Evaluating the vulnerability of freshwater fish habitats to the effects of climate change in the Cariboo-Chilcotin:
Part I – Summary of technical methods

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To British Columbia's scientists and managers, climate change poses a range of complex and somewhat daunting challenges. Developing solutions to overcome these challenges will require greater collaboration among resources agencies and stakeholders, as well as greater integration of activities than has typically been applied in the past. The level of collaboration and enthusiasm among agencies and individuals contributing to this project was a positive sign of the willingness to tackle the challenges that lie ahead. This level of collaboration was a foundation to this project's success.

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1.0 Introduction: Linking vulnerability to adaptation

Over the next century in British Columbia climate induced changes in precipitation and air temperature are expected to be variable by region and season (Rodenhuis et al. 2007; Pike et al. 2008a). The general trend is for increasing air temperatures across the province with the largest increases projected in the north and during the winter. In regards to changes in precipitation the general pattern is for drier conditions in the south and during the summer, with northern latitudes projected to receive more precipitation. In the Cariboo-Chilcotin by the 2050s average annual air temperatures and average annual precipitation are both predicted to increase from 2.0-2.5 °C and 5-20% respectively, although in some locations summer precipitation is expected to decrease by as much as 5% (Dawson et al. 2008).

Based on historic observations (Leith and Whitfield 1998; Whitfiled and Cannon 2000; Zhang et al. 2001) and future projections (Leung and Qian 2003; Whitfield et al. 2003; Merritt et al. 2006) these kinds of changes in climate are expected to lead to noticeable changes in watershed hydrology as mediated by changes in snow pack accumulation, patterns of snowmelt, and glacier cover among other factors. The magnitude and direction of streamflow changes in a watershed will vary according to the dominant pattern of runoff. Watersheds in the Cariboo-Chilcotin are generally snowmelt-dominated which tend to have peak flows in the spring, low flows in the late summer and fall – due to low precipitation and dwindling snowpack – and low flows through the winter due to cold conditions that lead to precipitation accumulating as snowpack (Eaton and Moore 2007). In the future, these types of watersheds are anticipated to see shifts in runoff patterns that more closely mimic mixed hydrologic regimes (rainfall-snowmelt patterns) where periods of snow accumulation are reduced and peak flows start earlier in the spring (Pike et al. 2008b).

Less is known about expected water temperature changes across freshwater systems in B.C. though stream and lake temperatures are generally expected to rise as a result of increasing air temperatures and changes in surface water and groundwater flows (Tyedmers and Ward 2001; Pike et al. 2008b). The Fraser River is the most well studied basin for water temperatures where historic analyses have shown increases in maximum water temperatures of approximately 1.8 °C over the last 50 years at Hell's Gate (Foreman et al. 2001; Morrison et al. 2002; Farrell et al. 2008) and climate change models estimate up to an additional 2 °C of warming by 2080 (Morrison et al. 2002). Given the known relationship between air and water temperatures in smaller streams (Stefan and Preud'homme 1993; Scholz 2001; Moore 2006; Nelitz et al. 2007b; 2008) increasing thermal regimes can also be expected in tributary and headwater systems.

The biological implications of climate-induced changes in physical environments are significant as alterations in the timing / magnitude of streamflow and stream thermal regimes are fundamentally linked to behavioural and physiological responses of life stages of freshwater dependent fish species, such as Pacific salmon (Nelitz et al. 2007a) and bull trout (Dunham et al. 2003). In snowmelt-dominated systems overall mean annual flow is expected to increase though an earlier spring freshet may extend the period of summer low flows, thus constraining availability of summer rearing habitats. Streams in headwater areas will likely be affected most negatively by this change. Historically, these areas provided some of the most suitable habitat conditions which may become inaccessible if flows are reduced or unusable as cool-water refugia if warming occurs. Additionally, low flow conditions may coincide and exacerbate stream warming during periods of peak summer air temperature which can create thermal barriers to adult and juvenile migration, increase physiological stress and mortality of adults and juveniles, and alter the thermal suitability of rearing conditions (Irvine 2004; Nelitz et al. 2007a; Bisson 2008). Ultimately, the effects of temperature on individuals can lead to shifts in species distributions (Dunham et al. 2001) and fish community structure (Wehrly et al 2003; Nelitz et al. 2008).

The effects of human activities – both stressors and restoration actions – on freshwater habitats are overlaid on top of these underlying biophysical changes. Stressors can magnify the adverse effects of climate change, for instance, by reducing water availability in stressed freshwater habitats, by removing riparian buffers from thermally sensitive habitats, or by imposing unsustainable exploitation rates on vulnerable populations.

Alternatively, restoration actions can mitigate the effects of climate change by restoring freshwater supplies to mitigate against low summer flows during adult migration and spawning or by adjusting harvest rates to account for poor ocean productivity or in-river conditions. Given our general understanding of the adverse effects of climate change and contributing role of human actions in both positive and negative ways, it is critical that we develop strategies to help freshwater fish species cope (see range of strategies in Nelitz et al. 2007a). Developing intelligent coping strategies, however, requires that we make decisions using detailed information so we know what to do, where and when so as to avoid wasting precious time, money, and people's energy. Evaluating the vulnerability of freshwater habitats to climate change is a critical first step to providing decision makers with that detailed information (Spittlehouse and Stewart 2003) and is consistent with previously identified priorities for improving management of B.C.'s freshwater habitats in the context of climate change (Tyedmers and Ward 2001).

This technical report describes the methods used to assess the vulnerability of freshwater habitats – changes in summer stream flows and water temperature – across the Cariboo-Chilcotin. It is the first study of its kind for this region and represents a pilot application of an approach for assessing vulnerability. The hope is that these methods could eventually be applied more broadly to assess other vulnerable regions in B.C. Results from this evaluation are presented in the second part of this report (Nelitz et al. 2009) and three species-specific habitat outlook papers (Porter and Nelitz 2009a; Porter and Nelitz 2009b; Nelitz and Porter 2009). The intention is that these results can eventually help regional decision makers understand potential vulnerabilities of freshwater habitats. Additional efforts are needed to help regional decision makers use this information and decide what actions to pursue today that will benefit human communities, freshwater habitats, and fish populations of the Cariboo-Chilcotin in the future.

2.0 Methods: Assessing vulnerability

Our approach to assessing vulnerability of freshwater habitats involved linking outputs from a series of readily available quantitative models (Figure 1). The first step involved downscaling climate projections from four Global Climate Models (GCM) and three emissions scenarios (see *Section 2.1*). Predictions of future air temperatures and precipitation were then used as inputs for a physically-based, macro-scale hydrological model (see *Section 2.2*) that generated daily flow measurements at focal "nodes" across the study area. Downscaled air temperatures were also used in an empirical model to predict an annual metric of stream temperature across a different set of "nodes" throughout the stream network (see *Section 2.3*). Next, fish observations, known barriers, and channel characteristics were used to develop reach-scale distribution layers in GIS (see *Section 2.4.1*) for three focal fish species: bull trout (*Salvelinus confluentus*), Chinook salmon (*Oncorhynchus tshawytscha*), and coho salmon (*Oncorhynchus kisutch*). Lastly, predictions from stream flow and temperature models were compared against biologically-based fish habitat criteria and combined with the species distribution layers to determine the spatial extent and suitability of freshwater habitats (see *Sections 2.4.2 and 2.4.3*) for a historic reference (1961-1990) and future time periods (2020s, 2050s, and 2080s).

We focused our vulnerability assessment on the above focal species for a variety of reasons. First, we wanted a set that represented a mix of anadromous and resident species. For salmon, we selected those species with life history strategies most reliant on freshwater habitat conditions for rearing (i.e., coho and Chinook). Sockeye salmon (*Oncorhynchus nerka*) were not included because of their reliance on lentic environments and we did not have any ability to predict the effect of flow and temperature changes in lakes. We included bull trout because it is highly sensitive to changes in temperature conditions (Dunham et al. 2003), is blue listed, and a vulnerable species in B.C. (WLAP 2002).

The Cariboo-Chilcotin study area (Figure 2) was delineated by tributaries to the Fraser River between the confluence of the Thompson and Nechako Rivers (exclusive). Tributary watersheds included, among others, Baker Creek, Bridge River, Chilcotin River, Churn Creek, Quesnel River, Seton River, Stein River, West Road River, and Williams Lake River.

