (Elsner et al, 2010; Mantua et al 2010), using climate projections from GCMs. In general across BC and the PNW, findings indicated that watersheds that have historically been dominated by snowmelt and transient conditions (rainfall and snowmelt) will shift towards transient and rainfall-dominant behaviour respectively, resulting in earlier spring runoff and more severe summer low-flow periods (Whitfield et al 2003; Rodenhuis et al. 2009; Elsner et al, 2010; Mantua et al. 2010). Reductions in the magnitude of summer low discharge are predicted to be widespread across the PNW, particularly in rain- and transient-dominant river basins, where the magnitude of summer low discharge is projected to decline by up to -50% by the end of the century (Mantua et al. 2010). Studies across BC projected similar trends, where summer season discharge is predicted to decrease by -37% to -90% by 2050 (Rodenhuis et al. 2009). In addition, the duration of the summer low-flow period is projected to expand significantly in all watershed types across the PNW (Elsner et al. 2010).

Although there was a mild negative correlation between summer mean daily temperature and summer mean daily precipitation, I assumed that these independent climate variables were not correlated. With this assumption, I neglected the observed characteristic that years with high summer temperatures occur more often along with low precipitation and vice-versa. The combination of high temperature and low precipitation would result in an increase in the frequency of low-flow events because of the opposite influence of those two climate variables. Therefore, it is likely that model predictions underestimated the frequency of low-flow events in the future. This is evident in the lower rate of change of the number of days of low discharge in the North Alouette River observed in the model projections (2010-2050) relative to the historical rate of change (1970-2010) (Table 2.3 and 2.7; Figure 2.2). This correlation between independent climatic variables should be incorporated in future analyses.

Conclusion

The projected increasing trend in frequency of critical low-flow periods has important implications for both aquatic resources and water resource management. Both fish and other components of the natural aquatic ecosystem may experience reduced quality or quantity of habitat during periods of low discharge (Poff and Zimmerman 2010). Even in the absence of water withdrawals for industrial, agricultural, residential, or hydroelectric purposes, the increased duration of the natural summer low-flow period resulting from changes in climate will almost certainly result in reduced productive capacity of streams for some fish species/life-history stages. Any prescribed water withdrawals that occur during summer months will only increase the frequency of low-flow events and increase the stress on fish and other aquatic biota. Mantua et al. (2010) mirrored this viewpoint when they concluded that decreasing summer discharge, in combination with increasing summertime stream temperatures (Isaak et al. 2011), will likely reduce the productivity of many salmon populations in the PNW. In particular, reduced discharge will likely limit rearing habitat in streams and increase mortality rates during spawning migrations of adults in summer months (Mantua et al. 2010).

Increased duration of low-flow periods will also have negative implications for hydroelectric generation in the PNW. In particular, those hydroelectric facilities that operate with a prescribed instream flow requirement (IFR) and have little water storage capacity, such as run-of-river (ROR) hydroelectric generation facilities in BC, will be increasingly affected in the future. My results from the North Alouette River case study suggest that low-flow events will force ROR hydroelectric generation facilities to shut down at an increased frequency in the future. The resulting reduced generation capacity of rivers in the future could have serious implications for the economic viability of projects and security of electricity generation for BC. Although my findings are from a case study of a single river, similar findings regarding projected reductions in summer discharge across BC and the PNW suggest that these implications are regional (Rodenhuis et al. 2009; Elsner et al, 2010; Mantua et al. 2010).

Climate change has and likely will continue to result in changes in stream discharge in BC. An understanding of these projected changes will be highly valuable to water resource managers and resource stakeholders as they develop appropriate plans. In order to effectively manage water resources in the future, these potential effects of climate change on hydrological resources must be incorporated into water management plans in BC. More predictive tools, such as the low-flow models developed here for the North Alouette River, are needed at regional scales in order to make accurate predictions regarding the effects of climate change on river discharge.

