Predicting the magnitude and timeline of climate change effects on spawning migration success for major populations of Fraser River salmon and implications for fisheries: SEF Final Report[†]

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[†] The materials in this report represent in-progress research. As such, the contents of this report are not to be cited without permission of the principal investigators and individual authors.

EXECUTIVE SUMMARY

OBJECTIVES

Four main objectives were provided in the framework for the development of this project. These objectives, as specified in the original project proposal, are as follows:

1. To develop a status report on the current risk to adult survival for key, representative Pacific salmon populations (Chinook, coho, chum, pink, and sockeye) for the Fraser River from adverse migration conditions.
    a. Document historic temperature and flow exposure, variability, and trends by population
    b. Species/population review on the effects of temperature and discharge on adult freshwater migration
2. To create daily forecasts of temperature and flow conditions in the Fraser River Basin under assumptions of climate change for 100 years into the future using different climate change models
3. To develop a series of models to predict the magnitude and timeline of climate change effects (thermal and flow regimes) on spawning migration success for major populations of Fraser salmon.
    a. Forecast the frequency, magnitude and timeline of exceedences over species thresholds and deviations from historical population exposures for each major population.
    b. Model changes in adult migration biology and success in response to forecasted river temperature and flow conditions.
4. To communicate to fisheries and habitat managers the risk to fish populations and associated fisheries from the future changes to temperature and flow conditions.

DELIVERABLES

Our final report consists of six main chapters, each of which addresses one, or more, of the original project objectives (Table 1). To best understand the potential effects of climate change, it is necessary to put forecasted changes in the context of current physical and biological norms. The first three chapters (*Chapter 1: Migratory behaviour of Pacific salmon; Chapter 2: Habitat variables influencing migratory success; Chapter 3: Temperature and flow reconstructions*) provide essential background on which to build our arguments for the effect of climate change on the adult freshwater migration of Fraser River salmon populations. There are large uncertainties with respect to both the magnitude and direction of expected regional changes in hydrology and the response of salmon to these changes. Given these uncertainties, one of the best ways to lend support to future forecasts is to demonstrate consistency in results across a range of different modelling tools. *Chapters 4* (*Future hydroclimatology of the Fraser River*) and *5* (*Temperature-survival relationships*) provide two alternative examples of climate downscaling techniques and biological models that can be combined to produce population-specific forecasts of spawning migration success under future climate scenarios. Finally, Chapter 6 (*Species vulnerability to climate change*) summarises the findings of earlier chapters into a qualitative assessment of expected impacts of climate change on the spawning migratory success, and potential implications for the future of fisheries management in BC. We provide executive summaries for each of these chapters below, with specific reference to the objectives outlined above.

Table 1. Spawning migration success and climate change SEF: description of chapters in the final report and associated project objectives.

Chapter	Title	Abbreviated chapter title	Authors	SEF objective #
1	Migratory behaviour of Pacific salmon populations in the Fraser River, British Columbia	Migratory behaviour of Pacific salmon	D. C. Mckay, L. A. Thompson, J. A. Hills, M. J. Hague, D. A. Patterson	1a
2	Literature review of the potential habitat variables influencing the upstream migration success of Pacific salmon in the Fraser River, British Columbia, Canada	Habitat variables influencing migratory success	J. Verspoor	1b
3	Reconstructing the thermal and flow history of key Pacific salmon populations along their freshwater migration through the Fraser River, British Columbia	Temperature and flow reconstructions	M. J. Hague and D. A. Patterson	1a
4	Modeling the future hydroclimatology of the Fraser River Basin and its impacts on the reproductive migration success of sockeye salmon	Future hydroclimatology of the Fraser River	M. J. Hague, M. R. Ferrari, J. R. Miller, D. A. Patterson, G. L. Russell, A. P. Farrell, and S. G. Hinch	2; 3a; 3b
5	Climate change and Pacific salmon: modelling and predicting the effects of temperature on survival of Fraser River sockeye salmon (*Oncorhynchus nerka*) during spawning migration	Temperature-survival relationships	E. G. Martins, S. G. Hinch, D. A. Patterson, and M. J. Hague	3b
6	Assessing the vulnerability of Pacific salmon migratory success to anticipated climate changes in the Fraser River, British Columbia	Species vulnerability to climate change	M. J. Hague and D. A. Patterson	4