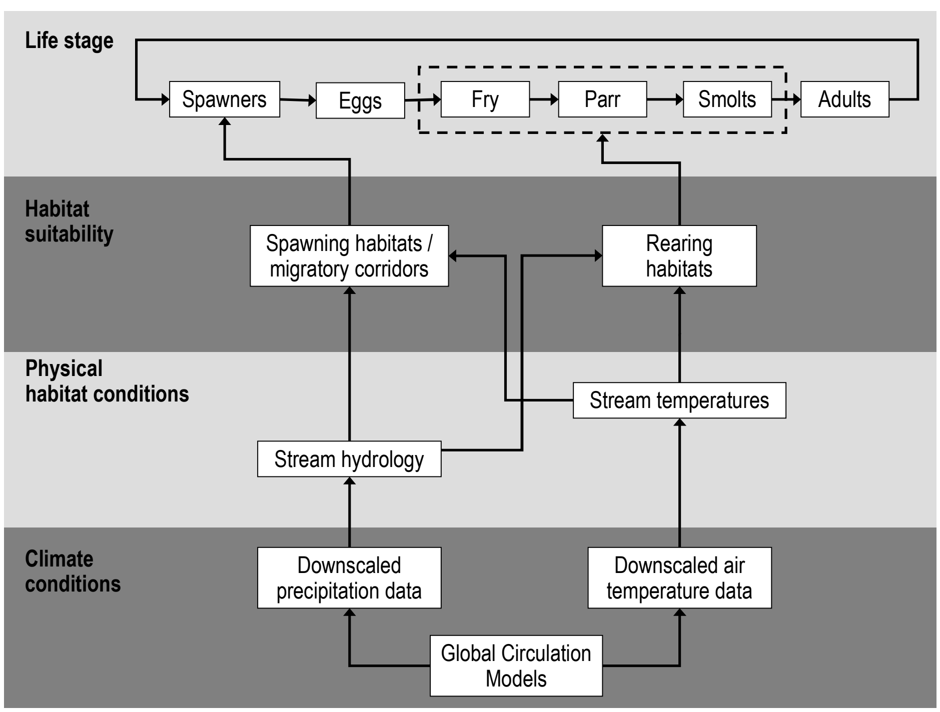

Figure 1. Simplified conceptual model illustrating the linkages among climate, physical habitat conditions, habitat suitability, and Pacific salmon life stages.

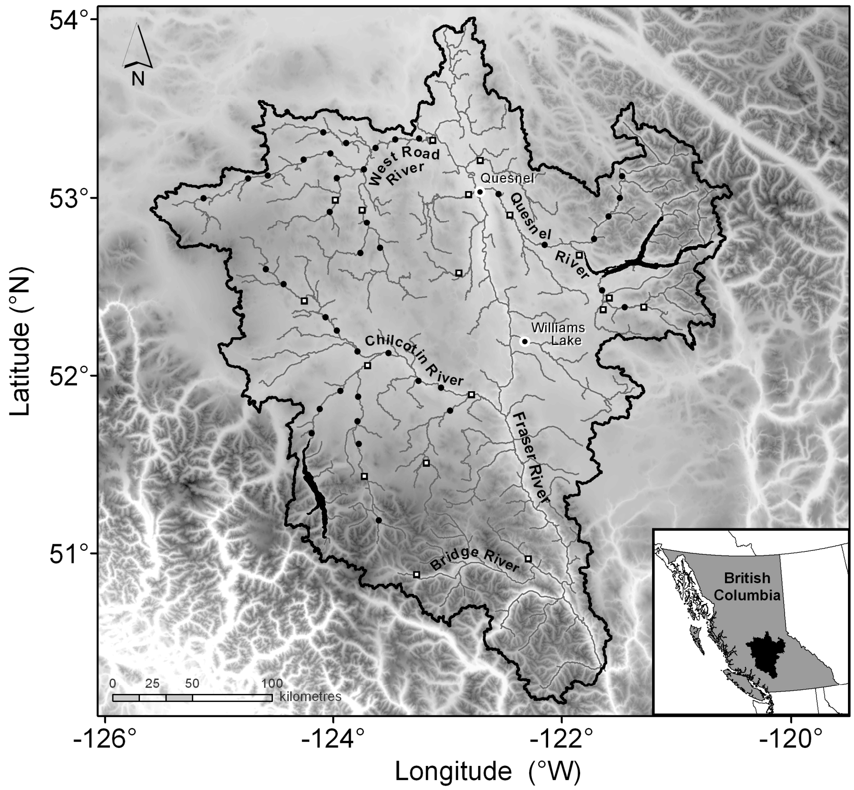

Figure 2. Delineation of the Cariboo-Chilcotin study area for the vulnerability assessment. Stream locations where flow modeling results were summarized are marked as ungauged locations (●) and those where hydrometric stations currently exist (□).

2.1 Modelling climate change

In developing scenarios of future climate change, a first task was to select the appropriate Global Climate Models (GCMs), emissions scenarios, and time periods over which to generate projections. The full suite of recent models and scenarios from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) were considered in our initial list[1]. Recognizing that all 184 combinations of 23 GCMs and 8 emission scenarios are plausible futures, our goal was to narrow this list to 6 combinations that represented a reasonable range of changes in air temperature and precipitation. For comparison purposes, it was also important that we select models, scenarios, and time periods that were comparable and consistent with similar studies. Based on a review of studies investigating the effects of climate change on fish populations and fish habitats in the Pacific Northwest (Table 1), we decided to focus on GCMs from the Canadian (*cccma_cgcm3*) and United Kingdom (*ukmo_hadcm3*) modeling laboratories. We also focused on the current set of IPCC emissions scenarios – A1B, A2, and B1 (Figure 3)[2] – and three commonly considered time periods – 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099).

[1] Data for all GCMs and IPCC emission scenarios are available from http://www.ipcc-data.org/ar4/gcm_data.html

[2] **A1B:** A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.

A2: A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.

B1: A convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

Table 1. Summary of models, scenarios, and time periods used for climate change modeling across recent fish habitat studies in the Pacific Northwest.

Citation	Title	Geographic focus	Global Climate Models (GCM)	Emissions scenarios	Reference year (time frame)
Battin et al. 2007	Projected impacts of climate change on salmon habitat restoration	Puget Sound, WA	HadCM3; GFDL_R30	SRES A2 (global); PSRC (regional)	2025s 2050s
Crozier and Zabel 2007	Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon	Salmon River, ID	CGCM_3.1; HadCM3; ECHAM5; CCSM3; PCM1; CNRM_CM3; CSIRO_MK3; Miroc_3.2; IPSL_CM4; GISS_ER	SRES A2 using (1) average monthly changes in temperature and precipitation as predicted across 10 GCM models, and (2) hottest and driest of the 10 GCM models	2040s
Cohen and Neale 2006	Participatory integrated assessment of water management in the Okanagan Basin, British Columbia	Okanagan Valley, BC	HadCM3	SRES A2	2020s (2010-2039) 2050s (2040-2069)
Taylor and Barton 2004	Climate change scenarios. Chapter 5 In: Expanding the dialogue on climate and water management in the Okanagan Basin	Okanagan Valley, BC	CGCM2; CSIROMk; HadCM3	SRES A2, B2	2020s (2010-2039) 2050s (2040-2069) 2080s (2070-2099)
O'Neal 2002	Effects of global warming on trout and salmon in U.S. streams	Entire USA	CGCM2; CSIRO-Mk2; HadCM3	SRES A1, A2, B1, B2	2030s (2016-2045) 2060s (2046-2075) 2090s (2076-2099)
Morrison et al. 2002	Climate change in the Fraser River watershed: flow and temperature projections	Fraser River basin, BC	CCGM1; HadCM2 (downscaled)	IS92a	2020s (2010-2039) 2050s (2040-2069) 2080s (2070-2099)
Tyedmers and Ward 2001	A review of the impacts of climate change on BC's freshwater fish resources and possible management responses	BC	CGCM1	Doubling of CO_2	2020s (2010-2030) 2050s (2040-2060) 2090s (2080-2100)
Cohen and Kulkami 2001	Water management and climate change in the Okanagan Basin	Okanagan Valley, BC	CGCM1; ECHAM4; HadGCM	IS92a	2020s (2010-2039) 2050s (2040-2069) 2080s (2070-2099)
Kyle and Brabets 2001	Water temperatures of streams in the Cook Inlet Basin, Alaska, and implications of climate change	Cook Inlet, AK	CGCM; HadGCM	Doubling of CO_2	2100s
Eaton and Scheller 1996	Effects of climate warming on fish thermal habitat in streams of the United States	Continental USA	CGCM	Doubling of CO_2	Time frame not specified