Tables

Table 2.1. Candidate models and corresponding AIC_c, ΔAIC_c, and AIC_c weights (w_i) to explain number of days that discharge in the North Alouette River fell below 0.45, 0.35, and 0.25 m^3/s from 1970-2010. Models are ordered by ΔAIC_c. Parameter symbols are: P (summer average daily precipitation), T (summer average daily temperature), and S (spring snowpack level). Interactions are represented by *.

Low-flow Benchmark	Model Rank	Model Parameters	AIC_c	ΔAIC_c	w_i
$0.45\ m^3s^{-1}$	1	P + S	361.55	0.00	0.386
	2	P + T + S	362.85	1.30	0.201
	3	P*S	363.70	2.16	0.131
	4	P*S + T	365.06	3.51	0.067
	5	T*S + P	365.20	3.66	0.062
	6	P*T + S	365.49	3.94	0.054
	7	P*S + T*S	366.76	5.22	0.028
	8	P*T + T*S	367.73	6.18	0.018
	9	P*T + P*S	367.98	6.43	0.016
	10	T + S	368.60	7.06	0.011
	11	T*S	369.48	7.93	0.007
	12	P*T + P*S + T*S	369.73	8.18	0.006
	13	S	369.84	8.29	0.006
	14	P + T	371.42	9.87	0.003
	15	P	372.51	10.96	0.002
	16	P*T	374.02	12.47	0.001
	17	T	376.19	14.64	0.000
	18	NULL	380.89	19.34	0.000
$0.35\ m^3s^{-1}$	1	P + T + S	359.03	0.00	0.271
	2	P + S	359.99	0.95	0.168
	3	P*S + T	360.97	1.93	0.103
	4	P + T	361.12	2.09	0.095
	5	P*T + S	361.44	2.41	0.081
	6	T*S + P	361.75	2.71	0.070
	7	P*S	361.99	2.96	0.062
	8	P*S + T*S	363.40	4.36	0.031
	9	P*T	363.58	4.54	0.028
	10	P*T + P*S	363.82	4.78	0.025
	11	P*T + T*S	364.15	5.12	0.021
	12	P	364.42	5.38	0.018
	13	T + S	365.60	6.57	0.010
	14	P*T + P*S + T*S	366.28	7.25	0.007
	15	T*S	367.28	8.24	0.004
	16	T	367.47	8.43	0.004
	17	S	369.96	10.93	0.001
	18	NULL	380.89	21.86	0.000

Table 2.1 continued on next page.

Table 2.1 continued from previous page.

0.25 m^3s^{-1}	1	P + T + S	346.08	0.00	0.315
	2	P*T + S	347.62	1.54	0.146
	3	P*S + T	347.72	1.64	0.139
	4	T*S + P	348.81	2.73	0.080
	5	P + T	349.14	3.06	0.068
	6	P + S	349.36	3.28	0.061
	7	P*T + P*S	350.04	3.96	0.044
	8	P*T + T*S	350.45	4.37	0.035
	9	P*S + T*S	350.50	4.42	0.035
	10	P*T	351.03	4.95	0.027
	11	P*S	351.22	5.14	0.024
	12	P*T + P*S + T*S	352.78	6.70	0.011
	13	T + S	353.86	7.78	0.006
	14	P	355.26	9.18	0.003
	15	T*S	355.97	9.89	0.002
	16	T	356.47	10.39	0.002
	17	S	361.03	14.95	0.000
	18	NULL	367.29	21.21	0.000

Table 2.2. Top model set R (ΔAIC_c <4), corresponding ΔAIC_c values, and re-scaled AIC_c weights (w_i) to explain the number of days that discharge in the North Alouette River fell below 0.45, 0.35, and 0.25 m^3s^{-1} from 1970-2010. Parameter symbols are: P (summer average daily precipitation), T (summer average daily temperature), and S (spring snowpack level). Interactions are represented by *.