CHAPTER 1: MIGRATORY BEHAVIOUR OF PACIFIC SALMON EXECUTIVE SUMMARY

- **Purpose:** to provide a brief literature review on each Pacific salmon species (coho, chum, Chinook, pink and sockeye salmon)
- **Report objectives:**
  - Highlight differences in life history traits, spawning migration characteristics and management
  - Compile the necessary background to assess species and population-specific differences in freshwater environmental exposure during the spawning migration (*Chapter 3: Temperature and flow reconstructions* and *Chapter 6: Species vulnerability to climate change*)
- **Result summary:**
  - 96 primary publications, technical reports, books, and web resources were reviewed
  - Populations of all five salmon species are broadly dispersed throughout the Fraser River watershed
  - Large variability with respect to the number of publications available for each species
  - Fraser River sockeye salmon migration tends to be the best studied, followed by Chinook, pink, coho and chum salmon
  - Information on some Fraser River populations had to be inferred from studies conducted in other systems (e.g. Columbia River Chinook salmon)
- **Key conclusions:**
  - Significant inter- and intra-specific differences in spawning migration variables will likely translate into different in-river environmental exposure both within and across salmon species
  - Limited information means that detailed assessments may not be possible for all populations/species
- **Future research:**
  - More information regarding migration behaviour is required for most species of Fraser River salmon in order to better understand population-specific differences in current and future freshwater migration conditions and ultimately impacts on migratory success

CHAPTER 2: HABITAT VARIABLES INFLUENCING MIGRATORY SUCCESS EXECUTIVE SUMMARY

- **Purpose:** to provide a literature review of the key freshwater environmental variables influencing spawning migration behaviour and success of Pacific salmon species
- **Report objectives:**
  - Summarise species-specific differences in migration timing, rate, behaviour, disease and mortality as a function of: water temperature, discharge, and quality
  - Provide a bibliography of key references related to freshwater environmental variables and salmon spawning migrations
  - Compile the necessary background to interpret species and population-specific differences in tolerances to environmental conditions experienced during the spawning migration (*Chapter 3: Temperature and flow reconstructions* and *Chapter 6: Species vulnerability to climate change*)
- **Result summary:**
  - 83 primary publications, technical reports, books, and web resources were reviewed
  - Effects of water temperature are best-studied
  - Limited information on sub-lethal/lethal effects of discharge
  - Limited information of any kind for effects of water quality
  - Environmental tolerance of Chinook and sockeye salmon has been well-studied; pink salmon - relatively well-studied; coho and chum salmon - poorly studied
  - Critical lethal thresholds are consistent across species
  - Magnitude and range of chronic thresholds varied across species and populations
- **Key conclusions:**
  - Some Pacific salmon species may be better adapted to increases in spawning migration temperatures caused by climate change because of higher chronic thresholds and/or tolerance across a wide range of temperatures
  - Population-specific differences are only available for some species and some populations
  - Information on environmental tolerances for Fraser River salmon populations will sometimes need to be inferred from studies on other systems (and occasionally other species)
- **Future research:**
  - Population-specific differences in environmental tolerance
  - Critical thresholds for discharge and water quality
  - More species-level detail for Fraser River chum and coho
  - Improved understanding of cumulative effects combined across environmental variables

CHAPTER 3: TEMPERATURE AND FLOW RECONSTRUCTIONS EXECUTIVE SUMMARY

- **Purpose:** to quantify current levels of temperature and discharge exposure during the freshwater spawning migration of key Fraser River salmon populations
- **Report objectives:**
    - Use information compiled in Chapter 1 (*Migratory behaviour of Pacific salmon*) to parameterise population-specific simulation models of upriver migration
    - Evaluate how environmental conditions change along migration routes, and as a function of migration rate and river entry timing
    - Quantify ambient environmental norms to act as a baseline for comparison to future conditions under warming climate change scenarios (*Chapter 6: Species vulnerability to climate change*)
- **Result summary:**
    - Differences in temperature and flow exposure were a function of migration route and timing of river entry
    - Magnitude and variability of exposure varied across populations
    - Warmest average temperatures experienced by the peak of the run was 17.4 ˚C (sockeye salmon Gates Creek population, Chinook salmon Nechako and South Thompson River populations)
    - Many populations have historically experienced temperatures exceeding critical thresholds (i.e. 21 ˚C), but such occurrences are relatively uncommon
    - Sensitivity of thermal exposure to migration rate was low
    - Sensitivity of thermal exposure to migration timing varied across populations
- **Key conclusions:**
    - Pacific salmon populations experience a broad range of freshwater temperature and flow conditions during their spawning migration
    - Some populations may have plasticity to adapt to changes in river conditions because (a) they have already adapted to a broad range of thermal and flow exposures, (b) they have the capacity to alter their thermal experience by shifting river entry date, (c) long freshwater residencies allow for flexibility in migratory behaviour (e.g. holding in cold-water refugia, delaying passage until temperature and flow conditions become more suitable)
- **Future research:**
    - Improve biological reality of migration model
    - Run forward simulations using the migration model framework to produce comparable metrics of freshwater exposure under alternate future temperature and flow scenarios