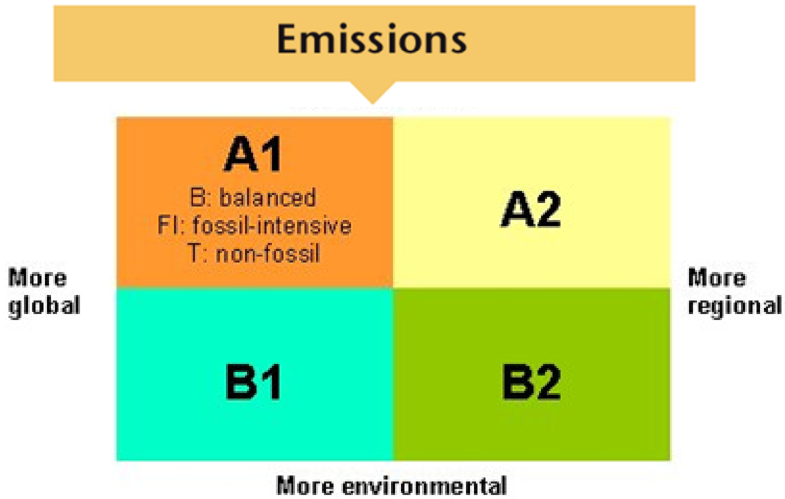

Figure 3. Alignment of emissions scenarios described by the IPCC Special Report on Emissions Scenarios (SRES) along axes of the spatial scale at which changes occur (global or regional – left to right) and the aggressiveness with which emissions reductions occur (less or more environmental – top to bottom).

To select the appropriate model and scenario combinations, we analyzed differences in summer climate conditions for the 2080s (2071-2100) across models and scenarios for the Fraser River basin (Figure 4). We focused this analysis on the summer because it was the season of most interest for fish habitat modeling, and explored model differences during the 2080s because differences due to emissions scenarios tend to be more detectable at this time than in the 2050s (2041-2070). In doing this analysis, we found the A1B and A2 scenarios for *ukmo_hadcm3* provided very similar temperature and precipitation projections. As well, the B1 scenario for *ukmo_hadcm3* was similar to the A2 scenario for *cccma_cgcm3*. There was a reasonable spread, however, among the A1B, A2, and B1 scenarios for *cccma_cgcm3*. Thus, among these models and scenarios we selected the A1B, A2, and B1 scenarios for the *cccma_cgcm3* and A1B scenario for *ukmo_hadcm3*. To get a better representation of extreme changes in precipitation and temperature across the basin, we also considered models that had a larger change in climate conditions than the above GCMs. The *gfdl_cm20* model A2 scenario showed substantial warming (4.0 °C) combined with a large precipitation reduction (-36%), and the *mpi_echam5* model under an A1B scenario projected increases in both precipitation (15%) and temperature (3.0 °C). These six scenarios provided a good range of predictions in summer climate for the Fraser River basin (Figure 4 and Table 2). Most GCMs have data available starting from the early 1900s, which allow for comparisons between past observations and GCM results over a historical reference period. Most projected results are shown as differences from a 1961 to 1990 reference period to eliminate the influence of model bias on projected changes. Biases in the GCMs were also corrected using a statistical downscaling technique by comparing them to historic climate observations (1950-2006) as described below (Bennett et al. in prep).

GCM resolution varies from model to model. Depending on the model, 10 grid cells or tiles are needed to cover British Columbia, each of which has a horizontal resolution from 300 to 500 km (Hutchinson and Roche 2008). At this coarse resolution the complex climatology of BC is not well represented, especially in areas where there are significant topographic features, such as the coastal mountain range. To create data that were more regionally relevant, future climate projections were created by downscaling (or increasing the resolution of) the GCM data for the models and emissions scenarios described above. To do so we applied a statistical downscaling approach developed by the Climate Impacts Group at the University of Washington based on methods developed by others (Wood et al. 2002; Widmann et al. 2003; Salathé 2005; Salathé et al. 2007). Originally this approach was developed for downscaling to 1/8th of a degree. For this study, we used these downscaling methods to create a 1/16th degree dataset (grid cells 27-32 km^2 in area depending upon latitude) because the Variable Infiltration Capacity (VIC) and water temperature models required data at this resolution.

The downscaling method applied here is referred to as the Bias Correction and Statistical Downscaling (BCSD) technique, most recently modified and updated by Eric Salathé of the Climate Impacts Group. With the BCSD technique, GCM simulations were bias corrected using quantile-quantile transfer functions between GCM simulations for the historical period and gridded-observed temperature and precipitation. Fitting was completed independently for each climate model using a 20th Century climate simulation that matches the period of observations. A transient, monthly dataset was produced and this was disaggregated to a daily time series by re-sampling the historic data set. Empirical orthogonal functions (EOFs) analysis, with spatial EOFs derived from the historic record, was applied to select an appropriate analog month that produced a daily weather sequence consistent with the monthly-mean state.

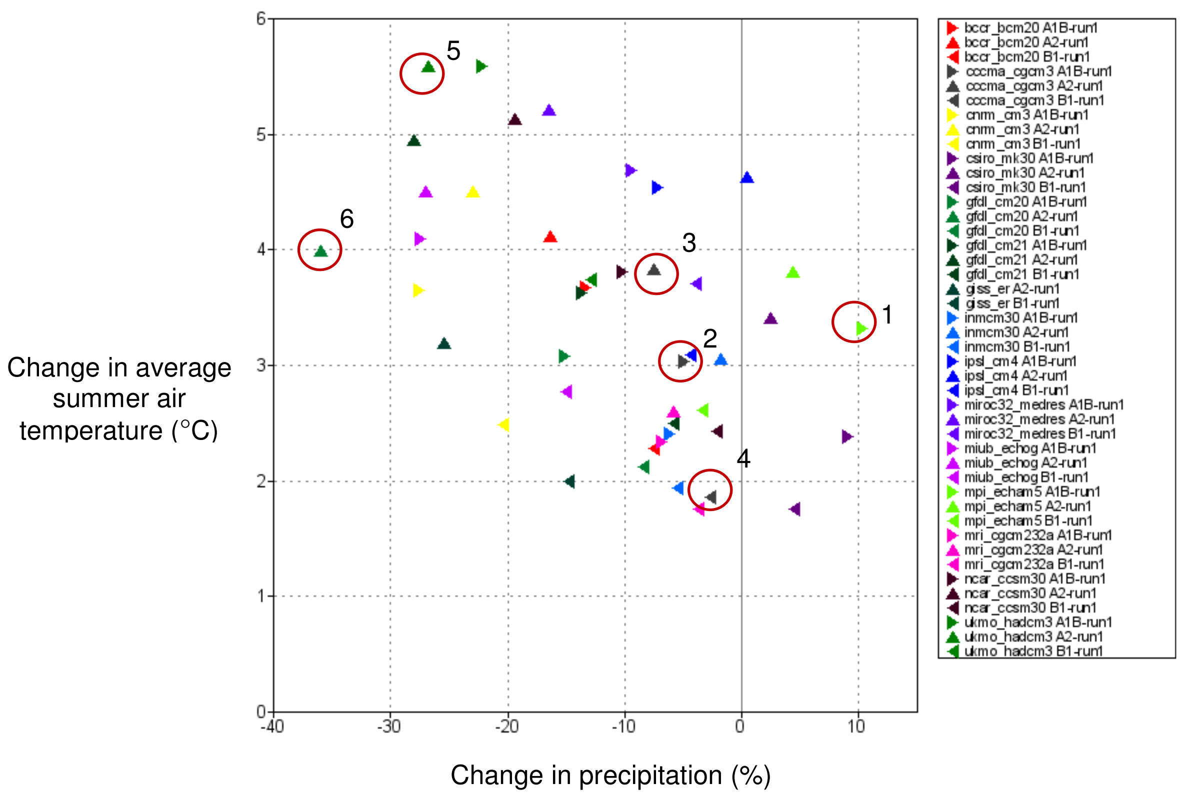

Figure 4. Plot of the change in average summer air temperatures against percentage change in precipitation for the 2080s from a range of GCMs and IPCC emissions scenarios applied to the Fraser River basin. Results from the six model-scenario combinations used in this study are circled: (1) mpi_echam5 A1B (warm-wettest), (2) cccma_cgcm3 A1B (middle of the road), (3) cccma_cgcm3 A2 (warm, small change in precipitation), (4) cccma_cgcm3 B1 (cool, minimal change in precipitation), (5) ukmo_hadcm3 A1B (warmest-dry) and (6) gfdl_cm20 A2 (warm-driest).