Low-flow Benchmark	Model Rank	Model Parameters	ΔAIC_c	w_i
0.45 m^3s^{-1}	1	P + S	0.00	0.428
	2	P + T + S	1.30	0.223
	3	P*S	2.16	0.146
	4	P*S + T	3.51	0.074
	5	T*S + P	3.66	0.069
	6	P*T + S	3.94	0.060
0.35 m^3s^{-1}	1	P + T + S	0.00	0.319
	2	P + S	0.95	0.198
	3	P*S + T	1.93	0.121
	4	P + T	2.09	0.112
	5	P*T + S	2.41	0.095
	6	T*S + P	2.71	0.082
	7	P*S	2.96	0.073
0.25 m^3s^{-1}	1	P + T + S	0.00	0.369
	2	P*T + S	1.54	0.171
	3	P*S + T	1.64	0.163
	4	T*S + P	2.73	0.094
	5	P + T	3.06	0.080
	6	P + S	3.28	0.072
	7	P*T + P*S	3.96	0.051

Table 2.3. The average number of days the discharge in the North Alouette River fell below 0.45, 0.35, and 0.25 m^3s^{-1} in 1970 and 2010, with the average annual rate of change from the time-trend regression, including 95% confidence intervals and a p-value from the linear regression analysis.

Low-flow Benchmark	1970 avg. (days)	2010 avg. (days)	Avg. change (days/yr.)	95% CI (days/yr.)		p
				lower	upper	
0.45 m^3s^{-1}	53.1	81.5	+0.70	0.08	1.31	0.028
0.35 m^3s^{-1}	40.4	65.3	+0.61	0.03	1.18	0.040
0.25 m^3s^{-1}	23.4	46.0	+0.55	0.03	1.08	0.040

Table 2.4. The average summer daily average temperature, summer daily average precipitation, and spring (April 1st) snowpack levels in 1970 and 2010, with the average annual rate of change for each climate variable from the time-trend regression, including 95% confidence intervals and a p-value from the linear regression analysis.

Climate Variable	1970 avg.	2010 avg.	Avg. change per yr.	95% CI (Avg. change per yr.)		p
				lower	upper	
Summer Temp.	15.7 °C	17.4 °C	+0.04 °C	0.02 °C	0.06 °C	<0.001
Summer Precip.	2.9 mm	2.7 mm	-0.006 mm	-0.03 mm	0.02 mm	0.628
Spring Snow.	331.1 cm	257.1 cm	-1.8 cm	-3.9 cm	0.3 cm	0.096

Table 2.5. Model-averaged parameter coefficient estimates in standard deviation units (SDU) to explain number of days that discharge fell below 0.45, 0.35, and 0.25 m^3s^{-1} in North Alouette River, reported with the R^2 value, unconditional standard errors (SE), 95% confidence intervals (CI) and Relative Variable Importance (RVI). Parameter symbols are: P (summer average daily precipitation), T (summer average daily temperature), and S (spring snowpack level). Interactions are represented by *.

Low-flow Benchmark	R^2	Parameters	Coefficient (SDU)	S.E. (SDU)	95% CI		RVI
					lower	upper	
0.45 m^3s^{-1}	0.46	Intercept	-0.001	0.121	-0.247	0.245	-
		P	-0.395	0.128	-0.655	-0.135	1.00
		S	-0.455	0.127	-0.713	-0.198	1.00
		T	0.065	0.116	-0.167	0.296	0.43
		P*S	0.020	0.076	-0.133	0.174	0.22
		P*T	-0.002	0.026	-0.055	0.051	0.06
		S*T	0.007	0.053	-0.099	0.113	0.07
0.35 m^3s^{-1}	0.44	Intercept	-0.004	0.126	-0.259	0.251	-
		P	-0.422	0.137	-0.699	-0.145	1.00
		S	-0.266	0.158	-0.582	0.051	0.89
		T	0.193	0.168	-0.142	0.529	0.73
		P*S	0.023	0.079	-0.136	0.181	0.19
		P*T	-0.006	0.037	-0.079	0.068	0.10
		S*T	0.003	0.052	-0.103	0.108	0.08
0.25 m^3s^{-1}	0.51	Intercept	-0.011	0.119	-0.252	0.229	-
		P	-0.408	0.128	-0.668	-0.149	1.00
		S	-0.275	0.145	-0.566	0.015	0.92
		T	0.297	0.151	-0.007	0.600	0.93
		P*S	0.027	0.082	-0.137	0.190	0.21
		P*T	-0.021	0.062	-0.145	0.102	0.22
		S*T	-0.002	0.052	-0.108	0.103	0.09