CHAPTER 4: FUTURE HYDROCLIMATOLOGY OF THE FRASER RIVER EXECUTIVE SUMMARY

- **Purpose:** to quantify the potential effect of future climate change on the spawning migration survival of populations of Fraser River sockeye salmon using physiological thermal tolerance thresholds
- **Report objectives:**
  - Generate daily forecasts of lower Fraser River temperature until the end of the 21st century
  - Demonstrate the use of aerobic scope-temperature relationships as a tool for predicting migratory survival
  - Simulate species and population-level migratory survival scenarios using a hybrid approach that links output from global circulation models to relevant biological models
  - Compare differences in future survival estimates for Gates Creek and Weaver Creek populations
- **Result summary:**
  - Forecast asymmetric increases in temperature across summer months with the greatest increases in June (3.5 ˚C)
  - Under moderate climate change scenarios there may not be a significant increase in the number of temperatures exceeding critical lethal thresholds (i.e. 21 ˚C)
  - Forecast moderate increases in future median river temperature for Gates Creek and Weaver Creek migrants (1.6 ˚C and 1.2 ˚C, respectively)
  - Weaver Creek fish more likely to experience temperatures exceeding critical aerobic scope thresholds (e.g. in 15% of simulations the entire population experienced temperatures > 18.6 ˚C, associated with a 50% reduction in maximum aerobic scope)
  - Greater potential for selective pressure on Weaver Creek river entry timing, as relatively small shifts towards later timing result in larger shifts to median river temperature exposure (17.2 ˚C to 18.7 ˚C) compared to Gates Creek salmon (18.6 ˚C to 19.1 ˚C)
- **Key conclusions:**
  - Highlights the importance of (1) population-specific sensitivity to shifting thermal regimes, (2) using daily resolution environmental data, (3) shifts in exposure relative to sub-lethal thresholds
  - Not all populations will experience declines in migratory survival as a function of collapse in aerobic scope
- **Future research:**
  - Develop tools for evaluating additional salmon populations
  - Expand temperature forecasts across a broader spatial and seasonal scale
  - Increase complexity of the biological model to also account for other temperature-related effects (e.g. swimming performance, stress and disease)

CHAPTER 5: TEMPERATURE-SURVIVAL RELATIONSHIPS EXECUTIVE SUMMARY

- **Purpose:** to develop population-specific temperature-survival curves and use them to forecast potential shifts in freshwater spawning migration survival for different populations of Fraser River sockeye salmon
- **Report objectives:**
    - Estimate survival during spawning migrations as a function of temperature experienced by individual fish
    - Use stochastic simulations to generate predictions of future survival assuming a moderate climate change scenario
    - Evaluate population-specific differences with respect to thermal tolerance
- **Result summary:**
    - Observed population-specific differences in the shapes of the temperature-survival curves: some populations were highly sensitive to high temperatures, others showed minimal temperature sensitivity
    - Late Shuswap sockeye salmon had the greatest decrease in survival with temperature, which is associated with a recent shift in river entry timing
    - Survival of Quesnel, Stellako-Late Stuart and Late Shuswap sockeye salmon is predicted to decrease if the Fraser River continues to warm at current rates
    - Future survival of Late Shuswap sockeye salmon is sensitive to river entry behaviour
- **Key conclusions:**
    - Large population-specific differences in temperature sensitivity
    - Survival estimates and predictions are likely conservative and therefore future survival may be even lower than predicted
    - Survival curves parameterised using years of moderate environmental conditions; extrapolations of future survival estimates at extreme temperatures may be inaccurate
- **Future research:**
    - Parameterise temperature-survival curves using additional years of extreme temperature data
    - Develop models that also account for cumulative temperature effects along entire spawning migration
    - Collect data to develop relationships for additional sockeye salmon populations and other salmon species