Table 2. Six model and scenario combinations selected for this study. Unique model-scenario numbers refer to labels used in Figure 4.

Modeling Laboratory (GCM name-version)	IPCC emissions scenarios			
	Historic baseline (1950-2006)	A1B (2007-2099)	A2 (2007-2099)	B1 (2007-2099)
Max Planck Institute for Meteorology (mpi_echam5)	X	1		
Canadian Centre for Climate Modelling and Analysis (cccma_cgcm3)	X	2	3	4
Hadley / United Kingdom Meteorological Office (ukmo_hadcm3)	X	5		
Geophysical Fluid Dynamics Laboratory (gfdl_cm20)	X		6	

2.2 Predicting stream flow conditions

To understand broad-scale implications of climate change on freshwater flows, we used the University of Washington's Variable Infiltration Capacity (VIC) hydrologic model[3], originally developed as a soil-vegetation-atmosphere transfer scheme to operate within a GCM (Liang et al. 1994; 1996). VIC is a research model capable of solving water and energy balances across broad spatial areas, and has proven successful for evaluating climate change impacts on global river systems (Nijssen et al. 2001). As well, the VIC hydrologic model has been validated in the Canadian portion of the Columbia River Basin (Hamlet and Lettenmaier 1999; Payne et al. 2004) and in the mountainous western US (Christensen et al. 2004; Hamlet et al. 2005; Vanrheenen et al. 2004). VIC is able to simulate hydrologic responses at basin scales of 500 km^2 or greater (Maurer et al. 2002).

The land surface in VIC is modeled as a grid of large (1/16th degree or approximately 32 km^2), flat, and uniform cells. Heterogeneity at smaller scales (e.g., elevation and land cover) is handled using statistical distributions. The VIC model simulates water and energy balances at the land surface at a daily or sub-daily time step. Model inputs include the climate forcings, a time series of daily climate drivers (e.g., precipitation, air temperature, and wind speed) generated for each grid cell, and gridded data describing vegetation, soils, topography, and the river network. Gridded climate forcings have been built for all of BC following the methods of others (Maurer et al. 2002; Hamlet and Lettenmaier 2005). Daily gridded climate surfaces were generated from 1915 to 2006 specifically for the BC-region.

There are a number of key considerations with regards to assessing output and analyzing results from the VIC hydrologic simulations. Water can only enter VIC grid cells via the atmosphere, or rather from the gridded forcings data that represents atmospheric input. Channelized stream flow across the land surface is performed using a routing model (Lohmann et al. 1996; 1998). Once water reaches the river routing network, or channel, it is assumed to stay in the channel (i.e., water cannot flow back into the soil), and crosses via the channel into neighboring cells. Non-channel flow between grid cells is ignored. Once the VIC model was parameterized with all forcings and input data, a baseline historic data set of daily flow predictions were generated across all 1/16th degree grid cells. The model was then calibrated and validated by comparing this baseline to measured flow at hydrometric stations located along rivers draining > 500 km^2 where records were continuous over the calibration and validation period of 1985 to 1995. Future projections from the above model-scenario combinations were used to develop daily gridded climate surfaces from 2007 to 2099. These inputs were then used as new forcings in the VIC model to generate flow predictions for each climate change scenario and model.

[3] University of Washington, Department of Civil and Environmental Engineering. Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model. Available at: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html

Given the immensity of flow data, for fish habitat modeling purposes we selected a subset of stream locations (i.e., “nodes”) at which to summarize flow predictions across the study area. To ensure continuity with historic observations of stream flow, we included 18 “nodes” that were used to calibrate the hydrologic model for which statistical and graphical comparisons of the simulations, historical GCMs results, and observations could be quantified and examined. Across locations, these comparisons showed relatively strong agreement between past observations and retrospective application of the GCM models (e.g., Figure 5), though the model did not perform well in a few other locations (e.g., Figure 6). We also selected 40 points that were to be distributed longitudinally at approximately 20 km intervals along the mainstems of the Chilcotin, West Road, and Quesnel Rivers. In assigning these additional “nodes” we ensured these locations were on streams with drainage areas > 500 km^2, were not represented by a nearby hydrometric station (i.e., one of the 18 nodes mentioned above), and did not fall within a lake. The resulting set of 58 “nodes” at which we summarized VIC hydrology predictions is represented in Figure 2, only 18 of which were used in our analysis for suitability of fish habitats.

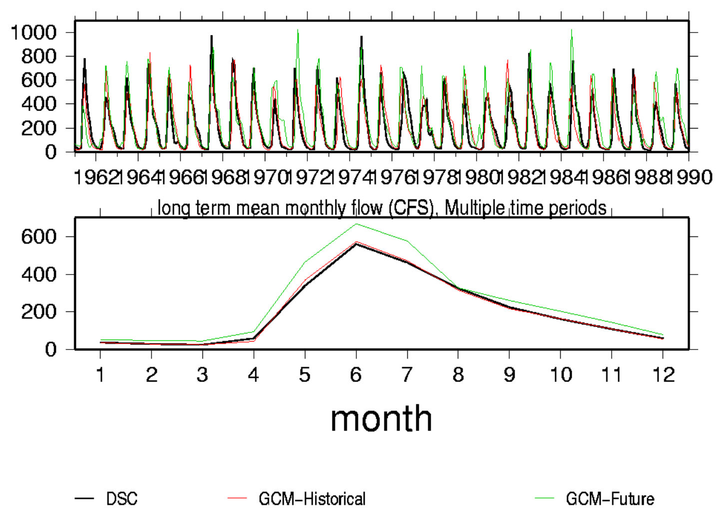

Figure 5. Mean monthly flow (in cubic feet per second) on Big Creek for historic observations, historic application of the cccma_cgcm3 model, and future projections to the 2050s. Top panel includes data across the historic period (1961-1990). Bottom panel includes monthly averages across the entire reference period.

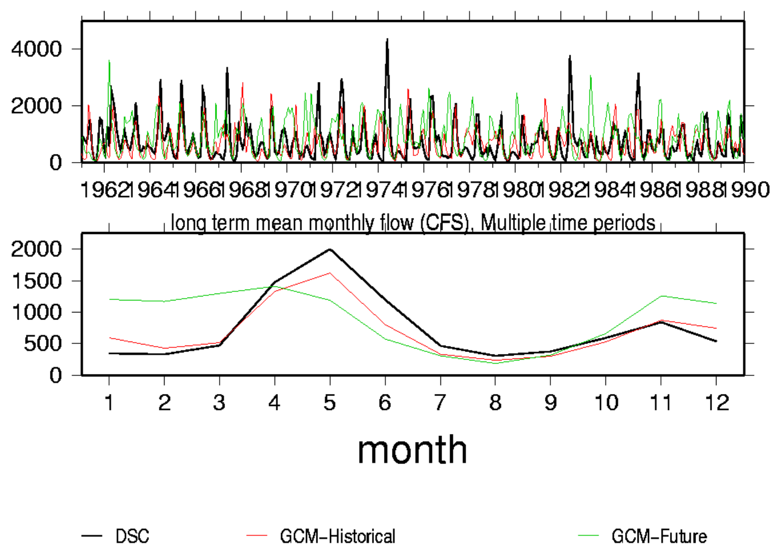

Figure 6. Mean monthly flow (in cubic feet per second) on Cotton Creek for historic observations, historic application of the cccma_cgcm3 model, and future projections to the 2050s. Top panel includes data across the historic period (1961-1990). Bottom panel includes monthly averages across the entire reference period.