Table 2.6. Observed (in 2010) and projected (in 2050) average summer mean daily temperature, summer mean daily precipitation, and spring (April 1st) snowpack levels with 95% confidence intervals and the probability that the variable will increase relative to 2010 levels, based on historical rates of change (Table 2.4).

Climate Variable	2010 avg.	2050 avg.	Avg. change per yr.	95% CI (2050 avg.)		Prob. of increase
				lower	upper	
Summer Temp.	17.4 °C	19.0 °C	+0.04 °C	18.2 °C	19.7 °C	1.00
Summer Precip.	2.7 mm	2.4 mm	-0.006 mm	1.5 mm	3.4 mm	0.31
Spring Snow.	257.1 cm	186.0 cm	-1.8 cm	109.3 cm	261.6 cm	0.05

Table 2.7. Multi-model average model predictions of the average number of days that the discharge in the North Alouette River will fall below 0.45, 0.35, and 0.25 m^3s^{-1} in 2050, including 95% empirical confidence intervals and the probability of increase between 2010 and 2050.

Low-flow Benchmark	2010 avg. (days)	2050 avg. (days)	Avg. change (days/yr.)	95% CI (2050 avg. days)		Prob. of increase
				lower	upper	
0.45 m^3s^{-1}	81.5	89.0	+0.19	74.7	103.9	0.85
0.35 m^3s^{-1}	65.3	76.4	+0.28	63.6	89.4	0.96
0.25 m^3s^{-1}	46.0	63.0	+0.43	50.1	76.4	0.99