CHAPTER 6: SPECIES VULNERABILITY TO CLIMATE CHANGE EXECUTIVE SUMMARY

- **Purpose:** develop hypotheses regarding the potential and severity of climate change on the spawning migration success of different Fraser River salmon populations
- **Report objectives:**
    - Provide brief literature reviews on (1) anticipated regional changes in river temperature and hydrology as a function of climate change, (2) variability in population-specific changes in lower Fraser River temperature exposure, (3) potential for phenotypic plasticity and/or genetic adaptations to climate change
    - Use information from previous five chapters to quantify key 'susceptibility variables' for each salmon population: (1) magnitude of anticipated environmental changes, (2) magnitude and range of thermal tolerance, (3) potential for use of cold water refugia, (4) current stock status
    - Rank salmon populations according to potential and severity of impact of climate change on spawning migration success
- **Result summary:**
    - Sensitivity of different populations is primarily a function of river entry timing
    - Phenotypic plasticity (e.g. variability in river entry time, time of spawn, migratory behaviour) has the potential to mediate the effects of climate change for some populations (e.g. Upper Chilcotin Chinook salmon)
    - Early Stuart sockeye salmon were ranked highest (most likely to be negatively impacted by climate change); South Thompson Chinook salmon were ranked lowest
    - Greatest uncertainty is with respect to ability for adaptive change
- **Key conclusions:**
    - Climate change will have variable effects on the spawning migration success of different Fraser River Pacific salmon populations
    - Large uncertainty still exists with respect to the timeline and magnitude of climate change effects on spawning migration success, and ultimately the productivity and persistence of Pacific salmon populations
- **Future research:**
    - Additional studies (physiological or tagging) to develop more detailed migration survival models
    - As uncertainty with respect to future climate and rate/extent of adaptation are unlikely to be resolved – evaluate shifts in population ranks as a function of different climate/adaptation scenarios

MAIN CONCLUSIONS

(Excerpt from Chapter 6: Species vulnerability to climate change)

Based on what we know about the life history and physiological traits of the various Pacific salmon populations discussed in this report, as well as anticipated changes in the Fraser River resulting from climate change, we made some speculations regarding the severity and timing of climate effects on spawning migration success.

For each of the populations considered, we first summarised key characteristics thought to be involved in influencing the probability of spawning migration success under climate change (Table 2). In the absence of human intervention, we determined that the effect of climate change on the migration success of Pacific salmon will likely depend upon:

1. Absolute changes in river temperature and flow
2. Changes in temperature relative to thermal optima
3. Thermal tolerance
4. Population-level variability in time of river entry and time of spawn
5. Opportunities for behavioural thermoregulation

(1) Absolute changes in temperature exposure were quantified as the difference between mean lower-river temperatures experienced by the peak of a salmon run during the baseline period (1981 – 2000) compared to the period representing climate change (2081 – 2100). These changes were restricted to values for the lower river since future temperatures were not known across the entire system. Absolute changes in flow were even more coarsely quantified based on the expected direction of shifts in seasonal flows reported in the climate change literature (see *Chapter 6*). (2) Relative changes in temperature were calculated as the percentage of future lower river temperatures exceeding thermal optima. Because thermal optima have not been explicitly defined for all populations, we defined population-specific optima as the current average temperature experienced by the peak of the run across the entire freshwater spawning migration (see mean temperatures in Table 6 in *Chapter 3*). (3) In instances where a thermal tolerance range was not available from physiological studies, the relative range of acceptable migration temperatures was assumed from the variability in temperatures encountered by the peak of the run (see SD in temperatures in Table 6 in *Chapter 3*). (4) Variability in river entry timing was quantified as the average run duration (see Table 1 in *Chapter 3*). (5) Staging time (i.e. freshwater residency minus average migration time to the spawning ground) was used as a surrogate to define opportunities for behavioural thermoregulation. Finally, we assigned scores to each population on the basis of these criteria to create a relative index of future impacts of climate change on spawning migration survival (Table 2).