2.3 Predicting stream temperature conditions

To predict changes in stream temperatures across the study area, we applied a recently developed empirical model to estimate the annual maximum of a seven-day running average of the daily mean water temperature – Maximum Weekly Average Temperature, MWAT (Nelitz et al. 2008). Equation (1) describes the relationship between MWAT and the landscape characteristics and climatic influences affecting the upstream watershed:

$$\begin{aligned} MWAT &= 7.911 + (0.4835 * T_a) + (1.176 * Log(A)) - (0.003059 * Z_m) \\ &- (0.9433 * \sqrt{f_g}) + (1.748 * \sqrt{f_l}) - (0.05291 * Slope) - (0.7194 * K_2) \end{aligned} \tag{1}$$

where average July-August air temperature (T_a), drainage area (A), fractional glacier coverage (f_g), fractional lake coverage (f_l), stream slope (slope), mean basin elevation (Z_m), and a 2-year flood frequency parameter (K_2) were significant predictors. This relationship was developed by analyzing water temperatures, watershed characteristics, and climate data from hundreds of streams across British Columbia, including many streams from the Cariboo-Chilcotin. Predictions from the model represent the expected average MWAT in a stream for a reference period (1990-2003), not a single estimate for a particular year. As well, predictions are generated at the most downstream points of interest across all third order (and larger) basins with drainage areas <10,000 km^2 (~1,000 polygons).

To link this model to the climate change projections describe above, we calculated the average July-August air temperatures across all models, scenarios, and years. Summer air temperature predictions were then averaged across three future reference periods — 2010-2039, 2040-2069, and 2070-2099 — to represent summer air temperatures at three points over the next century 2020s, 2050s, and 2080s. Next, these future summer air temperature conditions were assigned coordinates to represent each $1/16^{th}$ degree (35 km^2) grid cell across the study area. A nearest neighbour calculation was used to locate the grid cell closest to the stream location where an MWAT prediction was required. In many cases the elevations were very different and distance between these points large. Given the significant influence of elevation on air temperatures, we developed a regression relationship to adjust for such differences between locations. For this analysis we extracted historic (1961-1990) estimates of air temperature from Climate BC[4] for the centre of all grid cells and all points of interest for MWAT modelling. We then calculated differences in elevation and temperature for all grid cell-stream pairs and plotted them to determine an appropriate relationship to adjust air temperatures (Figure 7). Based on this analysis, we determined that for every 1,000 metre decrease in elevation there should be a corresponding ~4 °C increase in average air temperature. Consequently, all air temperature predictions from the downscaled GCM results were adjusted using this relationship before being applied in the MWAT model.

[4] Univesity of British Columbia, Centre for Forest Conservation Genetic. ClimateBC: A program to generate climate normal data for genecology and climate change studies in western Canada. Available at: http://www.genetics.forestry.ubc.ca/cfcg/climate-models.html

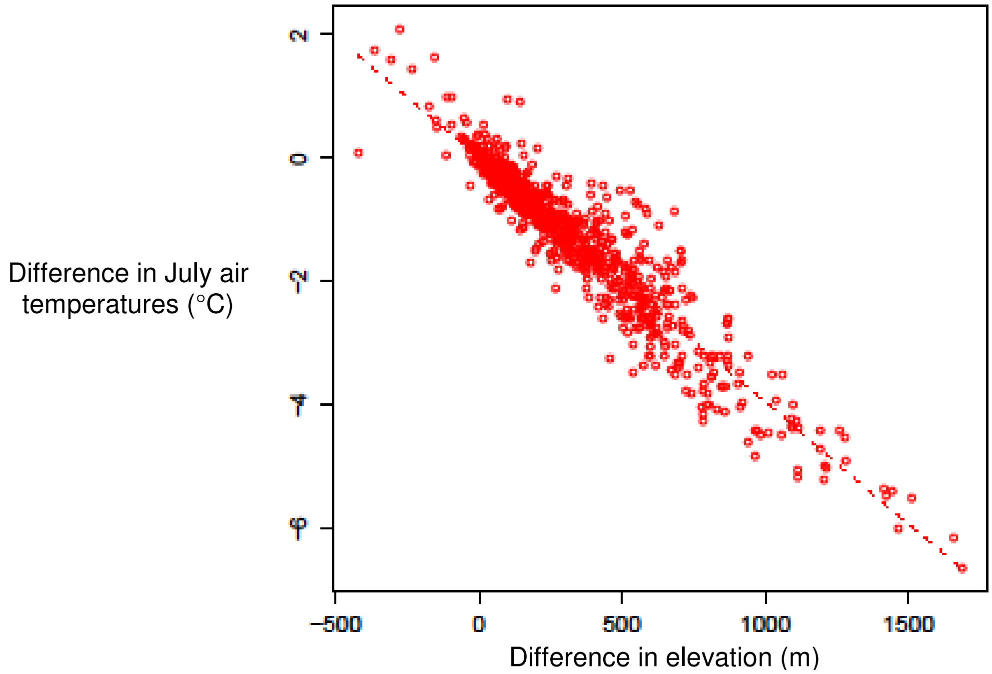

Figure 7. Plot of the calculated differences in elevation and temperature between all grid cell-stream pairs across the study area. Each data point represents the calculated difference in elevation and historic July air temperature between a location where an MWAT prediction is required and the nearest grid cell where air temperatures area available from the GCMs (~ 1,000 pairs). This relationship shows that for every 1,000 metre decrease in elevation there should be a corresponding ~4 °C increase in average air temperature.

2.4 Assessing suitability of habitats

Modeling the combined effects of expected climate change-induced temperature and flow changes on salmonid populations could employ different methods dependent on the spatial-temporal scales of interest and the quality of the information available for the exercise. One possible approach could involve linking fine resolution temperature and flow models into spatially explicit life-cycle models to predict changes in fish population dynamics. This has been undertaken recently by Battin et al. (2007) where various climate models predicting temperature and flow changes in Washington's Snohomish River Basin were linked to the Shiraz salmon population model (Scheuerell et al. 2006) to predict the effects of climate change on the basin's Chinook salmon populations. Similar modeling of climate impacts on Atlantic salmon is currently a focus for the USGS on the east coast, where watershed models predicting future flow (particularly focused on summer low flow) and instream temperatures are being linked to an USGS Atlantic salmon survival model to describe future scenarios of salmon population dynamics in the Gulf of Maine (USGS 2008). Such models are intended to provide great flexibility in evaluating climate change scenarios but are generally focused on relatively small spatial scales (e.g., single Basin) and require detailed information on life-stage specific survival and fecundity parameters, the specific form of functional relationships linking environmental variables to salmon survival (e.g., multiple temperature and/or flow thresholds for salmon at varied points in the life-cycle), and fish movement algorithms (Battin et al. 2006). To our knowledge, this level of data resolution does not currently exist across the Cariboo-Chilcotin study area, and that incorporating a life-cycle model into broader scale characterizations of climate impacts on fish habitat is not currently feasible for this pilot study.

In the absence of detailed population data a more feasible approach is to use broader-scale relationships among stream flow, water temperature and generalized fish responses. Such an approach was applied here, drawing upon a mix of existing modeling tools and presumed relationships that allow for coarse evaluation of potential fish responses as mediated by predicted changes in stream flows and temperatures.

2.4.1 Baseline species distribution

Modeling fish distribution was undertaken using the BC Watershed Atlas's 1:50K GIS watershed polygons and Seg5 stream reach hydrology layers. For each species we developed a baseline depiction of accessible stream habitat based on known fish distribution for each species (using the province's fish observation GIS layer), stream order criteria, reach habitat type, species-specific gradient thresholds (based on a review of literature and discussion with agency biologists), and variable use of potential migration barriers identified within the province's 1:50K GIS barriers layer. We recognize there is no mix of simple remote sensed criteria that will allow precise depiction of fish access to and use of stream habitats at this spatial scale, but we have chosen a suite of criteria generally consistent with the literature and past modeling exercises. We excluded lakes from the assessment of habitat because flow and temperature predictions were only available for stream habitats. We also excluded the Fraser mainstem from our modeling because the temperature model is not appropriate for this size of a river. We have included the 1:50K barriers layer as a criterion for limiting upstream distribution of coho and Chinook salmon only, not for bull trout which can maintain resident populations upstream of barriers. Not all barriers within the 1:50K barrier layer are obstructions to salmon migration. Barriers used in the distribution models for salmon were only those beyond which there were no upstream fish observations for that species (as suggested in Mount 2008; Parkinson 2007). The full rule set we applied to develop baseline distributions for each salmonid species is provided in Table 3.