Figures

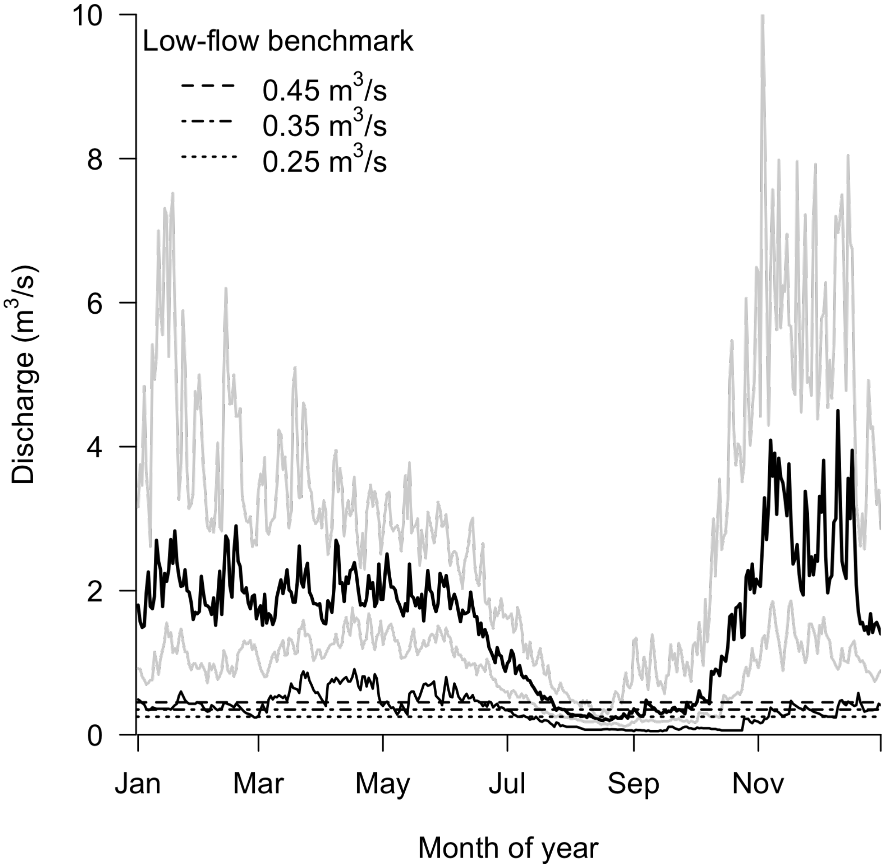

Figure 2.1. Hydrograph of the North Alouette River, BC, from 1970-2010, showing median daily discharge values (thick solid black line), upper/lower quartiles (solid grey lines) and minimum daily discharge (thin solid black line), and three low-flow benchmarks (0.25, 0.35, and 0.45 m^3s^{-1}) from Chapter 2 (dashed lines as indicated in the legend).