Although our scoring system is an obvious simplification of the complex nature in which climate change will affect Pacific salmon, it does serve as a useful tool for identifying some potential trends. Intra-specific differences in vulnerability arise due to population-level differences in exposure, tolerance and behaviour. In general, the populations most at risk will consist of spring/early summer migrants – largely due to the greatest increases in river temperature forecasted by our climate models (*Chapters 4* and *5*) for this time of year. As a result, most of the affected populations consist of either sockeye or Chinook salmon, while fall-migrating pink, chum and coho salmon populations may not be impacted as dramatically or as quickly by changes in climate. However, flexibility in migration behaviour due to variability in river entry timing and a long freshwater staging period may translated into increased opportunities for behavioural plasticity and adaptability to climate change for populations such as spring-timed Chinook salmon (i.e. upper Chilcotin). In addition, we may underestimate the trade-offs between temperature and flow for early-timed sockeye salmon, which could interact to result in lower overall impact of changing climate on migratory success, assuming an energy limitation hypothesis (Rand et al. 2006).

Climate impacts on migratory success appear to be moderate to low for many populations currently designated as “stocks of concern” (e.g. Thompson coho salmon; spring Chinook salmon). Unfortunately, populations currently recruiting above-replacement may suffer more as a result of increasing water temperatures (e.g. Gates sockeye salmon; Nechako Chinook salmon). Moreover, restraints on mixed-stock fisheries for both low and high productivity stocks will likely persist and/or increase, assuming decreases in migratory survival contribute to declines in total productivity.

The rankings provided Table 2 represent only one possible future, under a single set of climate forecasts and an assumption of no short-term adaptive responses. Using the extreme example of the Driftwood sockeye salmon population, we discuss potential alternate states of nature that could occur. For example, decreases in June flows could remove hydrological barriers currently preventing earlier migration, thus allowing earlier-timed fish to avoid increasing water temperatures. Extreme changes to spawning ground temperatures may also place selective pressure on time of spawn, favouring later spawning dates. This could also be enhanced by changes in lake productivity, producing trophic and temporal shifts in the peak abundance of zooplankton favouring early emergence and earlier spawning. Either shift in timing could also contribute to more flexibility with respect to migration behaviour, permitting Driftwood fish time to hold in thermal refugia en route to the spawning grounds. However, scenarios representing more extreme future migratory conditions could be equally plausible. For example, decreases in marine productivity may result in fish arriving at the river with lower energy conditions, which may counter any potential benefits of trade-offs between decreased flow/increased temperature (Rand et al. 2006). While changes in time of spawn may have a positive effect on migratory success, countering selective pressures on juvenile survival could prevent any noticeable shift overall productivity. Providing reasonable bounds to the range of potential climate and biological scenarios will be an important next step in better understanding the potential impact of climate change on migratory success.

Past experience already provides strong evidence that increased river temperatures will decrease the probability of spawning migration success (e.g. Crossin et al. 2008; Farrell et al. 2008); however, some populations may also benefit from the effects of a warming climate resulting in expansion of suitable spawning and rearing habitats (Nelitz et al. 2009). For Pacific salmon populations already on the cusp (replacement near 1), even small decreases in migratory survival could contribute to declining trends and ultimately reduce the probability of future persistence. Freshwater survival is thought to explain up to 50% of the variability in the overall survival of salmon (Bradford 1995), and declines in freshwater survival resulting from climate change do have the ability to push populations towards extinction (Crozier et al. 2008a). Nelitz et al. (2007) completed a detailed investigation of potential mitigation, compensation and restoration strategies that could feasibly be adopted to help reduce or balance the negative impacts of climate change on salmon. Given future uncertainties, perhaps the most important task is to preserve as much diversity among Pacific salmon populations as possible. This sentiment is echoed by Crozier at al. (2008a), who state that: “Because differences in habitat may contribute to the individualistic population responses we observed, we infer that maintaining habitat diversity will help buffer some species from the impacts of climate change” and Brannon (1987) who recognised 20+ years ago that “the critical relationships that salmonids demonstrate with their environment emphasises the need for management to include measures to preserve the uniqueness that stocks have acquired.”

Table 2. Spawning migration vulnerability indicators for different populations of Fraser River salmon. *Optimal T* = mean freshwater spawning migration temperature experienced by the peak of the run from 1995 – 2008 (see *Chapter 3* Table 6); *Thermal tolerance range* = relative ranking of thermal tolerance based on physiological studies of temperature and swimming performance (e.g. Lee et al. 2003); *Lower river mean T* = *x*-day mean lower river temperature centred on the historic peak river entry timing for each stock (see *Chapter 3* Table 1) where *x* = run duration (see *Chapter 3* Table 1); *% T > lethal* = the % of daily lower river temperatures > 21 ˚C (given the same stock characteristics as defined for *Lower river mean T* calculations); *% T > optimal* = the % of daily lower Fraser River temperatures > *Lower river mean T*; *% change in mean T)* = % change between current and future *Lower river mean T*; *Flow (direction of change)* = expected increase or decrease in encountered flows based on literature review results (see above). Lower river mean T values are from 1981 – 2000 for current conditions and 2081 – 2100 for future conditions (see *Chapter 4*).

