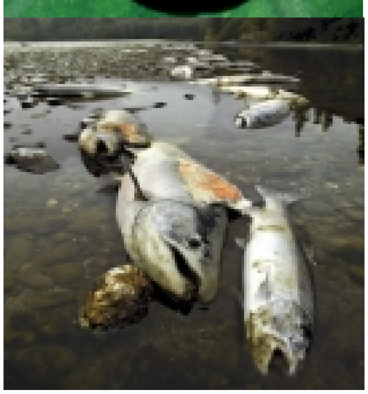

Living on the Edge: Climate Change and Salmon in Lang Creek, British Columbia.

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Executive Summary

Haslam Lake and Lang Creek, located just west of Powell River on the Sunshine Coast, are within a multiple-use community watershed that currently provides drinking water for approximately 20,000 people of Powell River and Brew Bay. The system is also a substantial fisheries resource, with 2003 returns of approximately 1800 Coho, 1800 Chinook, 1000 Pink, 10,000 Chum, 500 Steelhead, and some Sockeye. Water temperatures in this system are very warm during summer and are known to have exceeded 30^{o}C in the marshy headwaters of Lang Creek, though they cool downstream through contributions of cooler tributaries and groundwater, and from evaporation and riparian processes.

The British Columbia Ministry of Water, Land and Air Protection (MWLAP) hired Aquatic Informatics Inc. to complete an investigative study on the watershed. The objectives of this study were to:

1. Evaluate recent impacts of warm stream temperatures to salmonids in Lang Creek;
2. Estimate the impacts of climate change on Lang Creek salmonid populations;
3. Forecast the impacts of climate warming and climatic cycles on future stream temperatures in Lang Creek; and
4. Develop water temperature objectives for the protection of drinking water and aquatic life.

Within the observation period (1998-2004), summer water temperatures in upper Lang Creek routinely exceeded 24^{o}C, and occasionally exceeded 26^{o}C. In the mid and lower reaches, water temperature tended to be approximately 2 - 4^{o}C cooler, depending on the contributions from the cooler tributaries. Exposure (magnitude and duration) based risk assessment was conducted to evaluate the effects of high stream temperatures in Lang Creek during the observation period. Temperatures in upper Lang Creek were warm enough to potentially cause mortalities as high as 52% - 97%, depending on the salmon species. In mid and lower Lang Creek, temperatures were at least 2^{o}C and 4^{o}C below lethal thresholds respectively, even during the warmest year. This can be attributed to the downstream cooling processes.

Overall, although temperatures exceeded lethal thresholds in upper Lang Creek and approached lethal thresholds in mid Lang Creek, high water temperatures likely did not pose acute risk to salmon and trout species in the system during the observation period. This is because the fish are known to move to cooler refuge habitat in the tributaries and deep water of the lakes. Habitat exclusion and isolation, however, are likely occurring during summer as fish avoid warm temperatures in upper and mid Lang Creek and are inhibited from moving through these reaches to other suitable habitat. Even when temperatures in Lang Creek are below lethal thresholds, the temperatures are well above those considered optimal for rearing and would cause chronic impacts such as reduced growth and resistance to disease and stress. The fish in the watershed are therefore highly vulnerable to any habitat or water quality deterioration in the lakes and tributaries, to reduced summer flows in the tributaries, and to further warming in the mainstem.

As a background to how climate has been changing in the Powell River area, the impacts of global warming over the last 80 years were estimated. Our results suggest atmospheric warming of approximately 0.8^{o}C in winter and 0.3^{o}C in spring. Summer and fall appear not to have been affected. Precipitation has also increased, with highest increases during winter (~1.2 mm/day) and spring (~0.8 mm/day), and modest increases during summer and fall (~0.5 mm/day).

Climate forecasts for the Powell River area over the next 80 years were completed and used to predict impacts on Lang Creek summertime temperatures. The Canadian Global Coupled Model 2 was downscaled to the Powell River area. Local summer air temperatures were forecasted to warm by approximately 1.1^{o}C by 2020, by 1.8 - 2.1^{o}C by the 2040s, and by 2.4 - 3.5^{o}C by the 2080s. Projections of increases to local air temperature were then applied to water temperature in Lang Creek. The relation between Lang Creek mean daily water temperature and Powell River mean daily air temperature was approximately linear over the observation period, and accounted for 94% of the variability in water temperature. Given this relation and the forecasted increases in air temperature for Powell River, Lang Creek mean summer stream temperatures are forecasted to increase by 0.9^{o}C during summer by the 2020s, by 1.6 - 1.9^{o}C by the 2040s, and by 2.2 - 3.2^{o}C by the 2080s. Added to these increases, diurnal fluctuations are projected to increase by 4% (0.2^{o}C) by the 2020s, by 8% (~0.3^{o}C) by the 2040s, and 10% (~ 0.4^{o}C) by the 2080s. Combined forecasts are provided in the **table below**.

Forecasted increases to Lang Creek water temperatures.

Decade	2020s	2040s	2080s
Forecasted Increases	1.0^{o}C	1.8 – 2.1^{o}C	2.4 – 3.4^{o}C

These forecasts suggest that:

1. During a warm year in the 2020s, summer water temperatures in upper Lang Creek will cause very high mortalities to any salmon populations present. By the 2040s, high mortalities are likely to occur even during cool years.
2. For mid Lang Creek, temperatures are forecasted to approach acute thresholds for most species by the 2040s and exceed thresholds by the 2080s.
3. In lower Lang Creek temperatures are forecasted to approach but remain below lethal thresholds to the 2080s.

Chronic impacts to salmon and trout are likely already occurring in Lang Creek, and will become more significant with climate change. Therefore, over the next 20 – 80 years, suitable summer habitat for salmonids will likely become restricted to the small cooler tributaries, which unfortunately are mere trickles during summer and would be unable to support the populations.

During summer months, temperatures in lower Lang Creek are consistently much higher than provincial guidelines for drinking water (15^{o}C). These objectives cannot be met at the Brew Bay intake without diversion of cooler deepwater from upstream lakes. *Temperature objectives for drinking water at Brew Bay should be set for 15^{o}C*, though they will not be meet during summer. Temperatures throughout Lang Creek are also higher than provincial guidelines that are considered optimal for rearing salmon and trout. In upper Lang Creek, water temperatures already exceed acute thresholds for salmonids during very warm summers. Under climate change scenarios, thresholds will eventually be exceeded throughout Lang Creek. *Water temperature objectives for the protection of aquatic life have been recommended in this report, and are magnitude and duration dependant* (**table below**). *These objectives account for the naturally warm temperatures in Lang Creek, and should be set for upper Lang Creek at the outlet of Duck Lake.*

Recommended water temperature objectives for Lang Creek.

Water Use	Monitoring Location	Monitoring Frequency	Magnitude (°C)	Duration
Drinking Water	Brew Bay Intake	Continuous	15.0	Not to be exceeded
Aquatic Life	Duck Lake Outlet	Continuous	20.0	190 days
			20.5	100 days
			21.0	53 days
			21.5	28 days
			22.0	15 days
			22.5	8 days
			23.0	4 days
			23.5	2 days
			24.0	1 day
			24.5	15 hrs
			25.0	7 hrs
			25.5	4 hrs
			26.0	2 hrs
			26.5	1 hrs
			27.0	45 min
			27.5	30 min
			28.0	Not to be exceeded

Given the already warm summer temperatures in Lang Creek, and the forecasted increases under climate change, management steps should be taken to protect water quality and aquatic life in Lang Creek. *The following recommendations should be considered*:

1. Continue the thermistor monitoring program in the watershed. Thermistors should be maintained at Haslam Lake, Blackwater Creek, Duck Lake Outlet, Lang Hatchery, mid Lang Creek, Anderson Creek, Coho Creeks, and lower Lang Creek (Channel). Hourly water temperature should be recorded at the lower hatchery, rather than daily averages.
2. Future land use decisions need to specifically mitigate the negative effects of increasing stream temperatures. Land development, such as forest harvesting, should be limited downstream of Haslam Lake. In particular, riparian areas around tributaries need to be protected. Where development takes place, riparian buffers suitable to protect water temperatures should be maintained.
3. During July and August, deep cooler water from Mud Lake or Haslam Lake should be diverted into Lang Creek. Temperature/depth profiles for Haslam Lake and Duck Lake are available (PRSES). Profiles of Duck Lake should be collected.
4. Flows over the Haslam Lake weir should be reduced during summers when flows downstream are sufficient for downstream needs.
5. Water Temperature Objectives, as outlined above, should be set for Lang Creek.

Introduction

Keeping a watershed healthy while accommodating economic growth can be difficult. Land development activities such as logging, agriculture, and urban development make management for maintaining water quality, conservation, and biodiversity a challenge. Typically, management decisions rely on sparse datasets or short-term studies meant to characterize watershed conditions. Rarely, however, do these studies consider regional and longer-term trends, such as atmospheric cycles (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation, etc.) and climate change, which can be on a scale larger than that of local interventions. For example, summertime maximum stream temperatures can be more than 7^{o}C warmer during a strong El Niño year in coastal British Columbia (Quilty *et al*., 2004c), and climate change is estimated to have increased annual stream temperatures on the southern coast by 1 - 2^{o}C (MWLAP, 2001; Quilty *et al*., 2004a). Therefore, when making responsible land development decision, climate trends must be considered.

Natural Climate Change (Long Term)

Climate is naturally variable, and has changed greatly over the history of the Earth. Over the past one million years, the Earth's climate has alternated between ice ages and warm, interglacial periods with cycles that last about 100,000 years (EPICA, 2004; Petit *et al*., 1999). During this time, global average temperatures have changed by as much as 12^{o}C between glacial–interglacial periods (**Figure 1 - line b**; Petit *et al*., 1999). On shorter time scales, too, climate changes continuously. For example over the last 10,000 years most parts of Canada have experienced climate condition that, at different times, were warmer, cooler, wetter, and drier than experienced at present. Indeed, with respect to climate, the only constant is that of continuous change (Warren et al., 2004).

There are a number of factors that drive climate variability. These include changes in the Earth's orbit, changes in solar output, sunspot cycles, volcanic eruptions, and fluctuations in aerosols and greenhouse gases. These factors operate over a range of time scales but, when considered together effectively explain most of the climate variability over the past several thousand years. Greenhouse gasses such as water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), are emitted through natural processes, including plant decomposition and respiration, volcanic eruptions, and ocean fluxes (i.e. evaporation, oceanic CO_2 sequestering, etc…). Once in the atmosphere, these gasses trap and reflect heat back towards the Earth's surface through a process known as the greenhouse effect. This effect is necessary for maintaining temperatures capable of supporting life on Earth. Concentrations of greenhouse gases are known to vary naturally (**Figure 1: lines a**, **c**). CO_2, for example, has almost always been in a state of change during the past 420,00 years but within stable bounds of roughly 180 to 300 ppm. (Petit *et al*., 1999). The carbon dioxide levels in the atmosphere have marched in exact step with temperature for hundreds of thousands of years (Petit *et al*., 1999).

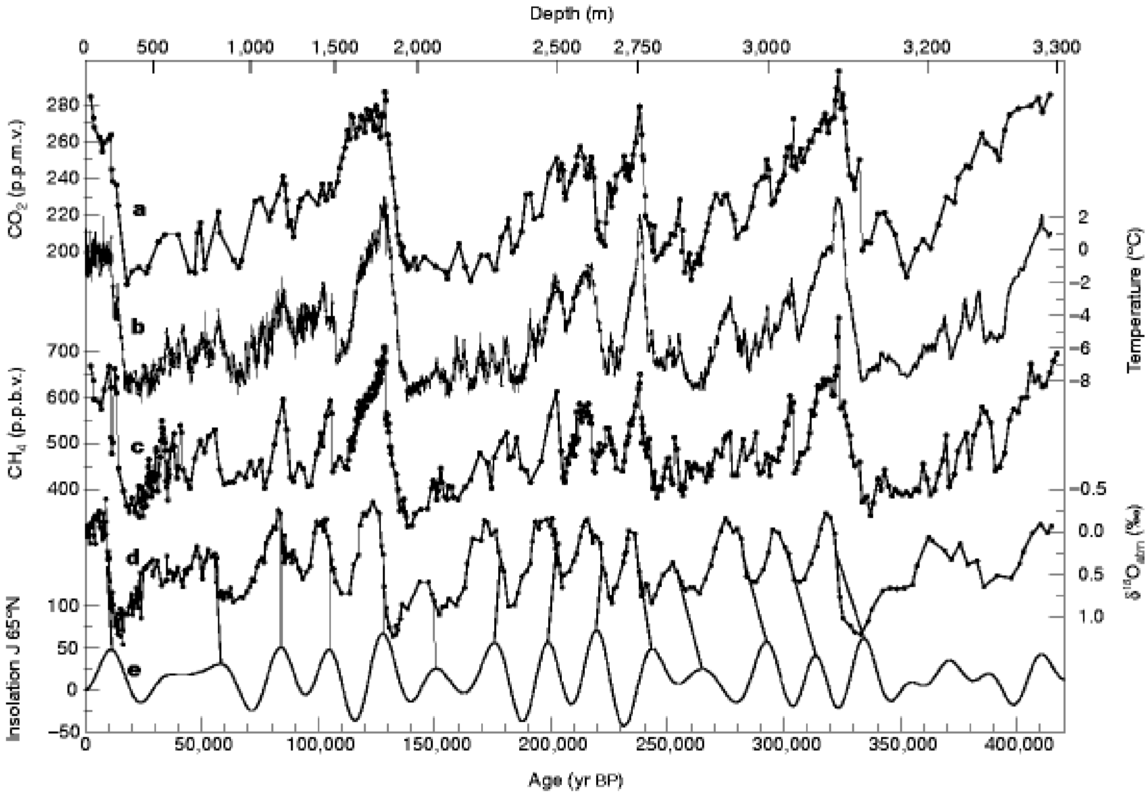


Figure 1. Changes in Earth's atmosphere and surface temperature during the past 420,000 years as estimated from ice-core drilling at Vostok, East Antarctica. Volstak time series for a) CO_2; b) isotopic temperature of the atmosphere; c) CH_4; d) $^{18}O_{atm}$; and e) mid-June insolation at 65° N (in W m^{-2}). From Petit *et al*. (1999).

Climatic Cycles (Shorter Term)

In addition to climate change occurring over thousands to hundreds of thousands of years, climatic oscillations on the order of decades or less, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have strong effects on climate variability. Every 2–10 years, a sudden warming of the coastal waters off Peru causes a phenomenon known as El Niño. El Niño is closely related to a global atmospheric oscillation known as the Southern Oscillation (SO). During El Niño episodes, lower than normal pressure is observed over the eastern tropical Pacific and higher than normal pressure is found over Indonesia and northern Australia (NOAA, 2003). These features characterize the warm phase of the SO, which is often referred to as an El Niño/Southern Oscillation episode. During warm (ENSO) episodes the normal patterns of tropical precipitation and atmospheric circulation become disrupted. These disruptions have global effects such as wetter and stormier than normal weather for Western North America and Western Europe, drought in Africa and Asia, and unpredictable monsoons in India.

The PDO has been described by some as a long-lived El Niño-like pattern of Pacific climate variability, and by others as a blend of two sometimes independent modes having distinct spatial and temporal characteristics of North Pacific sea surface temperature (SST) variability (Mantua and Hare, 2002). The PDO has been shown to cause climatic regime shifts lasting, on average, 23 years. In the past century, regime shifts were observed in 1947 ("cool" PDO) and in 1977 ("warm" PDO) (Mantua and Hare, 2002). The PDO has global climatic impacts that are broadly similar to ENSO.

Global Warming

The above natural drivers alone, however, are unable to account for the increases in temperature and accompanying suite of climatic changes observed over the 20th century (Warren et al., 2004). Over the past century, global average surface temperature has increased by 0.6^{o}C (IPCC, 2001). The 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1861 (IPCC, 2001). The 10 warmest years in global meteorological history have all occurred in the past 15 years. Human activities, such as the burning of fossil fuels and land-use changes, have significantly increased the concentrations of greenhouse gases in the atmosphere over the past century. For example the atmospheric concentration of CO_2 has increased by about 30% since the industrial revolution (**Figure 2**), from 280 parts per million (ppm) in the late 1700s to about 372 ppm in 2002 (Blasing, and Jones, 2003). These levels are unprecedented during the past 740,000 years and likely during the past 20 million years (EPICA, 2004; IPCC, 2001).

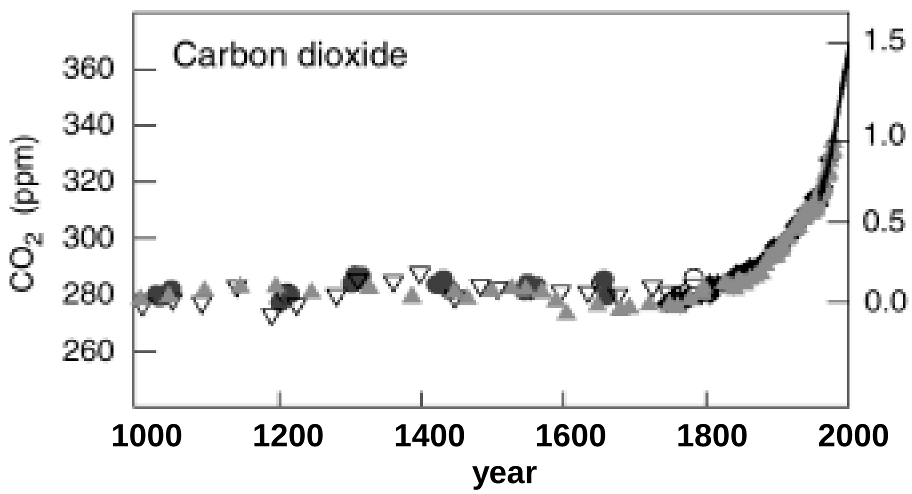


Figure 2. 1000-year record of past changes in atmospheric carbon dioxide (IPCC, 2001).