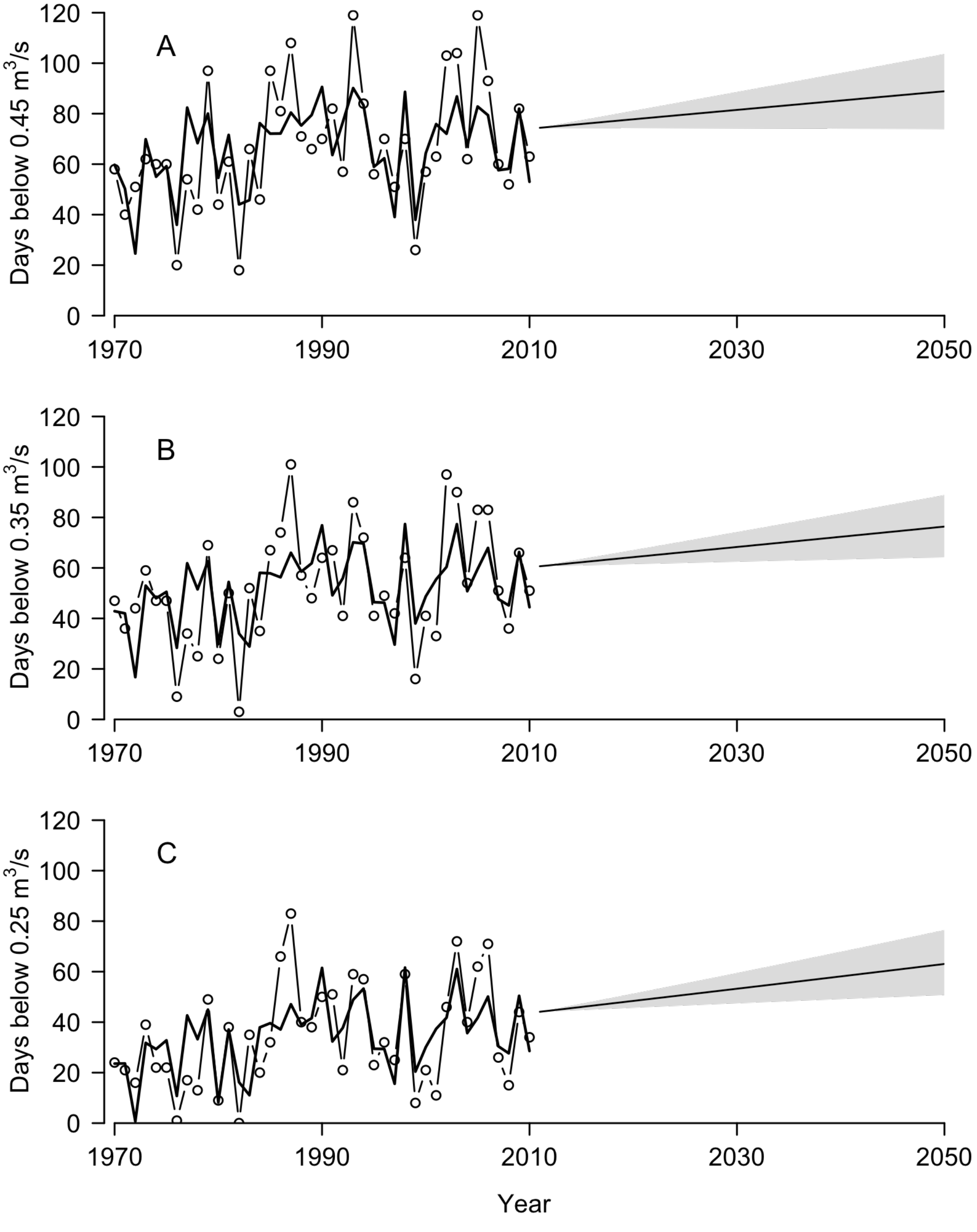

Figure 2.2. The number of observed days (open circles) that discharge in the North Alouette River fell below (A) 0.45 m^{3}s^{-1}, (B) 0.35 m^{3}s^{-1}, and (C) 0.25 m^{3}s^{-1} from 1970 to 2010, with multi-model averaged model predictions (thick solid line) and projections from 2011-2050 (thin black line with empirical 95% confidence interval grey band).