			Physiological tolerance		**Current environmental exposure**			**Future environmental exposure**				
Species	**Timing group**	**Population**	**Optimal T**	**Thermal tolerance range**	**Lower river mean T**	**% T > lethal**	**% T > optimal**	**Lower river mean T**	**% change in mean T**	**% T > lethal**	**% T > optimal**	**Flow (direction of change)**
CK	Spring	Upper Chilcotin	8.6	Unknown	9.7	0	61.1	11.5	18.6%	0	86.9	↑
CK	Early Summer	Slim Creek	15.3	Unknown	15	0.4	46.9	17.8	18.7%	1.4	82.3	↓
CK	Mid Summer	Nechako	17.4	Unknown	16.8	0.5	38	18.9	12.5%	2.2	89	↓/↑
CK	Mid Summer	Tete Jaune	15.6	Unknown	15.3	0	45.4	18.2	19.0%	1.7	96.6	↓
CK	Late Summer	South Thompson	17.4	Unknown	16.7	0.4	34.7	18	7.8%	0.9	60.2	↓/↑
CK	Fall	Harrison	12.4	Unknown	12.9	0	54.3	12.9	0%	0	54.7	↑/↓
CH	Fall	Weaver	8.7	Unknown	8.3	0	47.1	10	20.5%	0	70.4	↑/↓
CO	Fall	Chehalis	12	Mod	12.1	0	51.2	12.8	5.8%	0	60	↑/↓
CO	Fall	North Thompson	11.8	Unknown	12.1	0	52.5	12.8	5.8%	0	61.6	↑/↓
PK	Early	Thompson	14.5	High	14.2	0	45.3	15.3	7.8%	0	63.3	↑/↓
PK	Late	Weaver	14.5	High	13.1	0	31.1	14.3	9.2%	0	47.1	↑/↓
SK	Early Stuart	Driftwood	16.1	High	15.8	0	45.9	18.7	18.4%	2.2	98.8	↓
SK	Early Summer	Gates	17.4	Mod	17.3	0.6	48.2	19	9.8%	2.5	95.1	↓
SK	Summer	Chilko	16.7	High	17.2	0.5	65.3	18.6	8.1%	1.9	90	↓/↑
SK	Summer	Horsefly	16.8	Unknown	17.2	0.5	59.3	18.6	8.1%	1.9	88.5	↓/↑
SK	Lates	Adams	16.4	Low	16.1	0	46.2	17.2	6.8%	0.1	67.3	↓/↑

Table 1 (cont). Spawning migration vulnerability indicators for different populations of Fraser River salmon. *Peak river entry* = as reported in *Chapter 3* Table 1; *Peak spawn* = as reported in *Chapter 3* Table 1; *Freshwater residency* = number of days between peak river entry and peak spawn; *Staging* = peak spawn – peak river entry + migration days (where migration days = number of days to complete migration from river entry to spawning grounds assuming constant average migration rates, as reported in *Chapter 3* Table 1); *Variation in river entry time* = relative ranking of low/mod (moderate)/high/very high based on the run duration (number of days over which fish enter the river, as reported in *Chapter 3* Table 1); *Current harvest* = relative level of directed fishing pressure on each stock (based on review of the literature and recent DFO reports); *Mixed stocks* = whether directed harvest occurs as part of a mixed stock fishery; *Stock of concern* = ranking of low/mod (moderate)/high/extreme depending on literature reports and/or recent stock status assessments. For further background on all these variables see *Chapter 3* Table 1.