Regional Effects of Global Warming and Climatic Cycles

For British Columbia, the effects of global warming and climatic cycles vary regionally and across seasons (**Figure 3**). For the Georgia Depression, seasonal temperatures are estimated to have increased by 0.8^{o}C in spring, 0.5^{o}C in fall, and to have not changed in summer and winter (MWLAP, 2001). North in the Coast and Mountains Region, temperatures are estimated to have also changed by 0.8^{o}C in the spring, but to have increased by 1.4^{o}C in the winter and have not changed in the summer and fall (MWLAP, 2001). There have been numerous related effects on climate, such as increased precipitation in southern B.C., increased sea level and sea temperature along the coast, and retreating of glaciers (MWLAP, 2001).

During El Niño, coastal British Columbia experiences milder temperatures and below average precipitation in winter months (Redmond and Kock, 1991; Pulwarty and Redmond, 1997; Hamlet and Lettenmaier, 1999; Kiffney *et al.*, 2002). The warm phase of the PDO tends to coincide with anomalously warm temperatures in the Pacific Northwest, cool phases coincide with colder wetter weather (Mantua and Hare, 2002; Mote *et al.*, 2003). It has also been suggested that the PDO works to modulate the effects of tropical ENSO on Northern Hemisphere climate anomalies (Gershunov and Barnett, 1998; Gershunov *et al*., 1999, Kiffney *et al*., 2002). Strong El Niño and positive PDO events tend to lead to warmer and drier weather, especially in winter (Kiffney *et al*., 2002).

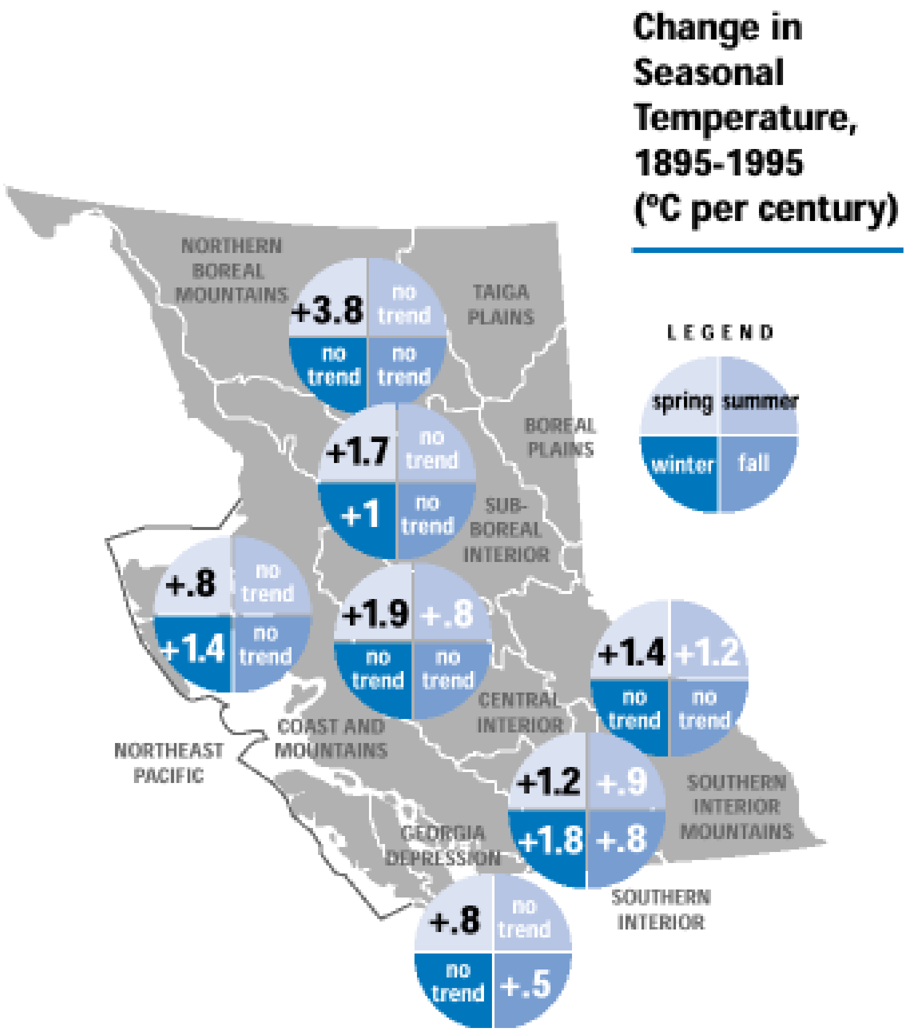


Figure 3. Change in seasonal temperature for regions in British Columbia between 1895 and 1995 (MWLAP, 2001)

Observed Impacts on Water Resources in Coastal B.C.

The impacts of climatic cycles on air temperature, precipitation, and stream flow in the Pacific Northwest are well documented (Redmond and Koch, 1991; Mantua *et al*., 1997; Pulwarty and Redmond, 1997; Zhang *et al*, 1997; Gershunov and Barnett, 1998; Gershunov *et al*., 1999, Hamlet and Lettenmaier, 1999; Miles *et al*., 2000; Hsieh and Tang, 2001; Kiffney *et al*., 2002). During El Niño, coastal British Columbia experiences increased winter precipitation and an increased likelihood of below average streamflow in spring and summer. The literature on the effects on stream temperature, however, is relatively sparse (Kiffney *et al*., 2002, Quilty et al., 2004a). Kiffney *et al*. (2002) showed that during in-phase El Niño years the greatest differences in water temperatures in a coastal pacific northwest stream were in maximum winter temperatures, which were 0.9 to 1.9^{o}C warmer.

The impacts of climate change on water resources in British Columbia have also been studied (Leith and Whitfield, 1998; Whitfield and Taylor, 1998; Whitfield, 2000; Whitfield and Cannon, 2000; and Whitfield *et al*, 2002). Findings from the Georgia Basin indicate important changes to the three hydrologic types found in the coastal region: rainfall-driven streams demonstrate increased winter flows, snowmelt-driven streams demonstrate an increasingly early onset to spring snowmelt, and hybrid (mixed rain and snow) streams become increasingly rainfall driven (Whitfield et al., 2002).

Forecasts for Global Temperature Increases

Climatologists use complex numerical integration models to predict future conditions under various scenarios (e.g. varying levels of greenhouse gases and aerosols). Many Global Circulation/Coupled Models (GCMs) have been developed over the last several decades (e.g. CGCM2, HadCM3, CSIROMk2b, ECHAM4, etc). These models are based on physical laws represented by equations that are solved using a 3D grid over the globe. These models couple submodels that represent the atmosphere, ocean, land surface, cryosphere and the bioshere (IPCC, 2001). The models are then run using various future scenarios, such as A1, A2, B1, and B2 (**Figure 4**). Scenarios prefixed with the letter 'A' are futures where human endeavour is focused on economic growth; 'B' scenarios have a more environmental stance (Nakicenovic *et al*., 2000). In addition, A1 and B1 are more global compared to the more regional A2 and B2 (ICPP, 2001):

- **A1 –** the A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in *per capita* income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system: fossil intensive A1F1, non-fossil energy sources (A11T), balance across all sources (A1B).
- **A2 –** The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally orientated and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- **B1 –** The B1 storyline and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions t o economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- B2 **–** The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Under these scenarios, these GCMs predict that global average temperature could rise by 1.4 ~ 5.8^{o}C between 1990 and 2100 (Albritton and Filho, 2001; IPCC, 2001).

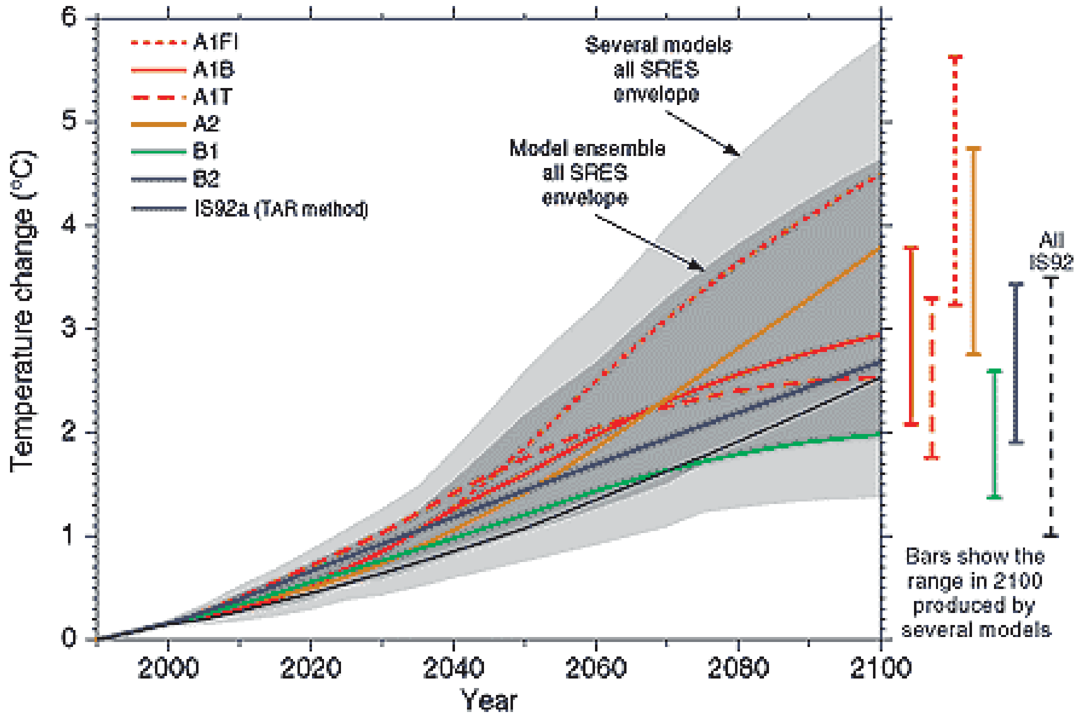


Figure 4. Atmospheric concentrations of CO_2 between 1990 and 2100 resulting from seven scenarios (IPCC, 2001).

Regional climate models (RCMs) as described by Leung and Ghan (1999b) provide higher resolution climatic information allowing for better assessment of local effects of global climatic change. The Canadian Regional Climate Model (C-RCM) predicts maximum increases in winter precipitation to occur over the steep topography of southwestern BC. Increased winter precipitation by up to 3mm/day is predicted in the region between Washington State and the BC South Coast (Laprise et al., 1998). The RCM proposed by Leung and Ghan (1999b) also predicts increases in winter precipitation with a strengthening of the dipole of low and high winter rainfall from California to the southern BC coast. Leung and Ghan (1999b) show a regional summer and winter warming that is approximately 3.3°C in winter and 2.0°C in summer after doubling of atmospheric CO_2 concentrations (most scenarios predict doubling to happen by mid 21st century, though some predict closer to the end of the century). More substantial increases in temperature in the winter are largely due to the decrease in the snow-albedo feedback as the snowline moves to higher altitudes as sea level temperatures rise (Mote, 2003).

Forecasted Impacts on Water Resources

Global climate change due to increasing concentration of greenhouse gases has stimulated numerous studies and discussions about its possible impacts on water resources (Leung and Ghan, 1999a). Schindler (2001) notes that habitats for cold stenothermic organisms will be reduced and warmer temperatures will affect fish migrations. Clair *et al*. (1998) used neural network modeling to evaluate the change in the hydrometric regime over the difference eco-zones in Canada. Peak runoffs were predicted to occur up to 1 month earlier then is currently the case. Clair *et al*. (1998) also predict considerable increases summer runoff specifically for the pacific maritime eco-zone. Weston *et al*. (2003) examined the flood patterns of the Lower

Englishman River on Vancouver Island under climate change scenarios and found increases of up to 17% in peak annual flow in the latter half of the 21st century.

Trends in Stream Temperature and the AT-WT Relation

Water temperature is arguably the most important physical property of streams and rivers (Webb, 1996). However, studying long-term trends in water temperature is difficult because there are only a handful of datasets that are detailed and long term enough for rigorous assessment of trends (Webb, 1996; Webb and Nobilis, 1997). Therefore, researchers tend to estimate water temperature from air temperature (Brown 1969, Johnson, 1971; Crisp and Howson, 1982; Webb, 1987; Stefan and Preud'homme, 1993; Webb and Walling, 1993; Webb and Nobilis, 1997; Pilgrim *et al*., 1998; Erickson and Stefan, 1996, 2000; Webb *et al*., 2003), which has been widely measured, and use the relation to estimate water temperature trends (Webb, 1996; Webb and Nobilis, 1997). The air-water temperature (AT-WT) relation has been found to be approximately linear, though it departs from linearity near zero and above 20^{o}C due to freezing and increased evaporation, respectively (Crisp and Howson, 1982; Mohseni and Stefan, 1999; Webb et al., 2003). Mohseni and Stefan (1999) characterize the relation as an S-curve type. The relation has also been found to change temporally, varying with flows and with contributions of snowmelt (Webb, 1996; Webb and Nobilis, 1997; Kobayashit *et al*., 1999; Langan *et al*., 2001; Webb *et al*., 2003), and to vary spatially due to differences in elevation, latitude, geology, drainage area, vegetation, land-use, (Smith, 1979, 1981; Crisp and Howson, 1982; Weatherley and Ormerod, 1990; Stefan and Preud'homme, 1993) and relative contributions of tributaries, groundwater, and hyporeic exchange (Johnson and Jones, 2000; Poole and Berman, 2001; Story *et al*., 2003).

Effects of Increased Temperature on Fish

Fish and other aquatic life are affected by changes to stream temperature. Fish are thermo conformers; that is they cannot maintain body temperatures much different from their aquatic environment. Water temperature is known to play a key role in virtually every aspect of salmon life (Brett, 1995). Adverse levels of temperature can affect behaviour (e.g. migration delays and timing), disease resistance, growth, and mortality (Brett, 1956). Considerable laboratory study has been conducted on a variety of salmon and trout species at differing life stages. Sullivan et al. (2000) describe how both lethal and sub-lethal effects of temperature depend on both the magnitude and duration of temperature exposure. For example exposure to water at 28^{o}C may have lethal effects on certain salmon after only minutes, whereas exposure at 24^{o}C will take several days to have the same lethal effect (**Figure 5**). Elliott (1981) established that acclimatization of fish to differing background water temperatures has a dramatic effect on lethal temperature curves. Fish acclimated at cold temperatures can have upper lethal limits 3~4^{o}C lower than those acclimated to warmer waters.

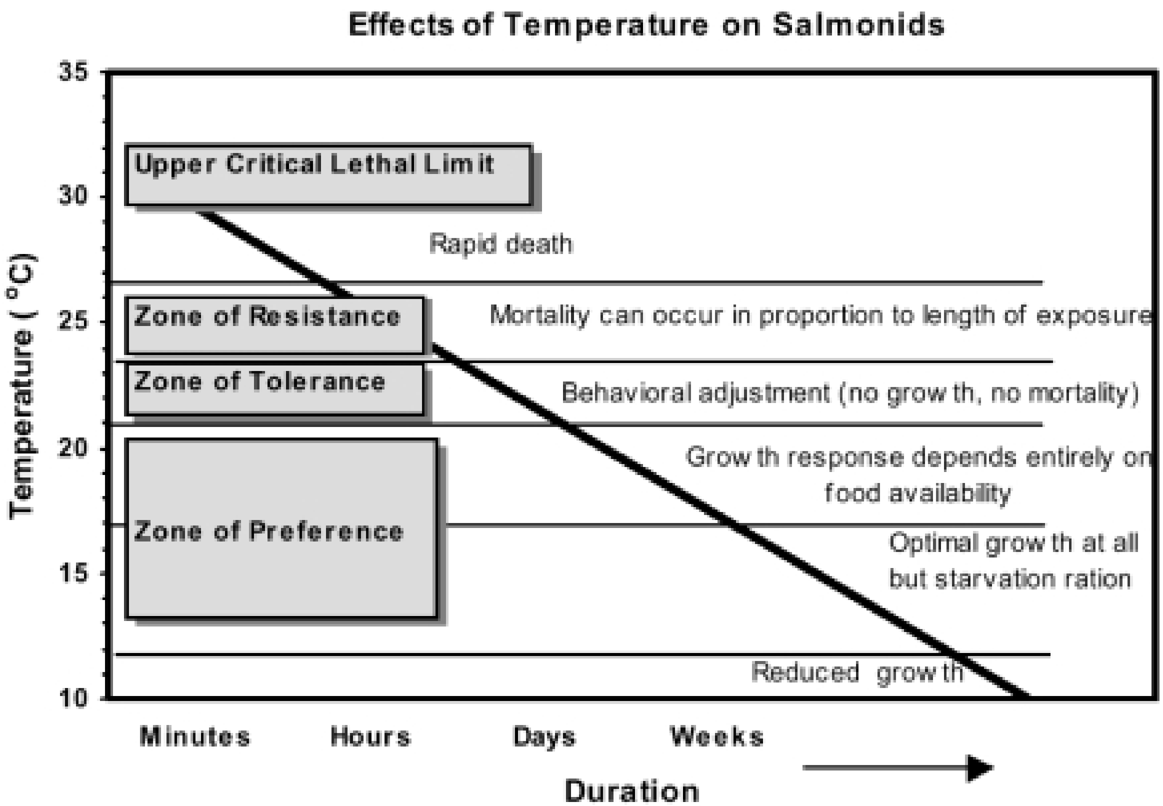


Figure 5. General biological effects of temperature on salmonids in relation to magnitude and duration of temperature. Taken from Sullivan *et al*. (2000).