We depicted stream habitats at the 1:50K scale to be consistent with the spatial scales of the temperature and flow modeling. We recognize, however, that modeling at this scale will fail to identify smaller streams potentially useable by salmonids that would be discernible at 1:20K or smaller spatial scales (Rosenfeld et al. 2002). Consequently, our depictions will likely be an underestimate of the amounts of accessible and useable habitat actually available for different salmonids. Other elements of modeling will also be coarse. Gradient attributes tied to Seg5 reaches represent averaging across the reach segment and may not fully reflect potential passage through or use of reaches based on gradient criteria that have been inferred at finer resolutions. As well, barriers at the 1:50K scale will not capture the full suite of obstructions that could impede fish passage in smaller tributaries. Conversely, 1:50K stream hydrology generally captures most permanently flowing streams, thus avoiding concerns about overestimating habitats at the 1:20K scale (due to inclusion of ephemeral streams). Although somewhat crude, we believe the 1:50K stream linework provides a reasonable framework for developing measures of the quality of salmonid habitats under varied climate change scenarios.

Baseline distributions for each species were mapped in GIS and then summed as the total length of useable stream habitat. These data were summarized by total linear extent within the entire study area and by various additional spatial delineations depending on the species: Conservation Units and stock units for Chinook, Fraser River subpopulations for coho, and major tributary drainages for bull trout.

2.4.2 Suitability of flow conditions

Hydrologic modeling (see *Section 2.2*) provided us with detailed baseline and future projected daily flows at selected stream nodes along the Seg5 hydrology network. We chose to focus on two critical periods in the salmonid life cycle that could be particularly affected by flow changes: (a) summer low flows required to maintain rearing juvenile populations, and (b) late summer / fall flows required to allow successful passage of migrating adults to upstream spawning areas at 18 stream "nodes" throughout the study area. We evaluated the biological relevance of flow changes using simple thresholds relating to summer low-flows for rearing salmonid juveniles (a time period where predicted hotter temperatures would likely exacerbate low-flow impacts) and late summer / fall high-flows for returning Chinook spawners. These flow thresholds have been established as part of processes for determining instream flow needs for fish in different jurisdictions within North America. Thresholds are not without scientific controversy, however, having been criticized for a lack of sufficient field validation and are likely to vary considerably based on river size and stream morphology type (Hatfield et al. 2003). As a simple approach, we believe these thresholds provide a starting point for evaluating broad patterns in potential flow-related impacts to salmonid habitats.

Table 3. Rule sets for delineating baseline distributions for Chinook salmon, coho salmon, and bull trout, and the temperature and flow criteria applied for defining potential climate-change induced impacts on use of stream habitat.

Fish species	Baseline distribution	Stream temperature criteria	Stream flow criteria	References for species baseline criteria
Chinook salmon	**Accessible habitat:** All reaches from the entry point to the primary tributary upstream to the last Chinook observation in each branched tributary and then extended from this point in the stream network to the next identified 1:50K identified Barrier or Seg5 stream reach gradient > 16% (whichever comes first) **Useable habitat:** All potentially accessible habitats as defined above except the Fraser mainstem, 1st order stream reaches, lakes, or stream reach gradients > 5%	• < 11.0 °C - cold water habitat **(suboptimal)** • 11.0 to 14.0 °C – cold water/cool water transition **(optimal)** • 14.0 to 18.5 °C - cool water habitat **(optimal)** • 18.5 to 21.5 °C – cool water/warm water transition **(suboptimal)** • 21.5 °C - warm water habitat **(unusable)**	• < 10% MAD summer low flow – likely impaired flows for rearing juveniles • 10% to 30% MAD summer low flow – questionable flows for rearing juveniles • > 30% MAD summer low flow – likely adequate flows for rearing juveniles • > 60% MAD summer/fall high flow – above minimum bypass flow threshold • < 60% MAD late summer/fall high flow – below minimum bypass flow threshold	Agrawal et al. 2005 Bryant et al. 2004 C. Parken (pers. comm.) ICTRT 2005 Parken et al. 2006 Sheer et al. 2006 WDFW 2000
Coho salmon	**Accessible habitat:** All reaches from the entry point to the primary tributary upstream to the last coho observation in each branched tributary and then extended from this point in the stream network to the next identified 1:50K identified Barrier or Seg5 stream reach gradient > 16% (whichever comes first) **Useable habitat:** All potentially accessible habitats as defined above except the Fraser mainstem, 1st order stream reaches, lakes, or stream reach gradients > 8%	• < 11.0 °C - cold water habitat **(suboptimal)** • 11.0 to 14.0 °C – cold water/cool water transition **(optimal)** • 14.0 to 18.5 °C - cool water habitat **(optimal)** • 18.5 to 21.5 °C – cool water/warm water transition **(suboptimal)** • > 21.5 °C - warm water habitat **(unusable)**	• < 10% MAD summer low flow – likely impaired flows for rearing juveniles • 10% to 30% MAD summer low flow – questionable flows for rearing juveniles • > 30% MAD summer low flow – likely adequate flows for rearing juveniles	Bocking and Peacock 2004 Bryant et al. 2004 Burnett et al. 2007 Lawson et al. 2004 WDFW 2000 Williams et al. 2006
Bull trout	**Accessible habitat:** All reaches starting from the first bull trout observation in a watershed extending upstream to the next identified Seg5 stream reach gradient > 30% **Useable habitat:** All potentially accessible habitats as defined above except the Fraser mainstem, lakes or stream reach gradients > 12%	• < 11.0 °C - cold water habitat **(optimal)** • 11.0 to 14.0 °C – cold water/cool water transition **(optimal)** • 14.0 to 18.5 °C - cool water habitat **(suboptimal)** • 18.5 to 21.5 °C – cool water/warm water transition **(unusable)** • > 21.5 °C - warm water habitat **(unusable)**	• < 10% MAD summer low flow – likely impaired flows for rearing juveniles • 10% to 30% MAD summer low flow – questionable flows for rearing juveniles • > 30% MAD summer low flow – likely adequate flows for rearing juveniles	Cannings and Ptolemy 1998 Mount. 2008 Parkinson 2007 Rich et al. 2003 E. Parkinson (pers. comm.)

Flow thresholds often use a watershed's mean annual discharge (MAD) as the base metric for comparisons with the most commonly employed (the Tennant method, developed initially from field studies on interior Montana streams) suggesting that summer flows below 30% MAD can result in impairment of rearing habitats and flows below 10% MAD can result in severe degradation (Tennant 1976). A modified-Tennant method developed by Ptolemy and Lewis (2002) for use in coastal BC streams recommends a flow of 20% MAD to maintain juvenile rearing habitat. Ptolemy and Lewis (2002) also recommend a flow for spawning in coastal streams that is a derivation of % MAD generated by the equation $1.56 \times MAD^{0.63}$. A more recent US agency approved recommendation for minimum bypass flows for spawning salmon has been developed in California (CSWRCB 2007; Merenlender et al. 2008) which also employs two MAD related thresholds (with the threshold algorithm varying depending on watershed size). For drainages greater than 290 sq. miles the recommended bypass flow to allow successful spawning is 60% of MAD. In the absence of more regionally-specific information we chose to use a synthesis of these published thresholds to define flow levels of concern for rearing and spawning conditions as measured at the flow "nodes". The flow thresholds and their presumed impact on Chinook, coho, and bull trout are provided in Table 3.

<u>Rearing summer low flows:</u> Based on the lowest moving 7-day average *minimum* flow over the July 1 to Sept. 30 summer rearing period, downstream node locations were rated as (1) "likely adequate for rearing juveniles" if flows were > 30% MAD summer low flow, (2) "questionable flows for rearing juveniles" if flows were between 10% and 30% MAD, and (3) "likely impaired flows for rearing juveniles" if flows were < 10% MAD. Nodes were colour-coded based upon the flow risk categories and mapped within the GIS to indicate points where reduced rearing flows might become an issue under different climate-change scenarios.