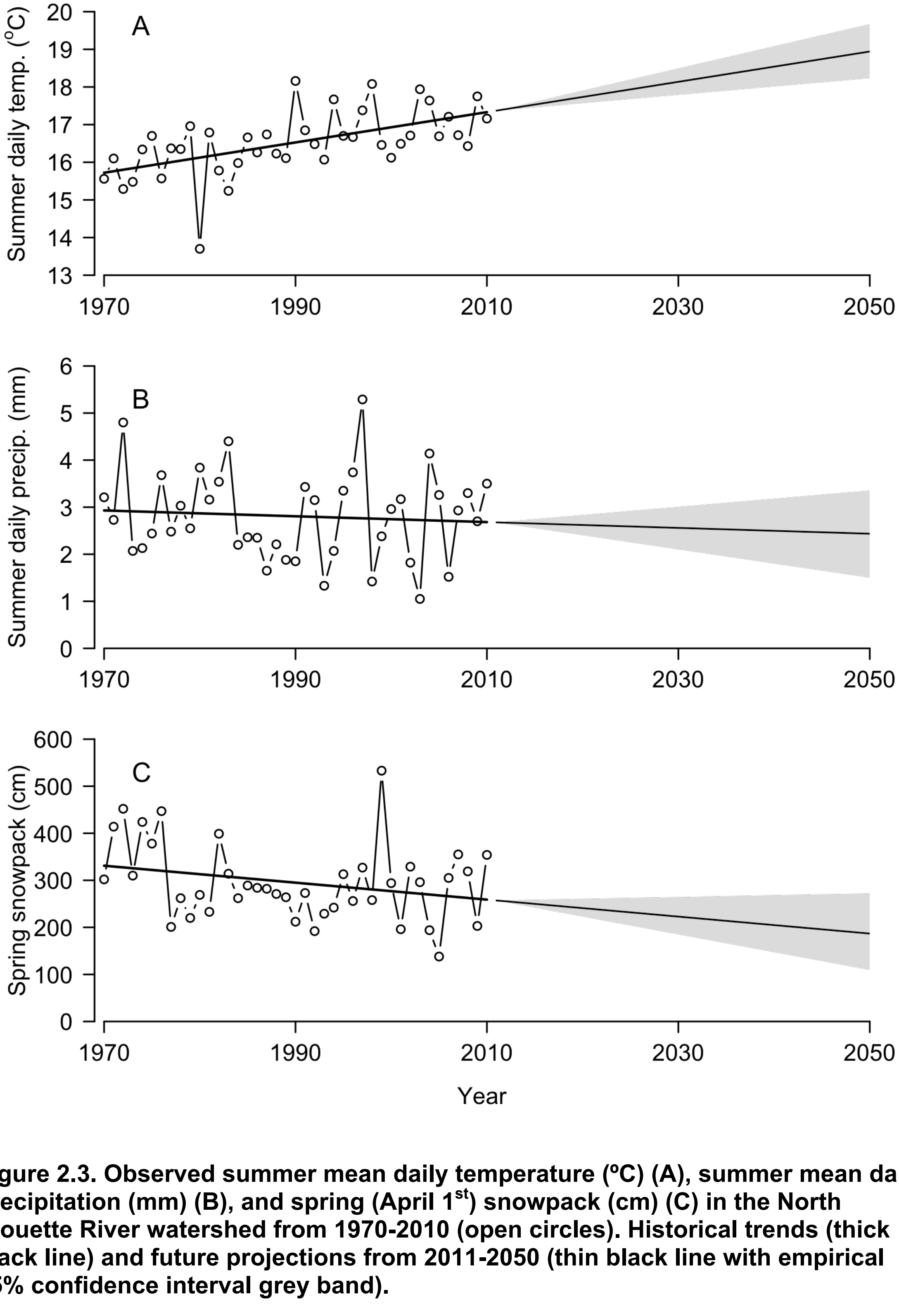

Figure 2.3. Observed summer mean daily temperature (ºC) (A), summer mean daily precipitation (mm) (B), and spring (April 1st) snowpack (cm) (C) in the North Alouette River watershed from 1970-2010 (open circles). Historical trends (thick black line) and future projections from 2011-2050 (thin black line with empirical 95% confidence interval grey band).

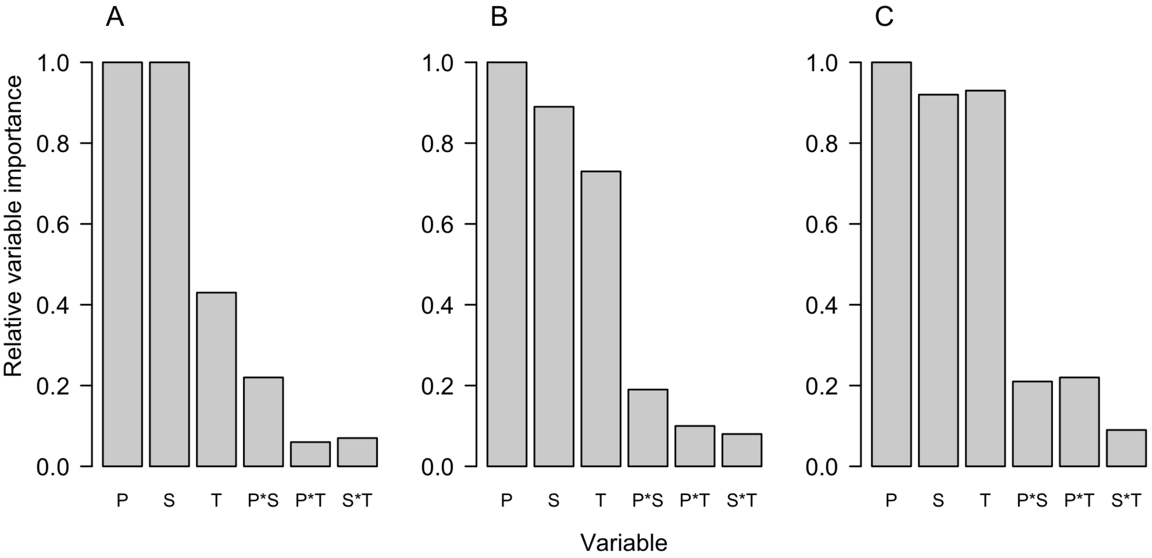

Figure 2.4. The relative variable importance (RVI) of summer mean daily precipitation (P), spring snowpack (S), summer mean daily temperature (T), and interactions (P*S, P*T, and S*T) in explaining the number of days that discharge in the North Alouette River fell below (A) 0.45 m^3s^{-1}, (B) 0.35 m^3s^{-1}, and (C) 0.25 m^3s^{-1} from 1970 to 2011.