Study Site

Haslam Lake and Lang Creek, located near Powell River on the Sunshine Coast, B.C. (**Figure 6**), are within a multiple-use community watershed that currently provides drinking water for approximately 20,000 people of Powell River and Brew Bay. The area is popular for hiking, mountain biking, non-motorized boating, and also provides a substantial fisheries resource. In 2003, returns were approximately: 1800 Coho, 1800 Chinook, 1000 Pink, 10,000 Chum, 500 Steelhead, and some Sockeye (Alex Dobler personal communication, 2004). These salmon populations are naturally restricted to the lower 10 km of the creek, where access above is blocked by a series of waterfalls. A salmon hatchery is located downstream of the falls, but releases fish above the falls in Duck Lake and Blackwater Creek (**Figure 7**). Every spring, approximately 120,000 Coho, 600,000 Chinook, and 370,000 Chum are released by the hatchery. Most of the watershed is composed secondary forest on crown land, having been logged or burned in the last 80 years (Carson, 2002). Forestry for timber harvesting is likely to be the major industrial use of the watershed for the foreseeable future. Agriculture is restricted to a few small hobby farms along lower Lang Creek.

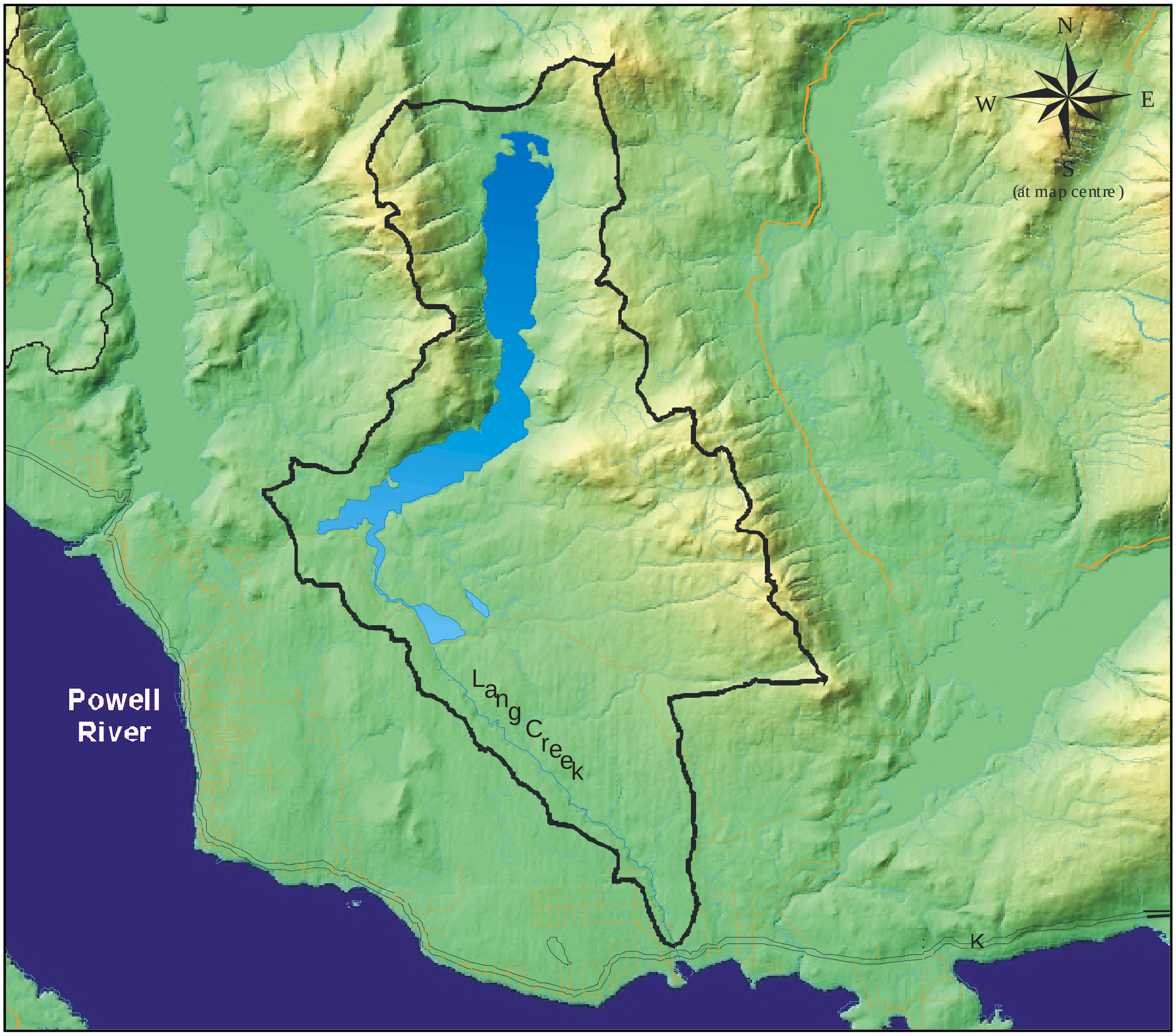


Figure 6. Location of Haslam Lake and Lang Creek. Scale ~ 1:150,000.

At the headwaters of Lang Creek is Haslam Lake (**Figure 7**). A weir at the outlet, built in the 1950s, maintains levels in the lake. Flows over the weir from September to July contribute most of the total discharge in Lang Creek, while during summer low flows the Lake tends to drop below the weir and DFO minimum flow requirements of 430 l/s (700 l/s during spawning season, October and November) are maintained by diversion (Carson, 2001). During this period, warm Haslam Lake water is estimated to still contribute approximately 75% of flows in Lang Creek (Carson, 2001). Highest stream temperatures correspond with the time of greatest contribution from Haslam Lake (Carson, 2002). Downstream of the weir is a series of marshy wetlands and shallow ponds (including Duck Lake) that become very warm in summer, with surface waters known to exceed 30^{o}C during hot years. Lang Creek water cools as it flows its 12 km length downstream, due to contributions from cooler groundwater and tributaries, from evaporation, and from riparian influences. At approximately 10 km (from mouth) are the falls and the hatchery, below which Anderson Creek empties into Lang Creek at approximately the 6 km point. A salmon sorting station, also know as "the channel" is located several hundred meters above the confluence with the Pacific Ocean. Mud Creek and Anderson Creek are the main tributaries, accounting for approximately 4% and 0.5% of Lang Creek flows during summer low flow respectively, and approximately 50% and 25% of discharge during fall storms (Carson, 2002).

Figure 7. Map of the Haslam Lake and Lang Creek watershed (diamonds mark sample sites).

Fish kills due to high temperatures have been documented in upper Lang Creek in the past. In 1989, over 250,000 Coho fry were lost at the hatchery when river water temperature was measured in excess of 29°C (Carson 2002). Although poor management response at the hatchery was partially blamed (Alex Dobler personal communication, 2004), high stream temperatures during summer are an ongoing concern. After release into the Lang Creek headwaters in spring, the fish tend to move into cooler waters of Blackwater Creek or the deep waters of Haslam Lake and Mud Lake where they spend the heat of the summer (Alex Dobler personal communication, 2004). Some are likely to move downstream into Lang Creek, and then into lower tributaries such as Anderson Creek and Coho Creek. Therefore, hatchery salmon have access to the entire watershed, though very warm water temperatures in upper Lang Creek significantly restrict summer habitat.

Draft drinking water quality objectives have been set for Haslam Lake and Lang Creek for bacteriological indicators, carbon, colour, alkalinity, conductivity, trihalomethanes, nutrients and metals (Carson and Quilty, 2003). Preliminary objectives were set for pH and turbidity until magnitude/duration criteria could be developed. Stream temperature objectives designed to protect aquatic life in Lang Creek also needed to be developed. To do this, quantification of sensitivity had to be completed. This task is completed in this report. Attainment of these objectives will help to protect drinking water and fish.

Study Objectives

The objectives of this study are:

- To evaluate recent (1998-2004) impacts of warm stream temperatures to salmonids in Lang Creek;
- To forecast the impacts of climate warming and climatic cycles on future stream temperatures in Lang Creek;
- To estimate the impacts climate warming and climatic cycles on Lang Creek salmonid populations;
- To develop magnitude and duration based water quality objectives for temperature in Lang Creek for the protection of aquatic life.

Methods

Outline of Methods

This study employed data from numerous sources, and was completed through a multiple stage approach. An overview of methods is provided here and details are provided in the proceeding sections:

1. The overall approach was to assess recent (1998 – 2004) summer stream temperatures in Lang Creek for risk to salmonids, and then forecast what future risks are likely to be under various climate change scenarios.
2. The Powell River Salmon Enhancement Society provided water temperature data for Lang Creek. Data was collected from nine sites at hourly, daily, or weekly intervals; however, all records were incomplete, either containing large gaps, outliers, or collected at too low of frequency (e.g. daily or weekly) to assess exposure impacts. We used statistical modeling to generate complete datasets from partial datasets for each site of interest.
3. The Canadian Global Coupled Model 2 (C-GCM2) was used to assess impacts of climate change on air temperatures for the South coast of British Columbia, and to forecast what impacts are likely to occur by the 2020s, 2040s, and 2080s.
4. The C-GCM2 results were statistically downscaled using Powell River climate data. This allowed for more localized forecasts of climate change. Historic impacts of climate change for the Powell River area, including those on air temperature and precipitation were determined using climate data provided by Environment Canada.

Data

In 1997, Forest Renewal B.C. funded a Water Resources Inventory project in the Haslam Lake and Lang Creek watershed. Under the auspices of this program, six monitoring stations were established from which weekly grab samples were collected by the Powell River Salmon Enhancement Society (PRSES). Continuous temperature dataloggers (thermistors) were installed at nine sites and a multiparameter monitoring station was installed near the mouth at the hatchery. Grab samples were collected until 2002 and continuous data was still being collected in 2004.

For this study, we obtained all stream temperature data collected by PRSES. This included hourly data, daily averages, and weekly spot sampling from a total of nine sites (**Table 1**). From a fisheries perspective, temperatures in the Lang Creek mainstem are most important and are the focus of this study (temperatures in the tributaries are much cooler in summer). Thermister data was obtained from the three mainstem sites: 1) *Upper Lang Creek* (outlet of Duck Lake and at Hatchery); 2) *Mid Lang Creek* (a couple km below Anderson Creek); and 3) *Lower Lang Creek* (at sorting station or "channel"). Data from upper Lang Creek included almost 4 years of hourly data, but contained many gaps (**Figure 8**). Hourly data from mid and low Lang Creek included about 2 years (**Figure 8**). Unfortunately, although hourly measurements were made at the lower multiparameter site (1997-2004), only daily averages were recorded, therefore the shorter thermister record was used. Weekly spot measurements were available for six sites (**Table 1**). Gaps and outliers in hourly data were detected and corrected by the use of artificial neural network modeling as described by Quilty *et al*. (2004b). In this approach, water temperature data from the site of interest was correlated with data from other stations and the relation used to validate and/or generate data. For example, for the mid and lower Lang Creek sites, hourly data was modeled by correlating weekly measurements with hourly data from other sites (**Figure 9**).

Table 1. Summary of temperature data collected from the Haslam Lake and Lang Creek watershed. Stations are numbered from upstream to downstream.

Sampling Interval	Station	Collection Period
Hourly	3. Blackwater Creek	1998 – present
	4. Mud Creek	1998 – present
	5. Outlet of Duck Lake/Hatchery	1998 – present
	6. Upper Anderson Creek	1998 – present
	7. Lower Anderson Creek	2000 - present
	8. Mid Lang Creek	2002 - present
	9. Coho Creek	2000 – 2003
	10. Lower Lang Creek (Channel)	2002 - present
Daily	10. Lower Lang Creek (Channel)	1987 – present
Weekly	1. Haslam Lake	1997 – present
	2. Haslam Slough	1997 – present
	3. Blackwater Creek	1997 – present
	5. Outlet of Duck Lake/Hatchery	1997 – present
	7. Lower Anderson Creek (Channel)	1997 – present

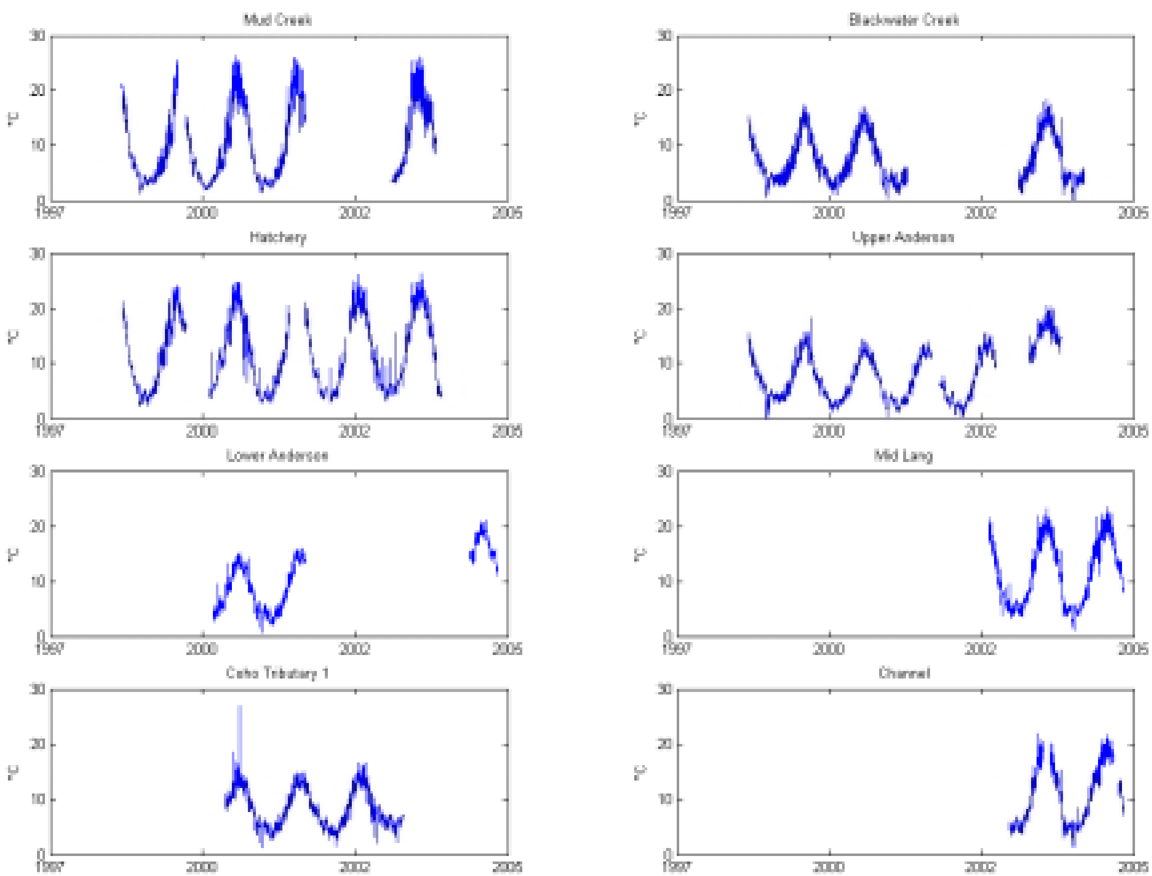


Figure 8. Plots of raw temperature data from each automated station, 1998-2004.

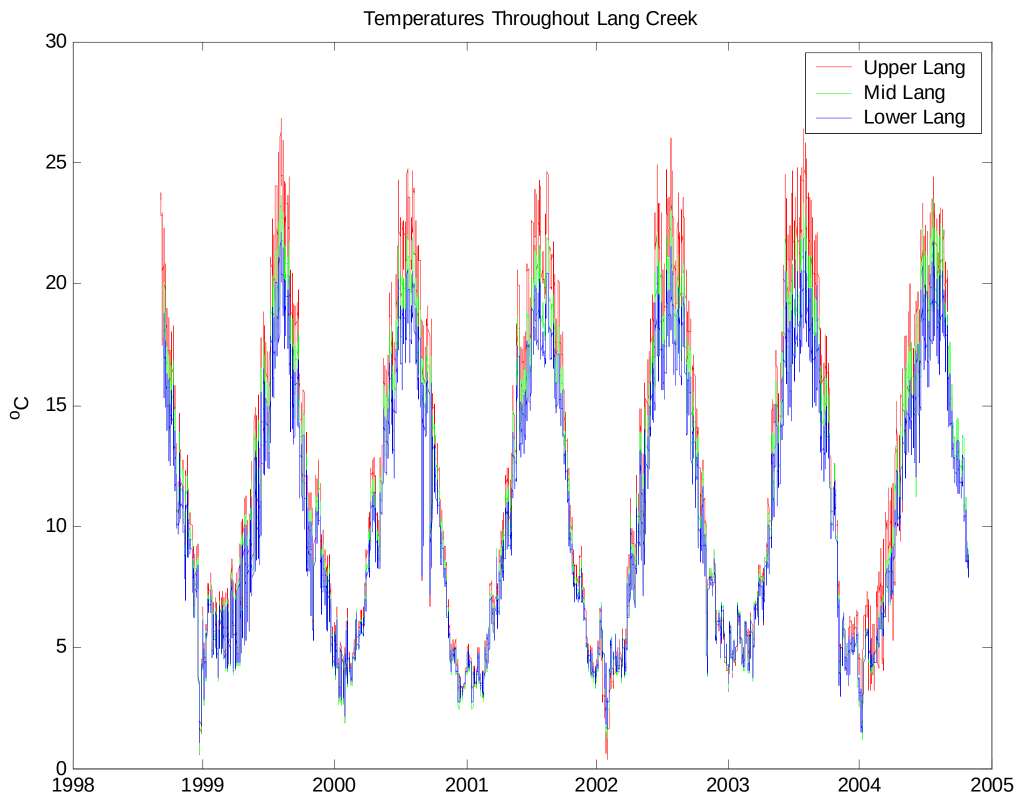


Figure 9. Validated and corrected hourly water temperature data (1998-2004) from upper Lang Creek, mid Lang Creek, and lower Lang Creek.