<u>Spawning late summer/fall high flows:</u> A similar approach was applied for assessing migratory spawning flows for Chinook salmon, such that, based on a moving 7-day average *maximum* flow over the period of July 15 to October 15 (general period of Chinook spawning in the study area - Cariboo-Chilcotin Conservation Society 2008; Parken et al. 2008), all nodes were rated as either 1) "above minimum bypass flow threshold" if flows at the node > 60% MAD or 2) "below minimum bypass flow threshold" if flows at the node were < 60% MAD. Nodes were colour-coded based upon the flow risk categories and mapped within the GIS to indicate points where reduced spawning flows might become an issue under different climate-change scenarios. This approach, if perceived as a sufficiently sensitive indicator, could be further refined for both Chinook and coho salmon by tightening the evaluations of spawning flow within each drainage to the unique spawn timing window of each salmon population or stock unit.

To evaluate changes in seasonal flows relative to % MAD (as opposed to an actual flow quantity) as the index of changing risk from flow changes under different climate change scenarios, all time periods were compared relative **only** to the historic baseline MAD at a node (e.g. summer low flow T1/MAD T1, summer low flow T2/MAD T1, summer low flow T3/MAD T1, etc.) as the historic MAD represents the degree of flow to which resident fish are currently adapted. In addition to quantifying possible changes in annual and seasonal flows across different projected climate change scenarios we also examined how the shape of the hydrograph at individual nodes might change, so as to determine whether the timing and magnitude of major flow events (such as spring freshet) critical to salmonid life-histories might display significant change.

2.4.3 Suitability of temperature conditions

Work by Nelitz et al. 2008 defined temperature thresholds delineating boundaries between coldwater-coolwater (MWAT of 12.5°C), and coolwater-warmwater communities (MWAT of 20°C). We bracketed these thresholds with a range of ± 1.5 °C to delineate transition zones. This model allowed us to determine the relative extent of accessible streams within the study area that would be considered within optimal, suboptimal, or unusable thermal zones for different salmonids (see criteria in Table 3). For this pilot exercise we sought to quantify the extent of currently useable habitat (as defined by our baseline distribution rule sets described in *Section 2.4.1*) that might become too warm to be occupied by bull trout (coldwater dependent) or salmon populations (coolwater dependent) under different climate warming scenarios.

3.0 Discussion: Understanding vulnerability

The methods outlined in *Section 2* describe our approach to assessing the vulnerability of freshwater habitats to the effects of climate change. Preliminary results are summarized in the second part of this report (Nelitz et al. 2009) and three future outlook papers (Porter and Nelitz 2009a; Porter and Nelitz 2009b; Nelitz and Porter 2009). Additional effort is needed to analyze and represent these findings in ways that are meaningful for decision making. Two considerations should guide additional analysis and interpretation. First, some of the underlying assumptions for each model may affect interpretation of the results or the level of belief in predicted outcomes (see Table 4). A second consideration is that there are an overwhelming number of ways to analyze results. When all dimensions and associated levels are considered (Table 5), there are over 1,000 unique combinations with which to represent this study's findings. Thus, a key to analyzing these data will be to hold some dimensions constant while examining results across a few other important dimensions. A useful way of identifying the most relevant insights is to have decision makers pose questions that can be answered through an analysis of the data – e.g., across the GCM ensemble, for a single fish species how do flow and temperature conditions change over time in a particular watershed? A sample of the results from this assessment are provided below.

Table 4. Assumptions and cautions for consideration when interpreting results from the vulnerability assessment.

Modeling component	Relevant assumptions / cautions
Climate change	▪ The downscaling method assumes that the empirical relationship between the observed air temperature and precipitation for the true climate (represented by the observational data) and a give GCM over the 1950 to 2006 will be maintain in 2007 to 2100. ▪ The downscaling method assumes that the observational record can be interpolated to represent the climate in areas where observations do not exist. ▪ The method assumes that the bias between the observed climate and one model run is representative although each model run yields slightly different results due to the climates naturally stochastic behaviour. ▪ The method assumes that monthly biases can be translated into daily values using daily values from one representative month. ▪ Due to the lack of physical information at the mesoscale included in this method, processes that cause increases in precipitation extremes, such as orographic uplift are not well represented.
Stream flow	▪ Streamflow in the Fraser was calibrated based on climate forcings data that was developed for long term (1915 – 2006), while an alternate data set (1950 – 2006) data was used to train the downscalng. Hence, there are differences between the calibration data set and the downscaled data set. These differences have been analysed and are minimal in most basins. ▪ Streamflow calibrations was based on 18 medium to large scale basins, while nodes used this study were not specifically calibrated. Hence there is no means to validate the streamflow obtained at the alternate node sites. The validations must come from the broader basins within which the nodes of interest are nested. ▪ Streamflow calibration parameters provided for this study represented the best results available, but were not, in all cases, the final calibrated parameters. Final results for the basins are available for future consideration. For some basins (Cotton Creek) this may be causing some reduction in quality of historical streamflow. This should not make a difference when examining projection results using the percentile differences from the baseline. ▪ Streamflow for this study was generated using a macro-scale hydrologic model that has inherent difficulty in assessing flow in small and arid basins. The application of the macro-scale hydrologic model streamflow results in habitat models (at smaller scales) has not been tested and validation of results should be included in future work.
Stream temperature	▪ The model assumes the historic relationship between air and water temperature will hold into the future. ▪ The model does not account for changes in land use cover due to human or natural disturbances (e.g., upslope or riparian harvesting, fire or insect disturbance). ▪ The model does not account for the effect of water withdrawls or flow management practices. ▪ The model does not account for the role of groundwater in regulating stream temperatures.

Modeling component	Relevant assumptions / cautions
Habitat suitability	▪ Assumes that the thermal criteria used to define fish communities within the original Thompson River dataset used to build the fish/temperature model would also apply in the Cariboo-Chicotin region ▪ Assumes that standard-set thresholds for summer rearing low-flow and minimum bypass flows (as defined by %MAD-based metrics) capture points of real concern for maintaining viable flows for rearing and spawning salmonids

Table 5. Dimensions and their associated levels as related to this vulnerability assessment.

Dimensions	Levels for each dimension
Species	bull trout, coho salmon, and chinook salmon
Time	Historic reference period (1961-1990), 2020, 2050, and 2080
Space	Conservation units, watersheds, watershed groups, and stock groups
Global Climate Model—emissions scenario combination	cgcm3-T47_A1B, cgcm3 T47 _B1, cgcm3 T47 _A2, ukmo_hadcm3_A1B, and gfdl_cm20 _A2, and echam5_A1B,
Stream flow criteria	Mean annual discharge, low summer flow, high late summer/fall flow
Stream temperature criteria	Maximum weekly average temperature

4.0 Next steps: Moving towards adaptation

4.1 Model improvements

Over the course of this pilot project, a variety of model improvements were identified as being useful for improving the scientific rigour and reliability of results (Table 6). These improvements could be integrated in future stages of work.

Table 6. Summary of the concerns and possible model improvements to address concerns.

Modelling component	Related concern	Possible model improvement
Climate change	▪ Daily values are estimated from an analogue month in the historical record. Volumes of precipitation on a given day can be anomalous although monthly averages are on par. ▪ Sea level pressure was not included as a predictor of precipitation. Sea level pressure relates to wind patterns that more accurately displace precipitation around mountain ranges. ▪ Quantile mapping was completed with average daily temperature. Thus, bias between GCM and observed temperature is applied to min and max temperatures equally although changes in min and max temperature are not uniform. ▪ This statistical downscaling method does not represent mesoscale climate features (such as orographic precipitation, convergence zones, snow-albedo feedbacks, and cold air drainage) that are likely to respond to the changing large-scale climate that dynamical downscaling would have. In complex terrain like BC, with mountainous terrain and land-sea interfaces mesoscale process are important.	▪ Complete more rigorous error checking and adjustment of the estimated daily values. ▪ Include sea level pressure as a predictor. ▪ Bias correct true min and max temperature from the GCMs where available and create a multiple linear regression to predict min and max temperature for models where they aren't available. ▪ Investigate regional climate model results for the region (dynamically downscaled GCM results).
Stream flow	▪ A limited number of streams were represented in the flow analysis. ▪ Limited extent of flow changes observed across the longitudinal profiles of Quesnel, West Road, and Chilcotin Rivers. ▪ Does not consider glacier cover or potential for loss in glacier cover. ▪ The scale of the model (inputs and results) is not aligned with the scale of application in this study.	▪ Increase the number of flow "nodes" selected across streams ▪ Reduce the number of flow "nodes" along these major rivers ▪ Use a hydrologic model that models glacier cover. E.g., reduce glacier coverage layer in hydrological model by 25% and 50% and use in relevant models (e.g., temperature and flow) ▪ A more comprehensive examination of methods to apply the model results at the scale of interest is important. Consider using a different model or more detailed information as a case study at one or more locations within the study region.
Stream temperature	▪ Model does not account for changes in land cover (e.g., forest harvesting, mountain pine beetle, fire disturbance) which will likely exacerbate effects of climate change. ▪ Model does not account for the effect of water withdrawl (extraction). ▪ Some watershed polygons are very large, which leads to errors in temperature predictions.	▪ Examine role of Normalized Difference Vegetation Index (NDVI) in stream temperature regression. ▪ Use BC water license database and locations of water license restrictions to examine role of water use in temperature regression. ▪ Reduce size of watershed polygons used as base layer for temperature modeling.