			Behaviour					Fishing constraints		
Species	**Timing group**	**Population**	**Peak river entry**	**Peak spawn**	**Freshwater residency (days)**	**Staging (days)**	**Variation in river entry time**	**Current harvest**	**Mixed stocks**	**Stock of concern**
CK	Spring	Upper Chilcotin	02-May	12-Aug	102	80	High	Limited	NA	Extreme
CK	Early Summer	Slim Creek	26-Jun	29-Aug	64	35	High	Limited	NA	Extreme
CK	Mid Summer	Nechako	18-Jul	04-Sep	48	22	Mod	Limited	Yes	Mod
CK	Mid Summer	Tete Jaune	01-Jul	04-Sep	65	30	Low	Limited	NA	High
CK	Late Summer	South Thompson	22-Aug	14-Oct	53	40	High	Limited	Yes	Low
CK	Fall	Harrison	05-Oct	06-Nov	32	27	Very high	Limited	No	Mod
CH	Fall	Weaver	22-Oct	30-Nov	39	32	Very high	Yes	Yes	Low
CO	Fall	Chehalis	07-Oct	23-Nov	47	43	Mod	None	NA	High
CO	Fall	North Thompson	07-Oct	23-Nov	47	34	Mod	None	NA	Extreme
PK	Early	Thompson	14-Sep	11-Oct	27	21	Mod	Yes	Yes	Low
PK	Late	Weaver	21-Sep	11-Oct	20	4	Low	Yes	Yes	Low
SK	Early Stuart	Driftwood	07-Jul	11-Aug	35	1	Low	None	NA	Extreme
SK	Early Summer	Gates	31-Jul	01-Sep	32	21	Mod	Limited	Yes	Mod
SK	Summer	Chilko	11-Aug	25-Sep	45	25	Mod	Limited	Yes	Low
SK	Summer	Horsefly	11-Aug	08-Sep	28	7	Mod	Limited	Yes	Low
SK	Lates	Adams	29-Aug	16-Oct	48	27	Low	Limited	NA	Extreme

Table 3. Relative ranking of Fraser River salmon populations across a range of variables characterising vulnerability to changes in the freshwater spawning migration environment resulting from climate change (using information provided in Table 1). Temperature (absolute) = ranked 1 – 15 with 1 = largest absolute increase in mean lower river temperature between 1981-2000 and 2081-2100; Flow (absolute) = ranked of 1 – 4 corresponding to anticipated increase in future flow (1 = ↑; 2 = ↑/↓; 3 = ↓/↑; 4 = ↓). Temperature (relative) = ranked 1 – 15 with 1 = largest % of 2081-2100 lower river temperatures exceeding optimum temperatures defined in Table 1. Thermal tolerance = ranked = 1 – 3 where 1 = low; 2 = mod; 3 = high (where physiological data was not available, ranks were assigned given the SD in migratory temperatures from Table 6 in *Chapter 3*); Variability in timing = ranked 1 – 15 with 1 = smallest run duration and 15 = longest run duration; Flexibility in migratory behaviour = ranked 1 – 15 with 1 = smallest number of staging days, 15 = greatest number of staging days; Current status = ranked 1 – 4 where 1 = extreme, 2 = High, 3 = mod, 4 = low. Threat to spawning migration success = average over all ranks; lowest rank = highest threat.

			Absolute magnitude of change		**Relative magnitude of change**	**Plasticity indicators**			**Management concerns**	
Species	**Timing group**	**Population**	**Temperature**	**Flow**	**Temperature**	**Thermal tolerance**	**Variability in timing**	**Flexibility in migratory behaviour**	**Current stock status**	**Threat to spawning migration success**
CH	Fall	Weaver	5	2	9	1	9	8	4	5.67
CK	Early Summer	Slim Creek	2	4	8	2	10	10	1	6.00
CK	Fall	Harrison	11	2	14	1	12	6	3	7.67
CK	Late Summer	South Thompson	7	4	13	1	11	11	4	7.83
CK	Mid Summer	Nechako	3	3	5	1	7	5	3	4.00
CK	Mid Summer	Tete Jaune	1	4	2	2	3	7	2	3.17
CK	Spring	Upper Chilcotin	4	1	7	2	11	13	1	6.33
CO	Fall	Chehalis	10	2	13	2	6	12	2	7.50
CO	Fall	North Thompson	10	2	12	2	6	9	1	6.83
PK	Early	Thompson	9	2	11	3	2	4	4	5.17
PK	Late	Weaver	8	2	15	3	2	2	4	5.33
SK	Early Stuart	Driftwood	1	4	1	3	1	1	1	1.83
SK	Early Summer	Gates	5	4	3	2	5	4	3	3.83
SK	Lates	Adams	9	3	10	1	4	6	1	5.50
SK	Summer	Chilko	6	3	4	3	8	5	4	4.83
SK	Summer	Horsefly	6	3	6	3	8	3	4	4.83