Powell River Climate Data

Daily air temperature and precipitation records have been recorded by Environment Canada at Powell River since 1924. Daily data from 1924-2000 was downloaded from the Environment Canada CanWest CD. Mean daily air temperature is shown in **Figure 10,** constructed in three-dimensions (days versus years versus temperature). This plot of yearly profiles highlights inter-annual variation.

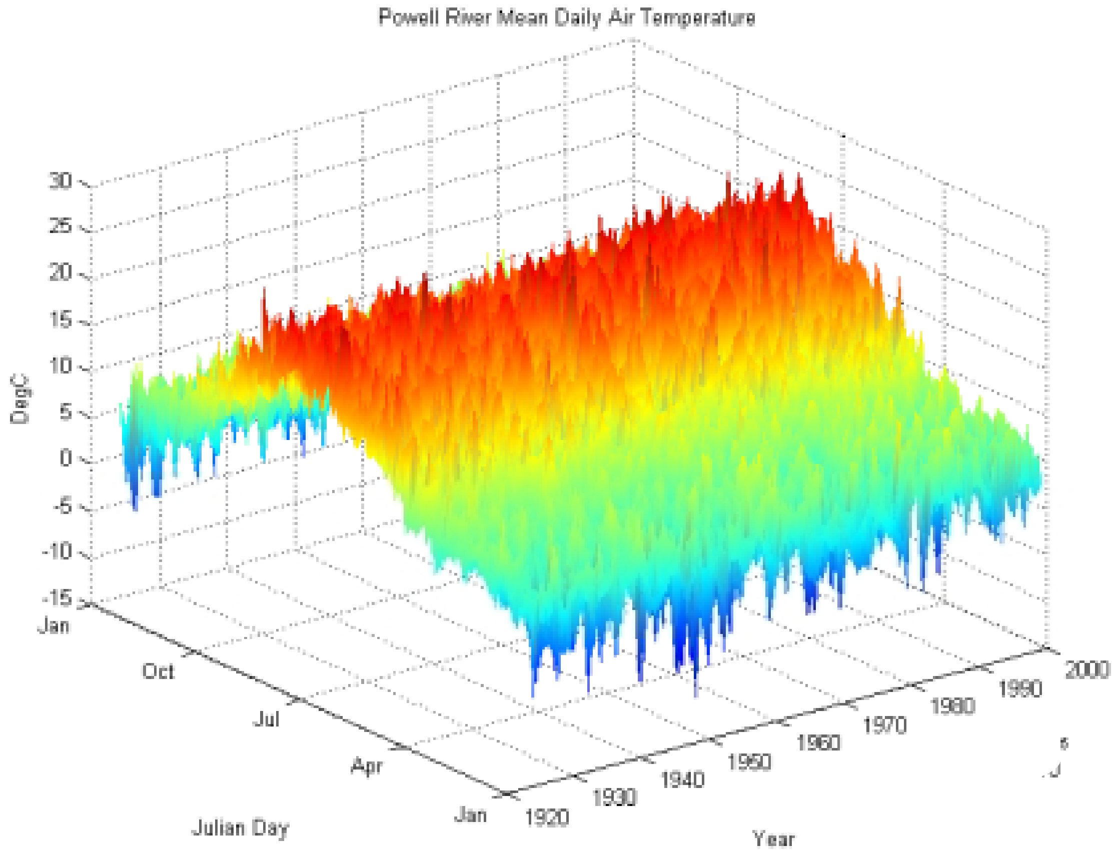


Figure 10. Mean daily air temperatures in Powell River, 1924-2000. Data is plotted in 3-dimension to highlight inter-annual variation.

Analysis Techniques

Environmental Risk Assessment

Environmental risk assessment is designed to combine the information from biological studies with an analysis of each population's exposure to quantified effects. Risk occurs when the stress' magnitude, frequency, and duration exceed the species ability to deal with that stress (Sullivan *et al*. 2000). For juvenile salmonids, each species tolerates different exposures (magnitude and duration) to high water temperatures (**Figure 11**). For example, steelhead can tolerate short durations (minutes to seconds) of very high temperatures (above 28^{o}C) better than other salmonids; however, they are not as tolerant to long durations (weeks to months) in warm temperatures (20-24^{o}C). In this study, observed water temperatures are compared to upper incipient lethal temperatures (LTs). For each species, LT10 (10% mortality) and LT50 (50% mortality) exposure curves were interpolated to estimate mortalities on a continuum to 100%. Curves for Coho, Chinook, Sockeye, Chum, and Pink were taken from Brett (1952). Curves for cutthroat were taken from Golden (1978). As an example, **Figure 12** shows the interpolated lethal exposure range for Chum salmon. It should be noted that exposure curves used for risk assessment were developed in laboratory-based studies and do consider local populations behavioural or evolutionary adaptations to warmer temperatures. It has been suggested by the PRSES that local runs have adapted fairly well to warmer stream temperatures since installation of the weir in the 1950s.

The magnitude and duration of all temperature events greater than 20°C were determined using the Automated Risk Assessment script developed by AI Inc. This script recursively calculates the magnitude and duration of every event above a given threshold (20°C in this case) at a resolution of 0.1°C and determines the risk to each species based on the continuum of exposure mortalities above the LTs. The script then returns the highest risk event for every interval. For example, if an event exceeded 24°C for 5 days, causing an estimated 12% mortality, but during that time also exceeded 27°C for 10 hours, causing an estimated 40% mortalities, then the script would return an estimate of 40% mortality for the entire 5 day interval. Several shorter but intense events can also compound to exceed a longer but less intense event.

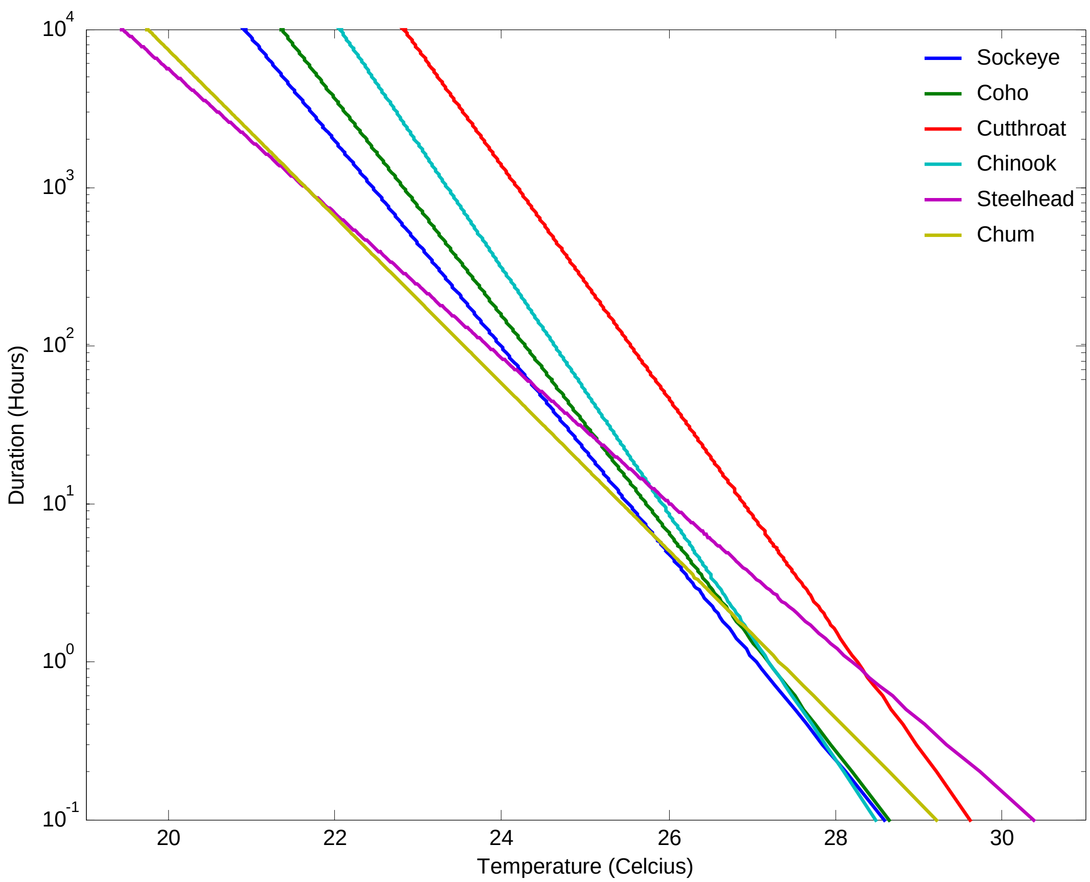
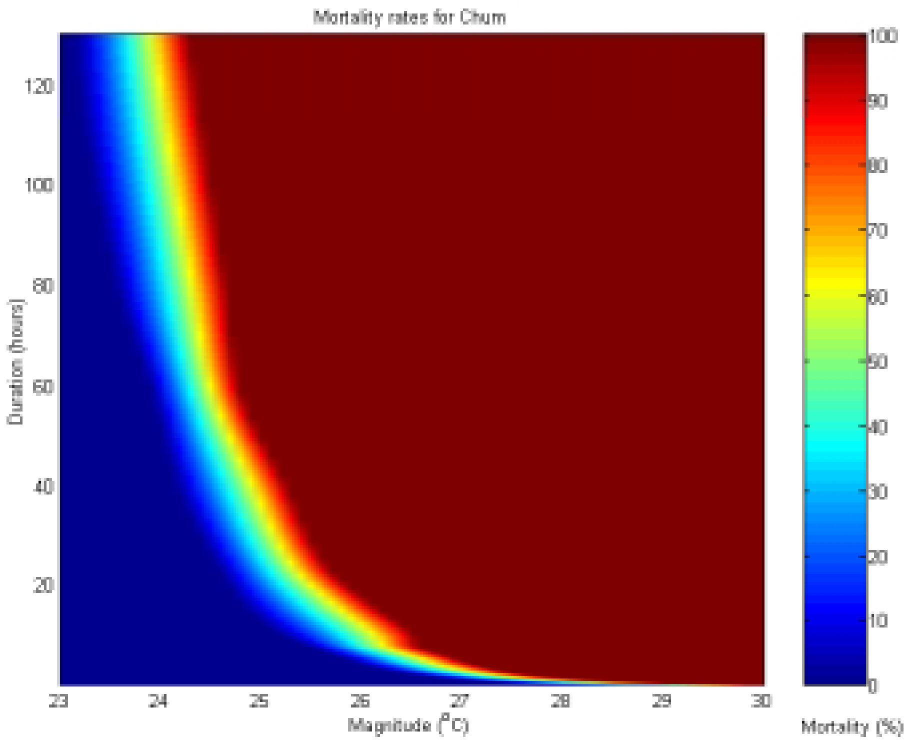


Figure 11. Temperature LT10 exposure curves for salmonids. Mortalities increase exponentially to the top-right of the curves.

a)



b)

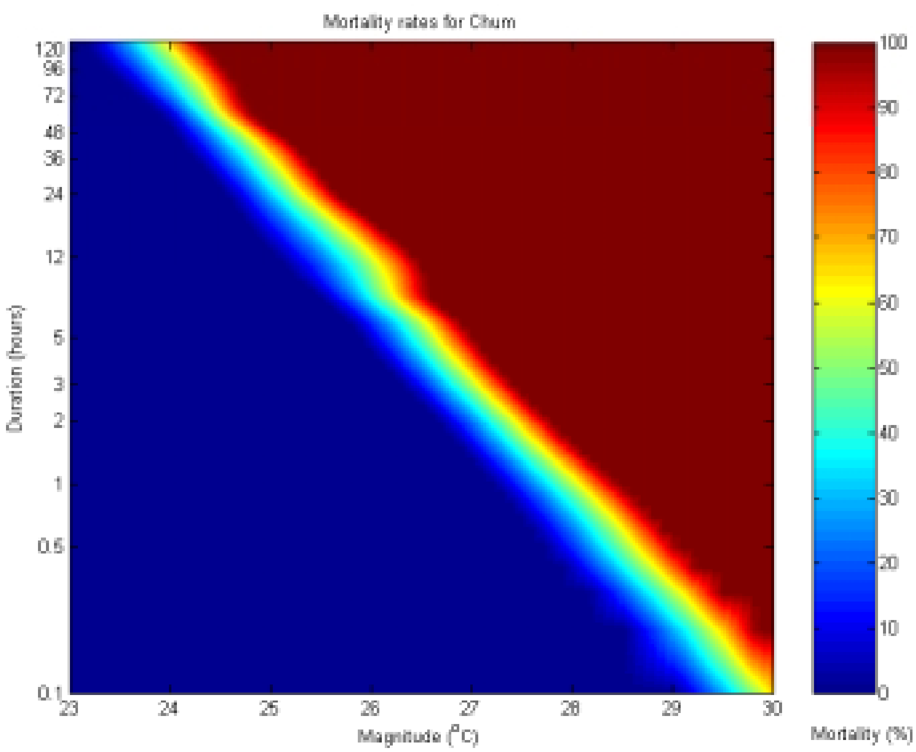


Figure 12. Interpolated lethal exposure times for Chum Salmon, a) linear scale, and b) log scale. Mortality increases at a near exponential rate above the LT10.

Detection of Historical Trends in Powell River Climate

To detect trends in the Powell River daily air temperature and precipitation data, the data was first smoothed using discrete wavelets. As the name suggests wavelet analysis uses small-localized waves to analyze a time series. This method is similar to low pass Fourier filtering (extracting low frequency signal components), but has a distinct advantage over the Fourier Transform because it is able to examine a signal simultaneously in both time and frequency. This feature allows for determination of where in a signal particular events occurred, and is relieved of edge effects. A more complete description of wavelet analysis and its applications can be found in Addison (2002). Once data has been smoothed to an appropriate level using wavelets, trends can be computed using the Mann-Kendall trend slope estimator, and confidence in the trend can be assessed using the Mann-Kendall statistic. The method used in this study expands on the seasonality of the seasonal Mann-Kendall test (4 seasons) to more continuous resolution (compares on daily level across years) to provide higher resolution trend information.

Regional Climate Forecasts

To forecast the climate change impacts on the Powell River area, the Canadian Global Coupled Model 2 (C-GCM2) was statistically downscaled from the computational cell centred at 50.0995N 123.7500W to Powell River regional scale using air temperature data recorded during the baseline period (1961-1990). The method of statistical downscaling follows Wilby and Dawson (2004). Two emission scenarios were analyzed for three future periods – 2020s, 2040s, and 2080s. A middle of the road high (A2) and a middle of the road low (B2) emission scenario were selected for forward modeling air temperatures. These represent high and low predictions for climate change, and are used to estimate range of possible change. Time series results of forecasts from various emissions can be completed through the Canadian Climate Impacts and Scenarios Project (www.cics.uvic.ca).

Forecasting Water Temperature

Although Webb and Nobilis (1997) point out that the relationship between air temperature and water temperature is not one of cause and effect, despite the valid exchange of heat energy between water and air; the strong overall relationship between air temperatures and water temperatures occurs because both systems are responding to similar stimuli where respective differences in heat capacity between the two media influences the nature of the relationship. To predict Lang Creek summer water temperatures in the 2020s, 2040s, and 2080s, local air temperature forecasts were applied to Lang Creek temperatures using the air temperature – water temperature (AT-WT) relationship. Since the relationship between air temperature and water temperature flattens near 0^{o}C and 20^{o}C, temperatures above 15^{o}C were regressed against each other to establish a summer specific AT-WT relationship. Changes to daily average temperatures were then applied to hourly data from the warmest and coolest years in the observed record (1999-2004).

The above forecasts are based on anticipated changes to daily mean values; however, to aquatic life, the daily extremes can be more critical. For example, the daily mean would not be affected by changes to the amplitude of daily oscillations. If a diurnal flux increased by 2^{o}C during the day and decreased by 2^{o}C during the night, then the daily mean would remain nearly unchanged (depending on durations); however, extremes would have increased significantly. Indeed high frequency measurements are key to assessing risks to aquatic life based on an exposure or magnitude and duration approach. Relative increase in the magnitude of diurnal air temperature oscillation is one of the output parameters of the C-GCM2. This relative increase in diurnal temperature oscillation was applied to water temperature records by means of a band pass Fourier filter.