Modelling component	Related concern	Possible model improvement
Habitat suitability	▪ The depiction of flow through the evaluated watersheds is very coarse and does not provide any interpolation of flows between nodes.	▪ Explore increasing the density of nodes within the study area to get better representation of the flow network. Develop interpolation routines that could allow finer interpretation of flows between nodes.
	▪ A fish community-based threshold is the only temperature relationship evaluated within our models. There are additional species-specific temperature thresholds that may be of interest and could be pursued within the general modeling approach.	▪ Explore use of MWAT model to predict changes in life-history of Chinook stocks (i.e., stream-type vs. ocean-type), based on summer rearing temperatures (Brannon et al. 2004). No current evidence that this response is facultative however (Healey 2001; Holtby and Ciruna 2007). ▪ If above seems worthwhile, extend modeling to estimate potential changes in Chinook production as determined from life-history specific production models (developed by Parken et al. 2006) ▪ Explore using MWAT predictions to extend existing coho production models (e.g., Bradford et al. 1997; Bocking and Peacock 2004) based on accessible stream length; provide thermal criteria as additional filter to define useable stream length as alternative, more dynamic predictor

4.2 Adaptation strategies

As mentioned throughout this report, the purpose of this study was to provide results that could be used to help regional decision makers understand potential vulnerabilities of freshwater habitats in the Cariboo-Chilcotin and develop appropriate adaptation strategies. Having completed this preliminary analysis, it is no trivial task, however, to move to this next stage. To provide guidance moving forward, we propose the following five principles as key considerations during the design, development, and implementation of adaptation strategies (adapted from Nelitz et al. 2007a).

A first principle is to **develop adaptation strategies that perform well across a range of future outcomes and are robust to uncertainties**. As represented by the range of predictions across space, time, models, and emissions scenarios it is not possible to definitively predict the future. As well, assessment approaches as applied here provide predictions using a series of linked models to depict biophysical changes along a relatively long cause-effect pathway, each step of which is subject to uncertainties – greenhouse gas emissions lead to changes in climate patterns, which alter stream flows and temperatures, which ultimately affect fish habitats and fish productivity. Given the large uncertainties it isn't appropriate to design coping strategies that perform well in a single future scenario, thus the need for robust decision making (Schindler et al. 2008).

A second principle is to **design adaptation strategies in freshwater environments with a consideration of other factors constraining fish production**. For instance, environmental conditions in the lower Fraser River are widely recognized as affecting the timing and migratory success of sockeye salmon as a result of elevated water temperatures and changes in flow conditions (Farrell et al. 2008). In addition, conditions in the ocean environment have a fundamental control on the productivity of salmon (Mantua et al. 1997; Beamish et al. 1999). When designing strategies to improve productivity in freshwater environments it is important to be aware of other factors affecting productivity at other life stages so as to properly manage expectations about the benefits of pursuing any particular strategy. A recognition of bottlenecks or constraints on productivity at other life stages should not, however, be used as a reason to do nothing in freshwater environments. Among other reasons, there may be situations where these other factors mask the effects of habitat degradation to the point where habitats eventually constrain production (Lawson 1993). As well, others have observed that population declines due to poor ocean survival are greater in watersheds that are more highly impacted by development activities (Bradford and Irvine 2000).

A third principle is to **consider the social values implied by pursuing a particular adaptation strategy**. As with most decisions there will be a tradeoff between the benefits of an action on fish production and the costs to society for pursuing that strategy (e.g., time, money, energy). Adaptation strategies will not be free from human values; they lie along a continuum (Figure 8). In this illustration, if society places a high values on salmon we might be willing to take any and all actions to help mitigate the effects of climate change (e.g., reduce water use for agricultural purposes or reduce forest harvesting opportunities to maintain riparian buffers). If valued highly, the range of strategies would be much greater and different than if society valued salmon very little. It is also important to recognize that different social and cultural perspectives will likely line up at different points along this continuum. For instance, some First Nations may be more willing to pursue any and all actions necessary to maintain salmon given their cultural, spiritual, and economic importance. In our opinion it is better to explicitly consider the tradeoffs and values associated with a particular strategy.

Figure 8. Illustration of how human actions (i.e., stressors and restoration actions) lie along a continuum of human values (from Nelitz et al. 2007a). Actions can favour human or salmon interests. This illustration is an oversimplification in that is does not consider tradeoffs among other values (e.g., other fish species or other resource users) and the possibility of win-win outcomes (i.e., actions that benefit both salmon and people).

A fourth principle is to **implement proactive adaptation strategies before reactive ones** (Roni et al. 2002). In the context of climate change, proactive strategies represent those that consider a longer term perspective by helping avoid bottlenecks in fish productivity before they become a constraint (e.g., protect high quality thermal refugia before they are degraded). Reactive strategies represent those actions that mitigate existing impacts on salmon survival (e.g., restore degraded riparian zones along reaches with high temperatures). For a variety of reasons, we believe a focus on proactive strategies will minimize costs in the long-run. The past cycle of watershed degradation and restoration has been recognized as an expensive endeavour with a questionable record of effectiveness (e.g., Bernhardt et al. 2005). As well, decision makers often underestimate the true value of natural resources or economic benefits of conservation and protection (Kroeger and Manalo 2006).

Finally, a fifth principle is to **implement adaptive management**. Developing adaptation strategies in the context of an uncertain future will be daunting. Although we expect that past conservation and restoration actions will be used as a guide, we believe scientists and managers will have a limited ability to predict the future effectiveness of adaptation strategies implemented today. Consequently, to be the most effective and efficient it will be valuable to implement strategies in an adaptive management framework that maximizes learning about what is and is not working over time. Implementing rigorous adaptive management is not trivial, however (e.g., Marmorek et al. 2006). If rigorous adaptive management is not possible, there will still be value in implementing a good effectiveness monitoring program.

Moving from principles to a more detailed description of activities, we envision the following four core tasks as necessary to move towards adaptation. A critical first task will be to build collaborations with technical, management, and stakeholder audiences, while also leveraging existing activities within the provincial and federal governments (e.g., BC's Climate Action Secretariat, Natural Resources Canada's Regional Adaptation

Collaborative, Mountain Pine Beetle Action Plan, recovery strategy for Interior Fraser coho, etc.). This audience would guide design, development, and implementation of adaptation strategies for a focal geographic area within the Cariboo-Chilcotin. Second, it will likely be necessary to conduct additional analyses to strengthen the rigour of model predictions and improve the level of information for decision making (see Table 6). For instance, model improvements could include an exploration of the effect of water withdrawls and loss of glacier cover on water temperature. As well, it will be important to overlay habitat vulnerabilities against existing land and water use activities to highlight opportunities for adaptation (e.g., priority habitat issues and areas of concern). Third, given the large number of ways in which to interpret the data, it will be important to work with external audiences to tailor and communicate the results from the vulnerability assessment to best inform decision making. Finally, a fourth core task will be to use the range of future outcomes from the vulnerability assessment and work with the external audiences to explore what strategies should be implemented, where and when. The intent would be to develop a mix or "portfolio" of strategies, evaluate their robustness to uncertainties as well as their feasibility of implementation, and select one for implementation.

Although not a guarantee for success, we believe that by following the above general principles and more detailed tasks, decision makers in the Cariboo-Chilcotin will have a greater chance of developing coping strategies that help with the future challenges of climate change.

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