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Chapter 4.

General Conclusion

In order to make well-informed decisions regarding water management, it is important to explicitly incorporate uncertainty in information into the decision making process. In particular, my results show that it is important to consider uncertainties in the assessment methods employed when making decisions regarding water withdrawal limits and instream flow requirements (IFR) of streams. If habitat-based assessment methods are utilized to identify IFR, uncertainties in how the quality and quantity of habitat change with stream discharge, and the habitat preferences of the organism of concern are both critical uncertainties to consider. In addition, my results indicate that it is imperative to incorporate the uncertain effects of climate change on natural stream discharge in water use plans. Incorporating such sources of uncertainties into the decision making process will allow for management decisions based on individual risk tolerances for habitat loss.

In chapter 2, using the British Columbia Instream Flow Methodology (BCIFM), I investigated the IFR of *O. mykiss* fry in the North Alouette River, BC. My results show that both uncertainty in habitat preferences of fish and variation in physical habitat among sampled transects translated into substantial uncertainty about the amount of usable habitat that is available to rainbow trout fry as a function of discharge (habitat-flow relation). In particular, uncertainty in habitat preferences of rainbow trout fry generally dominated uncertainty in the results of the BCIFM when large numbers of transects were used. In contrast, with <15 transects, variation in physical habitat among sampled transects was the major source of uncertainty in the habitat-flow relation. Understanding these relative contributions of uncertainty to the results of the BCIFM is important in order to set priorities for sampling efforts. Finally, my results showed that when uncertainty is incorporated in the habitat-flow relation, calculating the probability of different magnitudes of habitat loss allowed for clear and concise interpretation and communication of the management implications of this uncertainty. This information is important because it allows managers to develop IFR based on their risk tolerance for habitat loss. Without this sort of information, managers are left to set IFR based on best point estimates of available habitat as a function of discharge, with little knowledge of the certainty of maintaining the aquatic ecosystem health.

In chapter 3, I investigated how the number of days of low discharge, as described by three potential low-flow benchmark levels for *O. mykiss* fry, has changed in the North Alouette River. A historical analysis (1970-2010) showed there was a statistically significant increasing trend in the number of days that the North Alouette River's natural discharge receded below each of these critical benchmark levels each year. Three climate variables (summer daily average temperature, summer daily average precipitation, and spring snowpack levels) were used to explain these trends in the low-flow period from 1970 to 2010. Finally, simple projections of climate variables based on historic rates of change were used to model trends in the low-flow period in the North Alouette River from 2011 to 2050. These model projections suggested that there is a high probability that the number of days of low discharge in the North Alouette River will increase for all three low-flow benchmarks.

The projected increasing trend in critical low-flow periods has important implications for both aquatic resources and water resource management. Increases in duration and/or severity of natural low-flow periods in streams will likely reduce productivity of some stream fish species/life-history stages. Additional anthropogenic water withdrawals from the stream will only intensify the severity of low-flow periods and the effects on these fish species/life-history stages. In addition, the increased duration of natural low-flow periods may have negative implications for hydroelectric generation in the Pacific Northwest. The reduced generation capacity of rivers in the future could have serious implications for the economic viability of projects and security of electricity generation for BC and the Pacific Northwest. Understanding these projected changes to stream discharge will be highly valuable to water resource managers and resource stakeholders to develop appropriate planning measures. In order to effectively manage water resources in the future, these potential effects of climate change on hydrologic resources must be incorporated into water management plans in BC.