Results

Risk Assessment of Upper Lang Creek Water Temperature Data (1999-2004)

Hourly temperature data from upper Lang Creek (at Hatchery) was assessed for risk to Sockeye, Coho, Chinook, Steelhead, Chum, and Cutthroat. 1999 had the warmest summer during the six years of monitoring, and 2004 had the coolest. **Figure 13** shows results from the risk assessment of hourly stream temperatures observed at the Lang Creek Hatchery station during 1999. There were 2 events that exceeded the threshold for Chum, the most sensitive species in the 22 - 26^{o}C temperature range, resulting in potentially 97% mortality. The signal is shown in **Figure 14**, with exceedances highlighted red. These warm temperatures resulted in potentially high mortalities for all species except cutthroat (**Table 2**), which were within 1^{o}C of predicted mortalities. It should be repeated (from methods section) that these mortalities do not consider adaptive behaviour, such as moving to cooler tributaries or groundwater upwellings, or to evolutionary adaptations thought to have occurred in the Lang Creek runs. Plots for 2000, 2001, 2002, 2003 and 2004 are provided in **Figure 15, Figure 16, Figure 17, Figure 18,** and **Figure 19,** and mortality estimates for all years are summarized in **Table 2**. From 2000–2004, temperatures only exceeded lethal thresholds once, during 2003 for chum and sockeye; however, temperatures were routinely within 1^{o}C of thresholds.

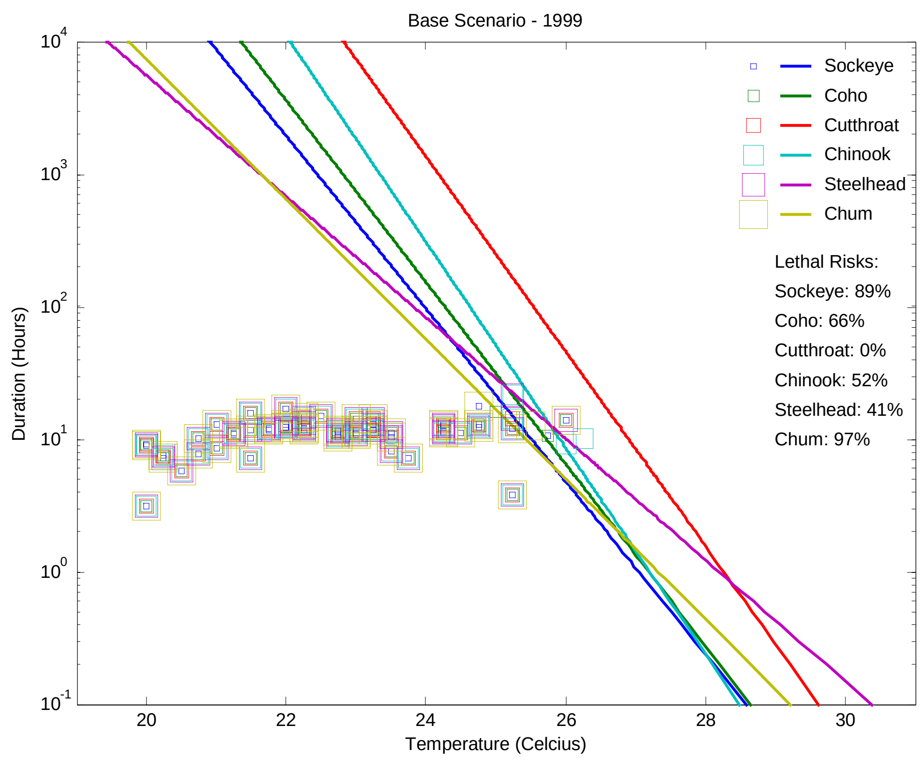


Figure 13. Risk assessment of stream temperatures in upper Lang Creek, 1999.

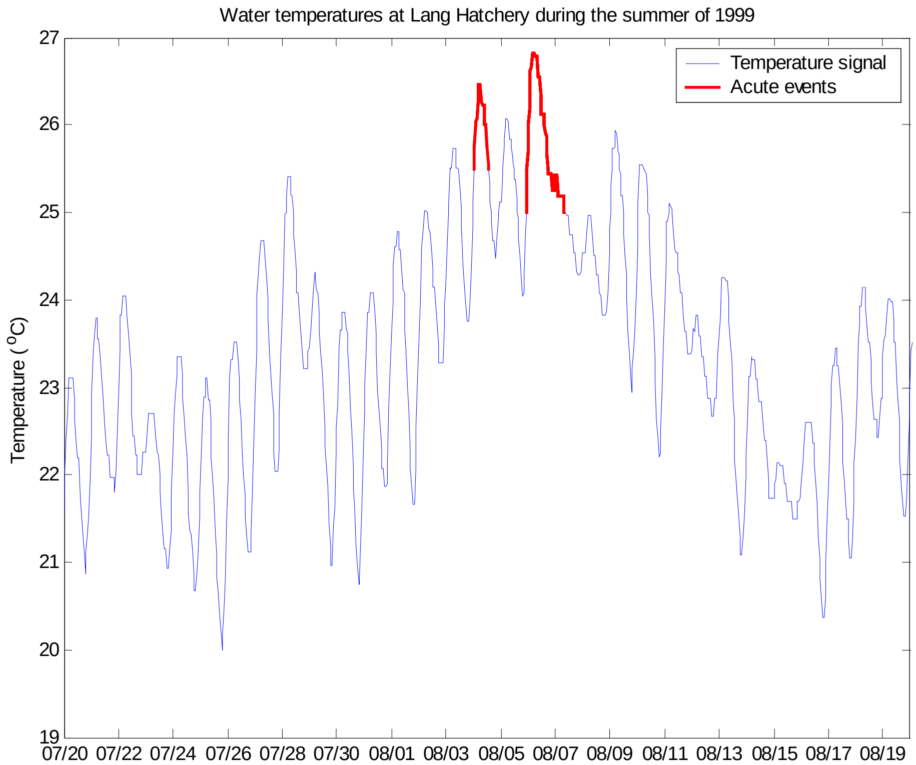


Figure 14. 1999 water temperature events considered lethal for Chum salmon.

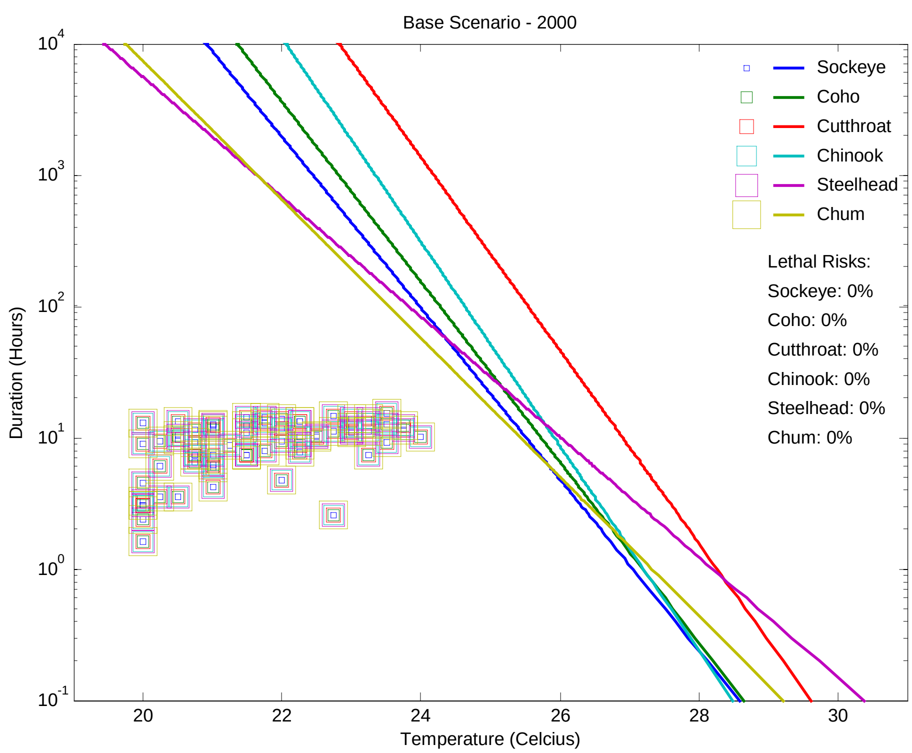


Figure 15. Risk assessment of water temperatures in upper Lang Creek, 2000.

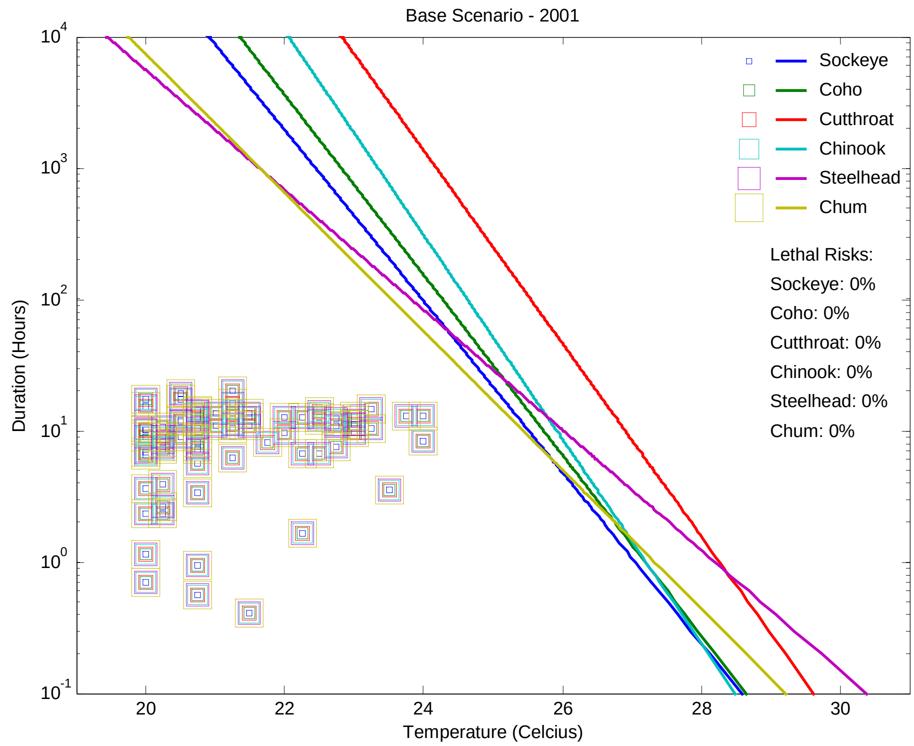


Figure 16. Risk assessment of water temperatures in upper Lang Creek, 2001.

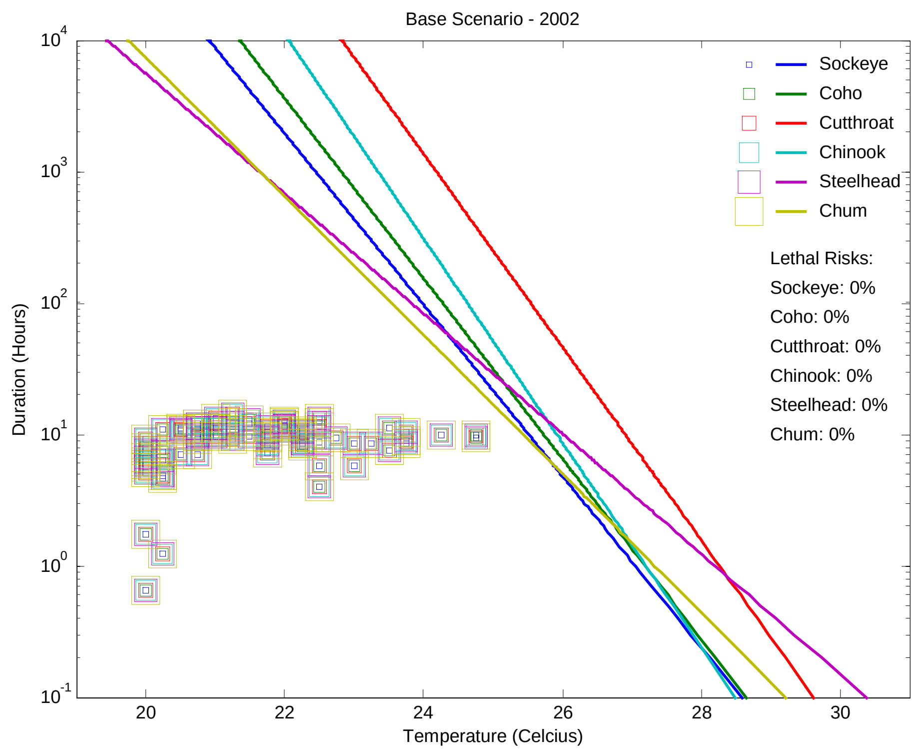


Figure 17. Risk assessment of water temperatures in upper Lang Creek, 2002.

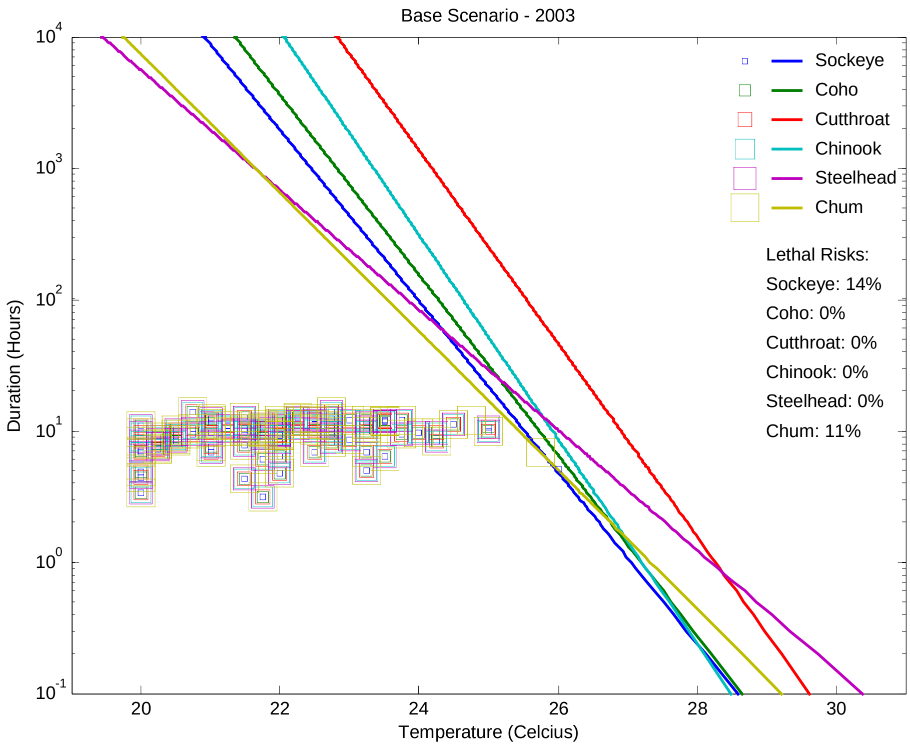


Figure 18. Risk assessment of water temperatures in upper Lang Creek, 2003.

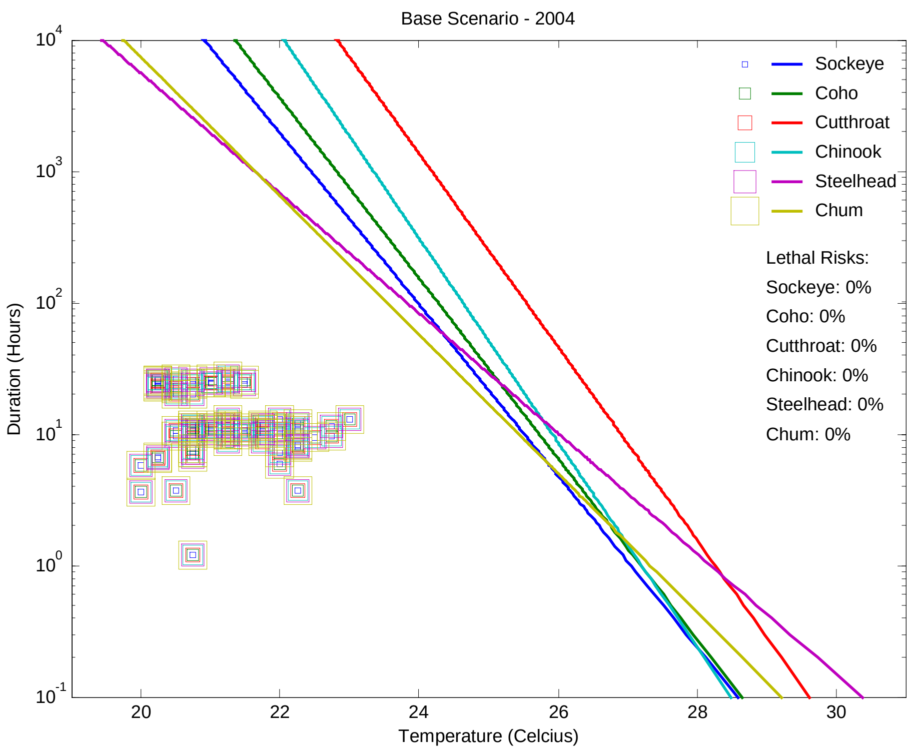


Figure 19. Risk assessment of water temperatures in upper Lang Creek, 2004.

Table 2. Potential mortalities to salmonids in upper Lang Creek, 1999-2004.

	1999	2000	2001	2002	2003	2004
Coho	**66%**	0%	0%	0%	0%	0%
Cutthroat	0%	0%	0%	0%	0%	0%
Chinook	**52%**	0%	0%	0%	0%	0%
Sockeye	**89%**	0%	0%	0%	**14%**	0%
Chum	**97%**	0%	0%	0%	**11%**	0%
Steelhead	**41%**	0%	0%	0%	0%	0%

Risk Assessment of Mid Lang Creek Water Temperature Data (1999-2004)

Modeled hourly temperature data from Mid Lang Creek was assessed for risk to salmonids. **Figure 20** and **Figure 21** show risk assessments for 1999 and 2004 respectively, the warmest and coolest years in the observed record. No lethal events were predicted (**Table 4**), as the warmest temperatures were approximately 2^{o}C below thresholds even during the warmest year.

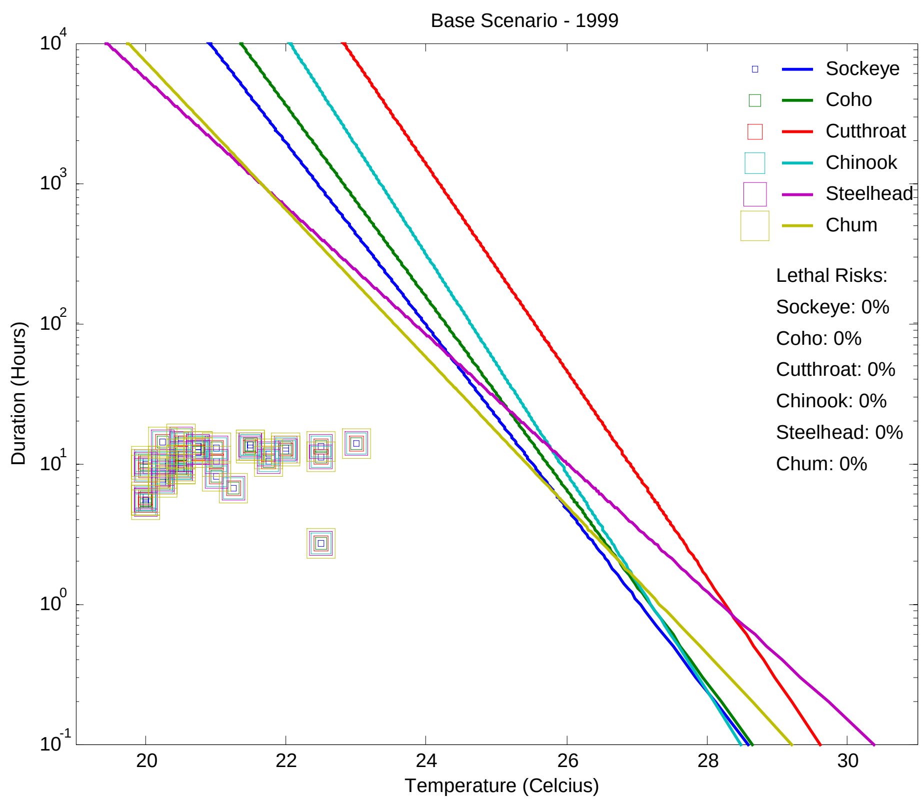


Figure 20. Risk assessment of water temperatures in mid Lang Creek, 1999.

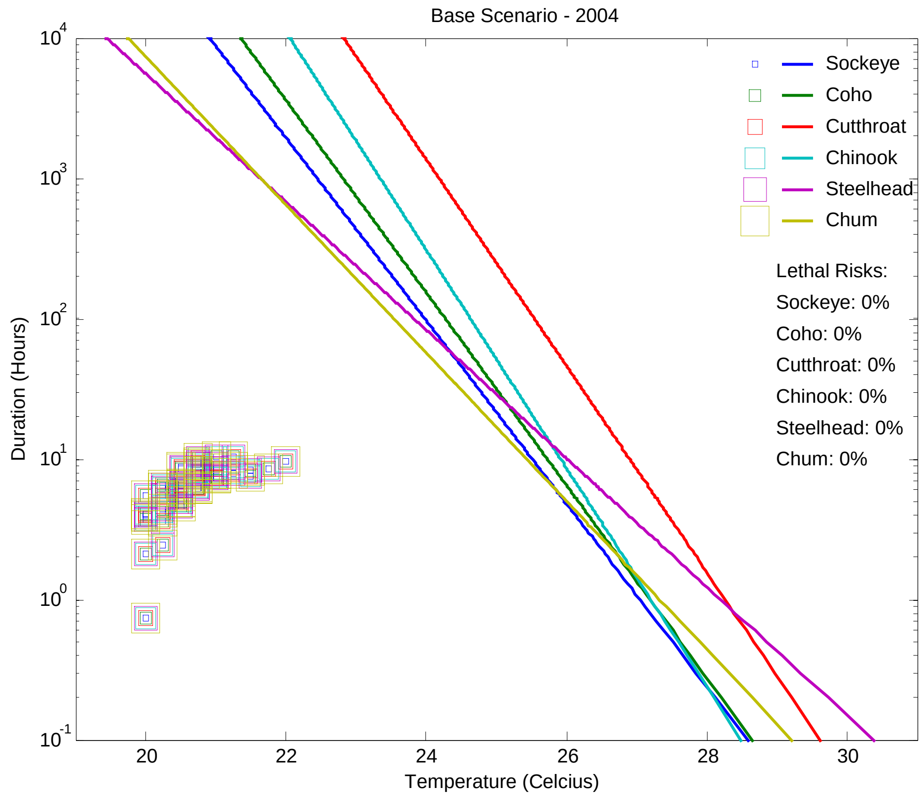


Figure 21. Risk assessment of water temperature in mid Lang Creek, 2004.

Table 3. Potential mortalities to salmonids in mid Lang Creek during recent summers.

	1999	2000	2001	2002	2003	2004
Coho	0%	0%	0%	0%	0%	0%
Cutthroat	0%	0%	0%	0%	0%	0%
Chinook	0%	0%	0%	0%	0%	0%
Sockeye	0%	0%	0%	0%	0%	0%
Chum	0%	0%	0%	0%	0%	0%
Steelhead	0%	0%	0%	0%	0%	0%

Risk Assessment of Lower Lang Creek Water Temperature Data (1999-2004)

Modeled hourly temperature data from Lower Lang Creek (channel) was assessed for risk to salmonids. **Figure 22** and **Figure 23** shows risk assessment for 1999 and 2004, the warmest and coolest years respectively. No lethal events were predicted (**Table 4**) since the warmest temperatures were approximately 4^{o}C below thresholds even during the warmest year.

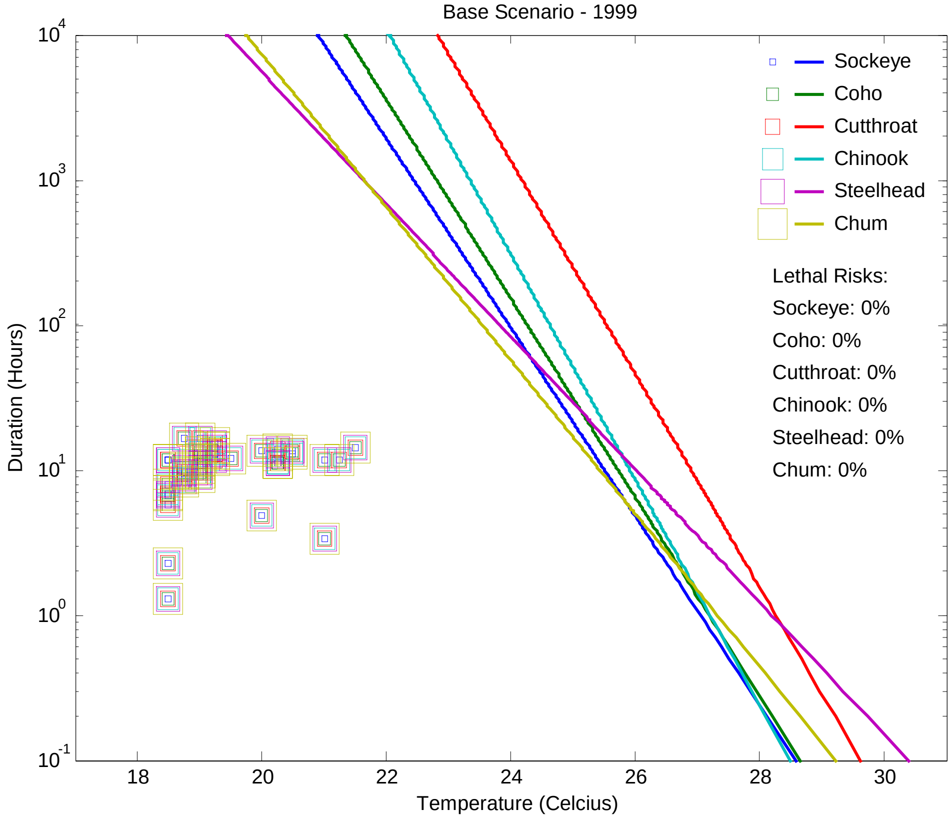


Figure 22. Risk assessment of water temperature in lower Lang Creek, 1999.

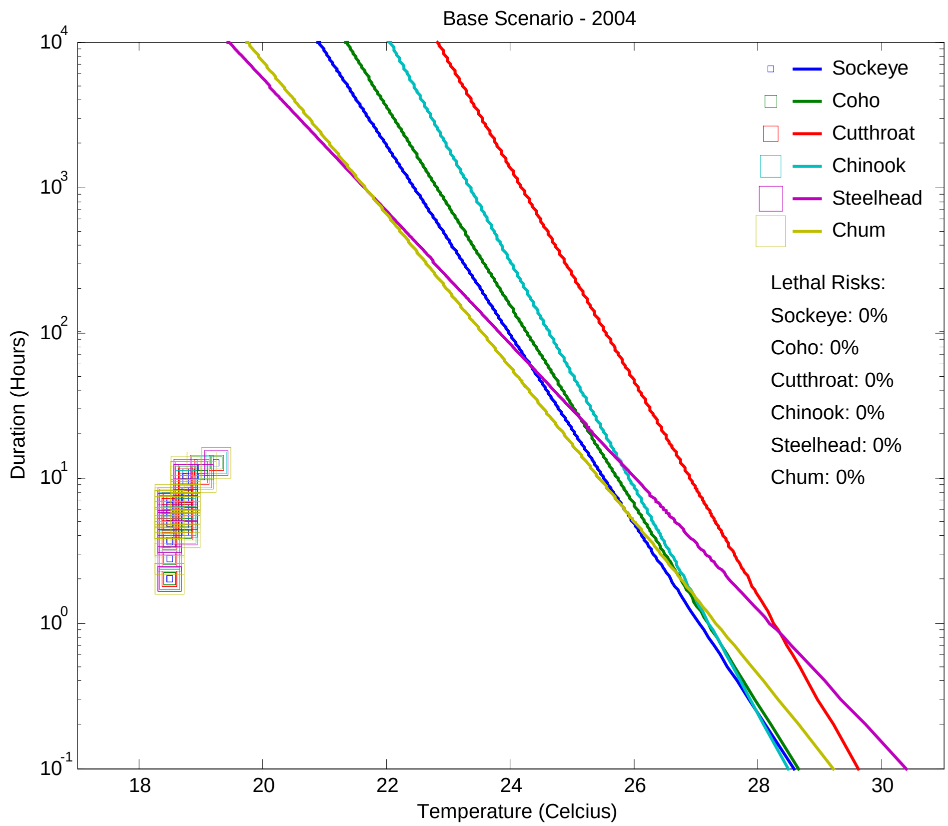


Figure 23. Risk assessment of water temperature in lower Lang Creek, 2004.

Table 4. Potential mortalities to salmonids in Lower Lang Creek during recent summers.

	1999	2000	2001	2002	2003	2004
Coho	0%	0%	0%	0%	0%	0%
Cutthroat	0%	0%	0%	0%	0%	0%
Chinook	0%	0%	0%	0%	0%	0%
Sockeye	0%	0%	0%	0%	0%	0%
Chum	0%	0%	0%	0%	0%	0%
Steelhead	0%	0%	0%	0%	0%	0%

Observed Effects of Global Warming on Powell River AT (1924-2000)

Daily average air temperatures from Powell River were smoothed at various levels to observe cycles and estimate trends. **Figure 24** shows the results of using wavelet decomposition to the 4^{th} level – this can be interpreted as removing oscillations up to and including 16 (or 2^4) days. Smoothing at this level removes high frequency noise, such as daily oscillations, and highlights annual variance in air temperature. Years with strong El Niño's are apparent and tend to be warmer (1972/73, 1982/83, 1991/92, 1997/98).

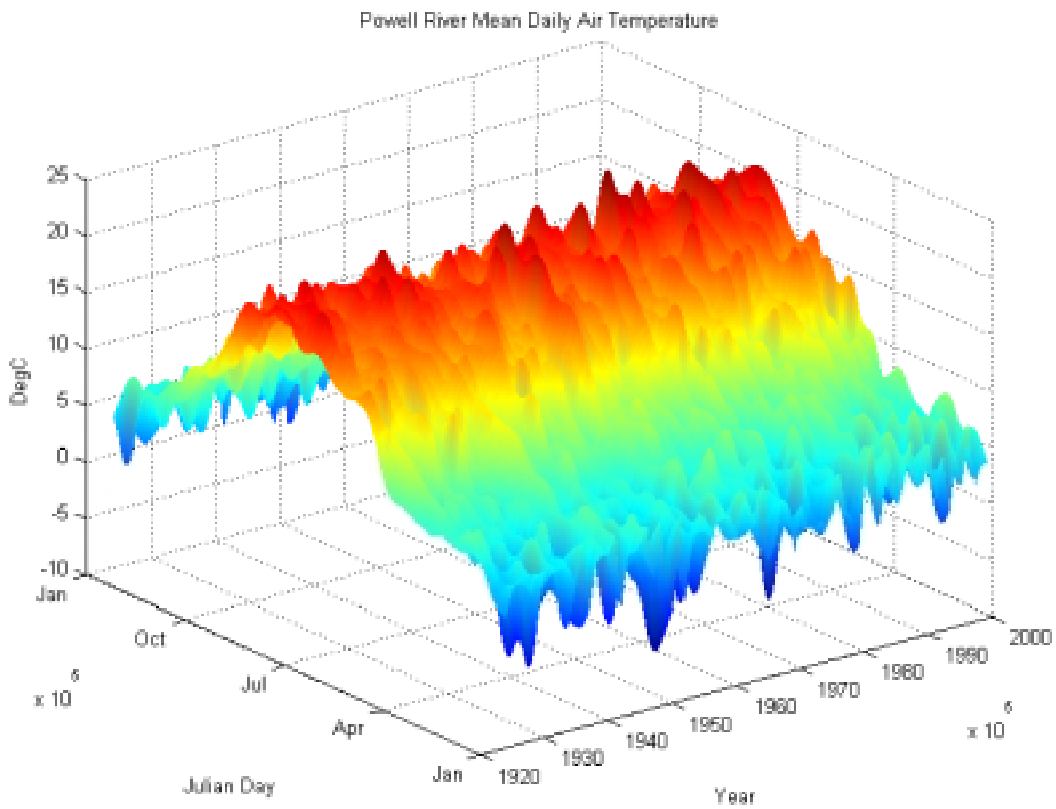


Figure 24. Powell River mean daily air temperature smoothed at 16-day level.

When smoothed over a longer interval, such as 16 years**,** trends such as the Pacific Decadal Oscillation (PDO) are observed (**Figure 25**). A regime shift from a "cool phase" PDO to a "warm phase" PDO is observed in 1977.

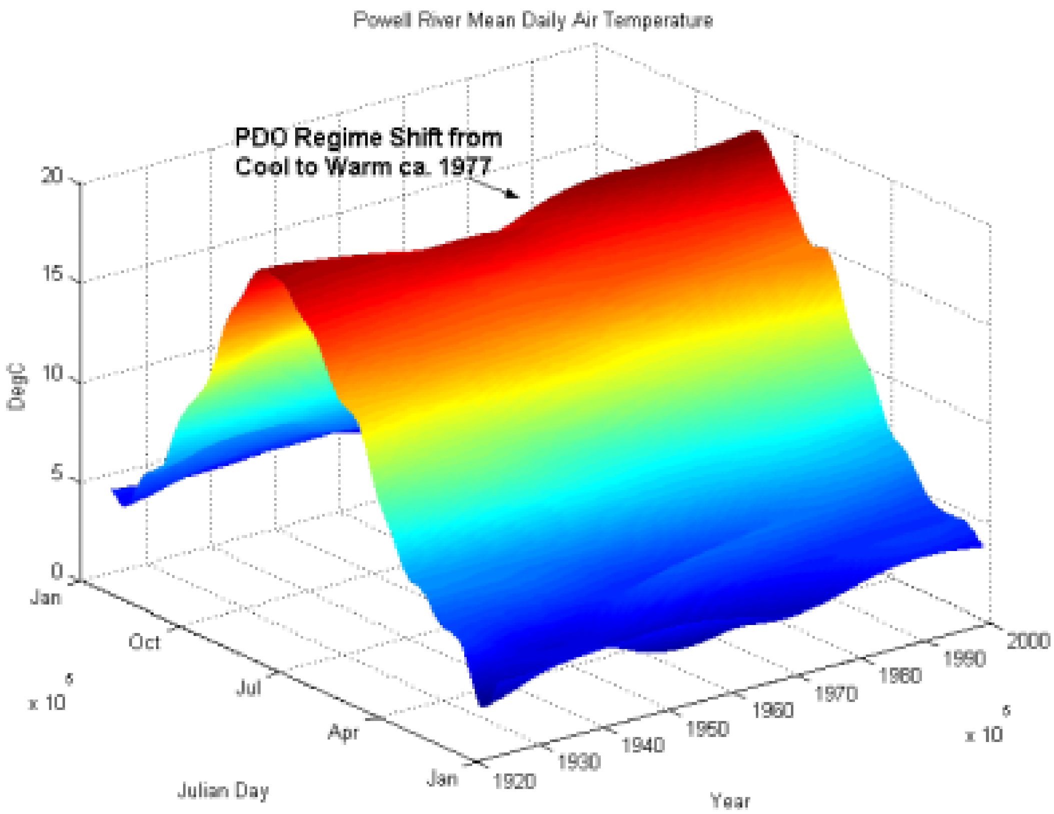


Figure 25. Powell River mean daily air temperature smoothed to highlight oscillations longer than 16 years. The Pacific Decadal Oscillation regime shift in 1977 is apparent.

Increasing the level of wavelet smoothing further allows for observation of apparent longer periodic and monotonic trends (**Figure 26**). Using the seasonal Mann-Kendall test for trend and trend slope estimator, long-term monotonic trends for the period 1924 to 2000 were estimated. Warming of approximately 0.8^{o}C has occurred during the winter months (Dec Jan Feb), and slight warming (~0.3^{o}C) has occurred in spring (Apr May Jun). Midsummer temperatures appear to not have changed since 1924. This result is consistent with regional scale results for the Coast Mountains and the Georgia Depression (MWLAP 2001). On a larger scale this result is congruent with a decrease in the winter snow albedo effect. Weaver (2003) notes that "global warming is amplified in the winter and to a lesser extent the spring…"

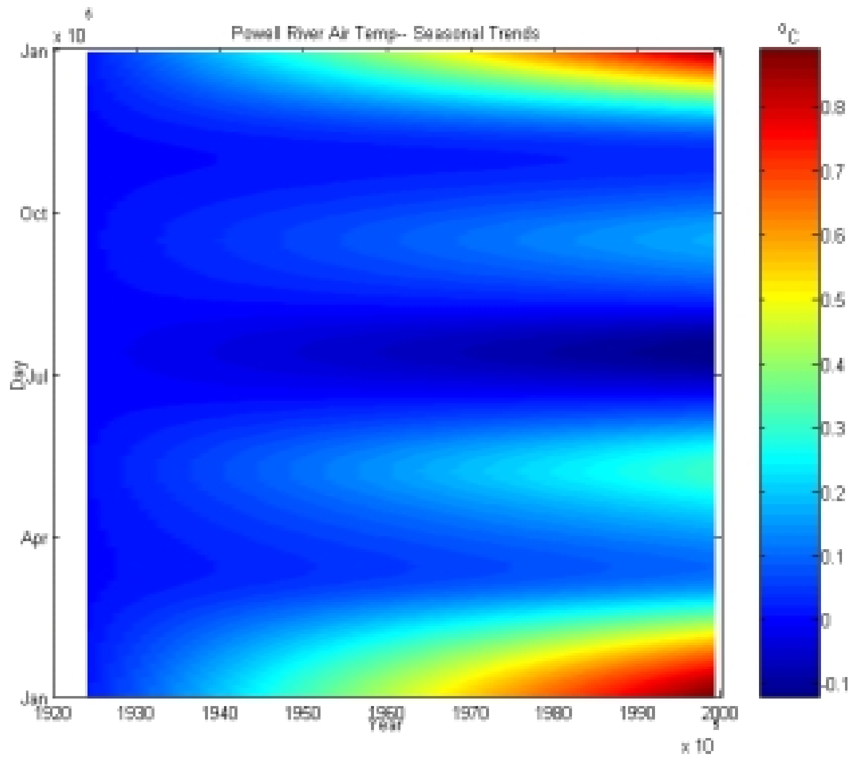
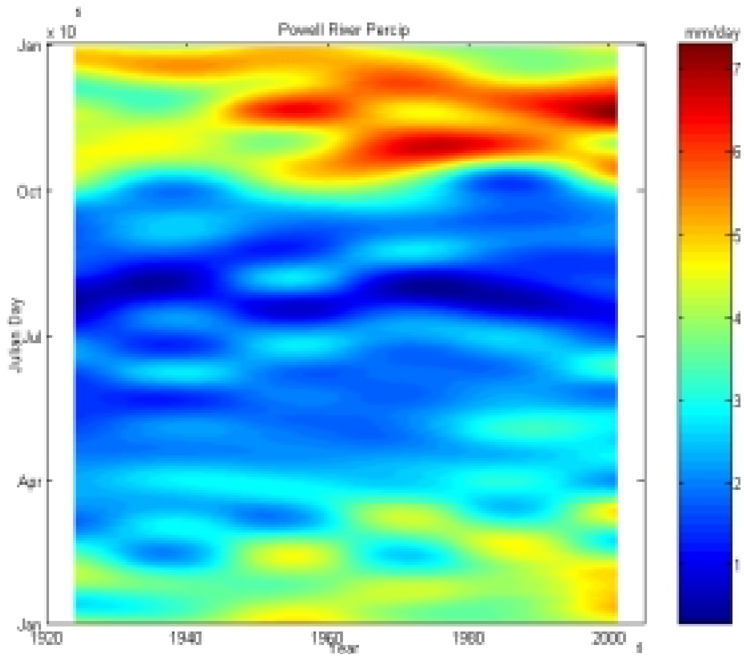


Figure 26. Powell River Air Temperature Trends From 1924 to 2000. Winter (DJF) and spring (AMJ) mean daily air temperatures appear to have increased by approximately 0.8°C and 0.3 °C respectively, whereas summer (JJA) daily mean temperatures have not changed (or cooled slightly).

Observed Effects of Global Warming on Powell River Precipitation (1924-2000) and Lang Creek Flows (1960-1994).

Daily total precipitation from Powell River and daily average flows from Lang Creek were smoothed at the 4th level (~16 years) to observe cycles and estimate trends. **Figure 27a** shows the results for precipitation and **Figure 27b** shows the results for discharge. Smoothing at this level shows distinct trends observed in both datasets, and a high degree of correlation between the datasets. This suggests that the timing and magnitude of Lang Creek flow is closely related to precipitation events, despite the buffering effects of Haslam Lake. This is likely the result of high contributions of flow from the tributaries below the lake during storm events. Longer-term trends in precipitation were detected using 6th level (~64 years) smoothing (**Figure 28**). From 1924-2000, precipitation was observed to increase year round in Powell River, with marginal increases during summers (average ~0.5 mm/day), and highest increases in winters (~1.2 mm/day) and springs (~0.8 mm/day). Given the strong correlation between precipitation and Lang Creek flows, flows are likely to have increased during fall and winter in Lang Creek from climate change. Furthermore, summer flows are known to have increased since installation of the weir at Haslam Lake during the 1950s.

a)



b)

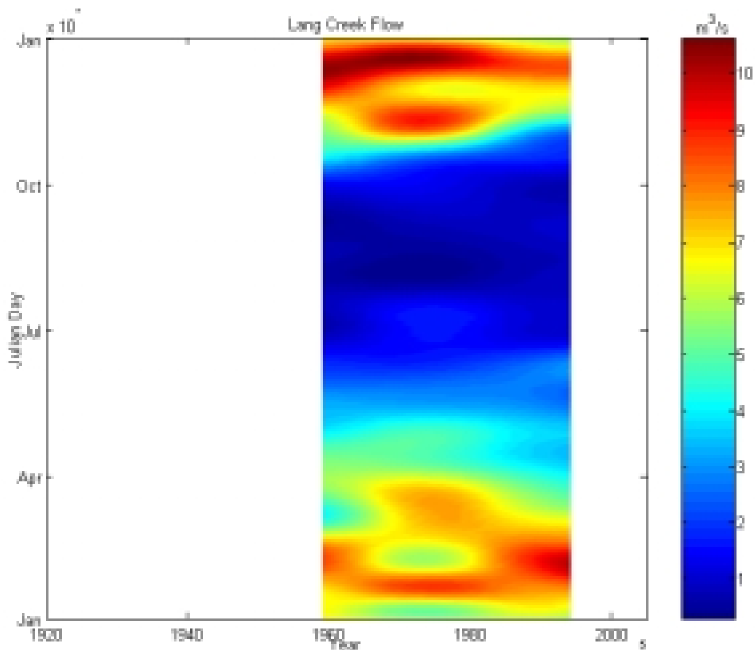


Figure 27. Smoothed a) Powell River daily precipitation and b) Lang Creek mean daily flows. Patterns in the data are highly correlated with each other.

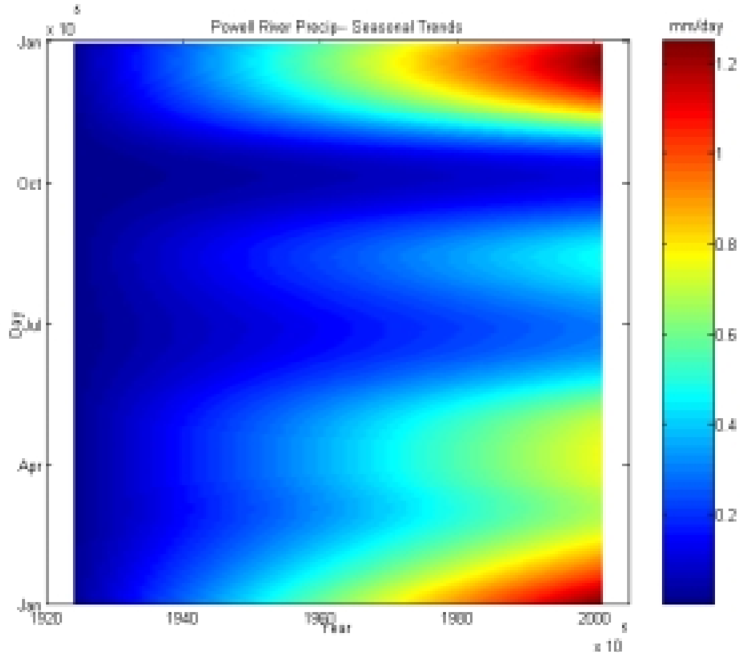


Figure 28. Long term trends in Powell River daily precipitation. Largest increases in precipitation are have occurred during winter and spring.

Forecasted Effects of Global Warming on Powell River Air Temperature

The C-GCM2 model was used to predict changes to mean summer temperature in coastal B.C. by the 2020s, 2040s, and 2080s. **Figure 29** shows the forecasted change by 2020 for Canada under the A2 SRES emission scenario. The south coast of B.C. is expected to warm by approximately 1^{o}C during summers by 2020s under both the A2 and B2 scenarios. By the 2040s, summer temperatures are expected to have warmed by 1.6 - 1.9^{o}C (B2 – A2 scenarios), and by 2.2 - 3.2^{o}C by the 2080s (**Table 5**).

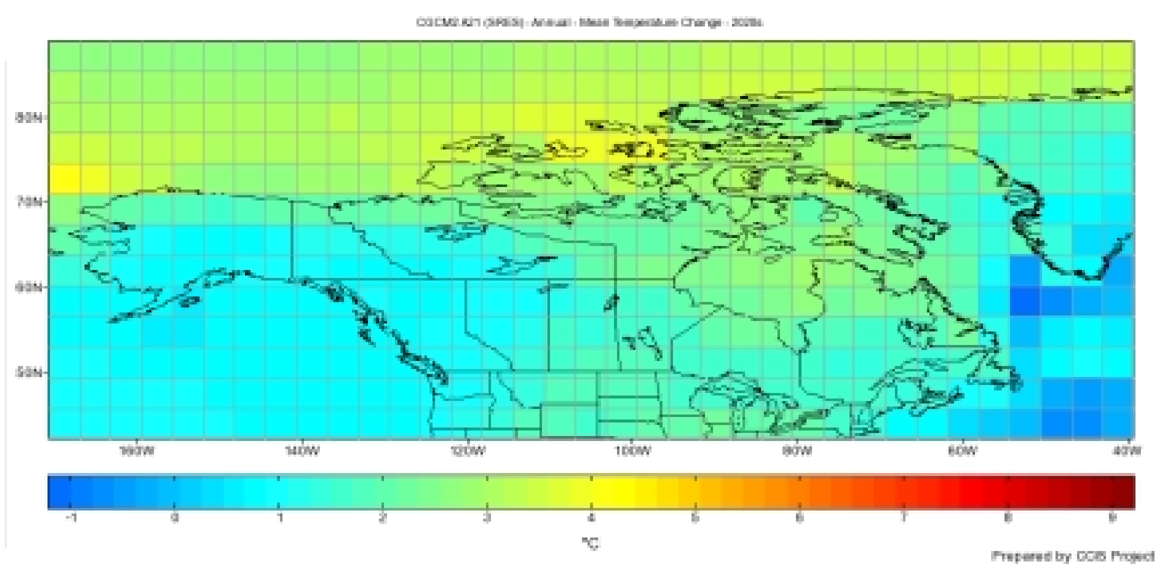


Figure 29. C-GCM2 A2 forecasts for changes in mean summer air temperature by 2020.

The resolution of the above C-GCM model is quite coarse and therefore statistical downscaling was conducted. Baseline (1961-1990) monthly mean air temperatures at Powell River were regressed against CGCM2 monthly mean temperatures from the regional cell (**Figure 30**). The flattening at low temperature is likely due to maritime stabilization since Powell River is situated close to the Georgia Straight, while the cell contains the Coastal Mountains. Variation in baseline cell temperature for the period accounts for 88% of the variability in Powell River air temperature. The relation tightens at higher temperatures (summer). Coefficients of regression indicate that a 1°C increase in cell temperature produces a 1.1°C increase in Powell River air temperature, or a 10% increase in warming predictions. This relation was then used to forecast air temperatures specific for the Powell River area (**Table 5**). According to this downscaled model, the Powell River area is expected to warm by approximately 1.1°C by the 2020s under both the A2 and B2 scenarios. By the 2040s, temperatures are expected to have warmed by 1.8 - 2.1°C, and by 2.4 - 3.5°C by the 2080s (**Table 5**).

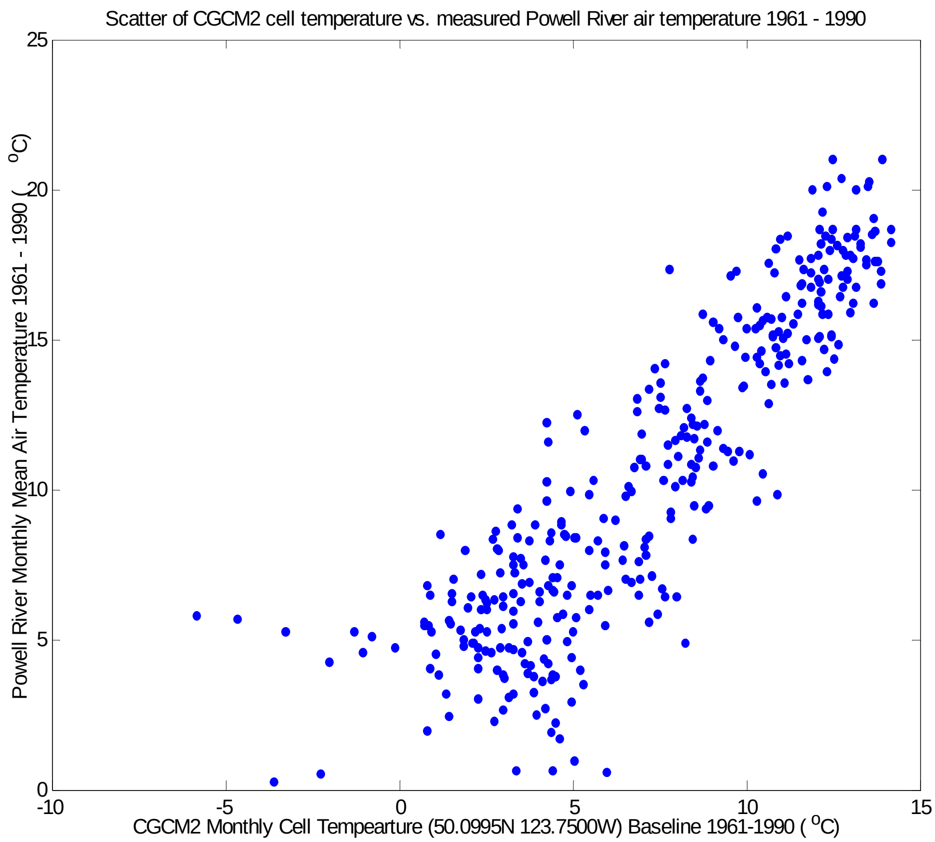


Figure 30. Scatter plot between monthly mean air temperature at Powell River and monthly mean air temperature in the C-GCM regional cell, 1961-1990.

Table 5. Forecasted changes in mean annual air temperature for Coastal B.C. under high and low emission scenarios.

Area	Scenario	2020	2040	2080
Pacific Coast	A2 SRES (high)	1.0 °C	1.9 °C	3.2 °C
	B2 SRES (low)	1.0 °C	1.6 °C	2.2 °C
Powell River (downscaling)	A2 SRES (high)	1.1 °C	2.1 °C	3.5 °C
	B2 SRES (low)	1.1 °C	1.8 °C	2.4 °C

Forecasted Effects of Global Warming on Powell River Precip. and Lang Cr. Flow

The ECHAM4 global circulation model was used to predict changes to mean monthly precipitation in coastal B.C. by the 2020s, 2040s, and 2080s. **Figure 31** shows the baseline precipitation patterns for Canada for the period 1961 – 1990. The south coast of B.C. is expected to receive an annual increase of 5% in precipitation by 2020 under both the A2 and B2 scenarios (**Figure 32**). By 2040, precipitation is expected to have increased by 7% under the A2 scenario and 6% under the B2, and by 12% under A2 and 8% under B2 by 2080. These increases are expected to increase Lang Creek flows.

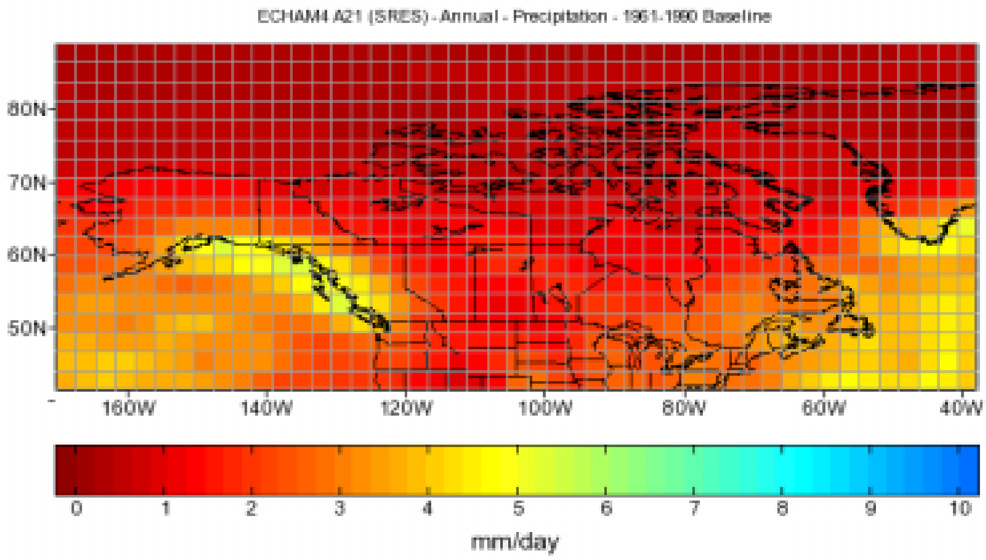


Figure 31. Annual precipitation averages for Canada, 1961-1990.

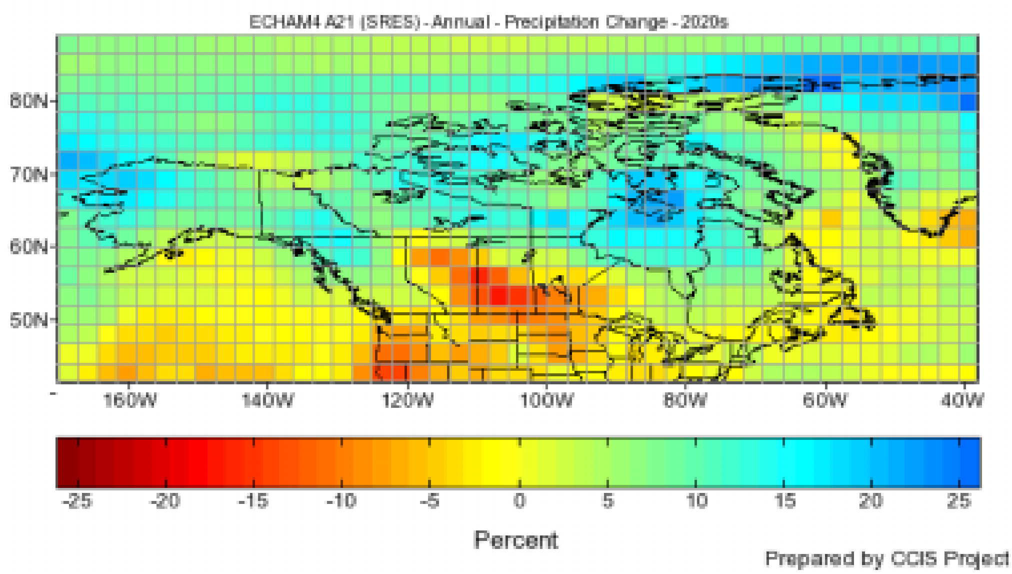


Figure 32. ECHAM4 forecasts for precipitation changes by the 2020s.

Modeling Water Temperature

Lang Creek daily mean water temperature and Powell River daily mean air temperature show a high degree of correlation (R^2 = 0.94, **Figure 33**). The fit is highly linear in the 3 – 20°C range and flattens off outside this range. This high correlation allows for modeling water temperature from air temperature, which has a much longer record and for which change can be forecasted under various climate change scenarios. The regression slope for high temperature (>15°C) is approximately 0.9, meaning that for every 1.0°C change in air temperature, Lang Creek water temperatures are predicted to change by 0.9°C.

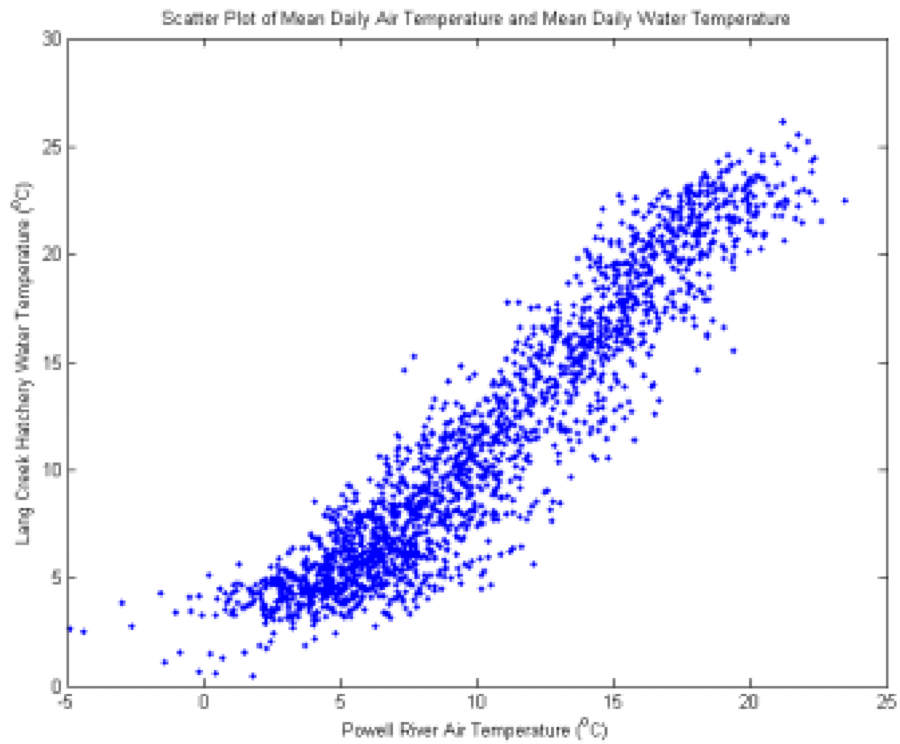


Figure 33. Scatter Plot of mean daily air temperature at Powell River with mean daily water temperature from the Lang Creek.

Forecasts of Changes to Water Temperature

In this study, forecasted changes to Lang Creek water temperatures include changes to mean summer temperatures (estimated above) and to diurnal oscillations. **Figure 34a** shows summer diurnal air temperature oscillation for the period 1969-1990. For South Coast B.C., oscillations averaged about 8°C. The derived change in diurnal air temperature oscillation during summer by the 2020s is shown in **Figure 34b.** The diurnal flux is predicted to increase by 4% by the 2020s, by 8% by 2040s, and by 10% by the 2080s. The effect of this relative increase in air temperature oscillation was then modeled for water temperature by applying a band pass amplifier to Lang Creek water temperature data (**Figure 35**). The magnitude of diurnal amplification was based on the relative change in diurnal air temperature oscillation. Band pass amplification was also performed on the echo diurnal signals to ensure clean amplification of all the characteristics of the diurnal temperature signal.

a)

b)

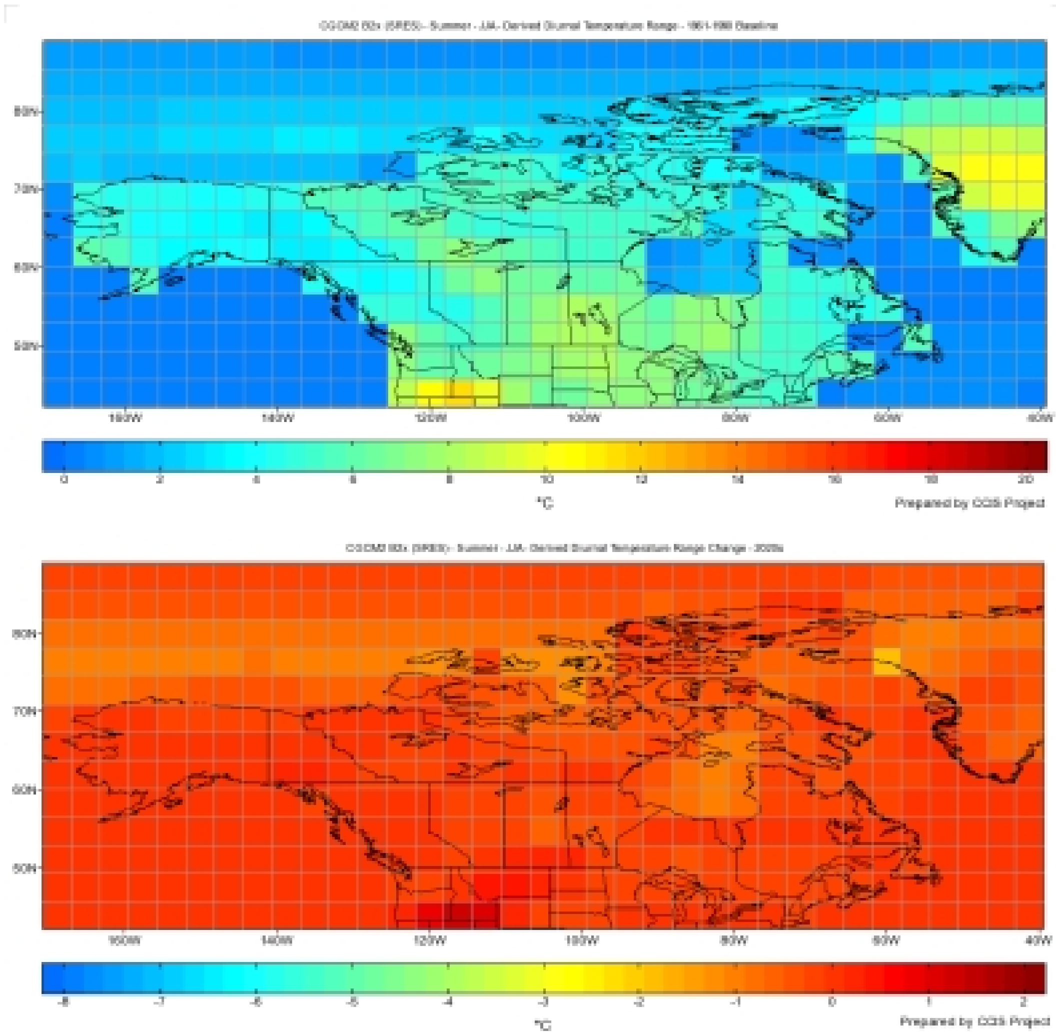


Figure 34. a) Summer (JJA) diurnal air temperature oscillation for the period 1969-1990; and b) Derived change in summer (JJA) diurnal air temperature oscillation under the Canadian Global Climate Model 2 (CGCM2)

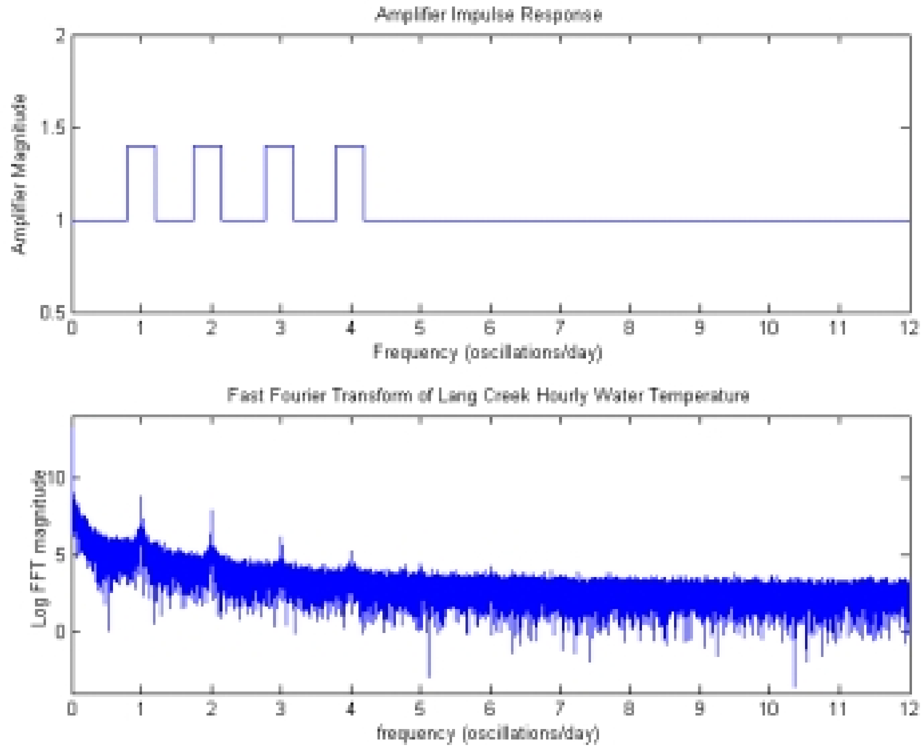


Figure 35. a) the amplifier used to increase the diurnal water temperature signal, and b) the effect on the Lang Creek temperature in the frequency domain.

Combining the effects of forecasted increases to mean water temperature and to diurnal oscillations results in projections of substantial increases to Lang Creek summer water temperatures. By the 2020s, Lang Creek mean water temperatures are forecasted to increase by 1.0°C on average, plus have a small increase (4%) in diurnal oscillations (**Table 6**). By the 2040s, mean water temperature is projected to increase by 1.6 - 1.9°C, plus an 8% increase to diurnal oscillations. By the 2080s, temperatures are projected to increase by 2.2 - 3.2°C plus a 10% increase to diurnal oscillations.

Table 6. Forecasted changes to summer water temperature under the A2 & B2 scenarios.

Decade	Emission Scenario	Mean Air Temperature Increase in Powell River	Mean Water Temperature Increase in Lang Creek	Diurnal Water Temperature Amplification	Total
2020s	A2 / B2 / IS92a	1.1°C	1.0°C	4%	1.0°C
2040s	B2	1.8°C	1.6°C	8%	1.8°C
2040s	A2	2.1°C	1.9°C	8%	2.1°C
2080s	B2	2.4°C	2.2°C	10%	2.4°C
2080s	A2	3.5°C	3.2°C	10%	3.4°C

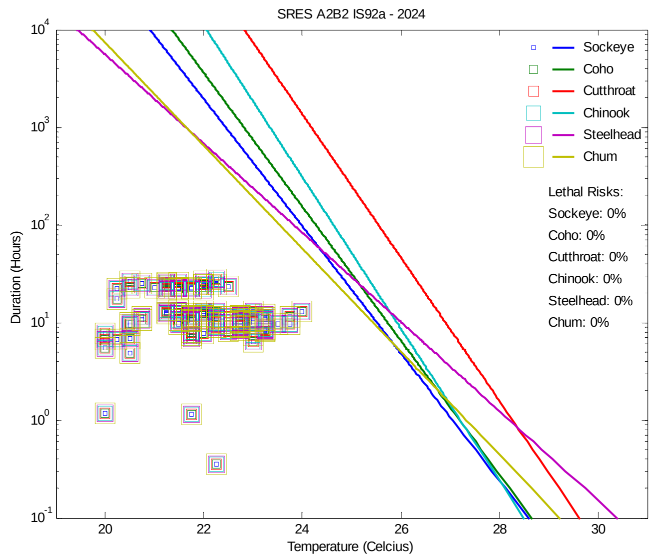
Risk Assessment in Upper Lang Creek Under Climate Change Scenarios

Forecasted increases in water temperature were applied to the warmest and coolest years in the Upper Lang Creek observation record, 1999 and 2004 respectively. This approach partially accounts for natural variability caused by phenomenon such as El Niño and La Nina, and influences of variable contributions from Haslam Lake over the weir.

2020s

For the 2020s, there was no difference in results from the emission scenarios A2 and B2, and therefore only one set of forward modeling results is presented (**Figure 36**). Predicted mortalities are presented in **Table 6**. During a cool year, the model predicts no mortalities, though temperatures will approach lethal thresholds. During a warm year, temperatures are forecasted to reach nearly 28°C and mortalities are predicted to be 55% for cutthroat and 100% for all other species.

a.



b.

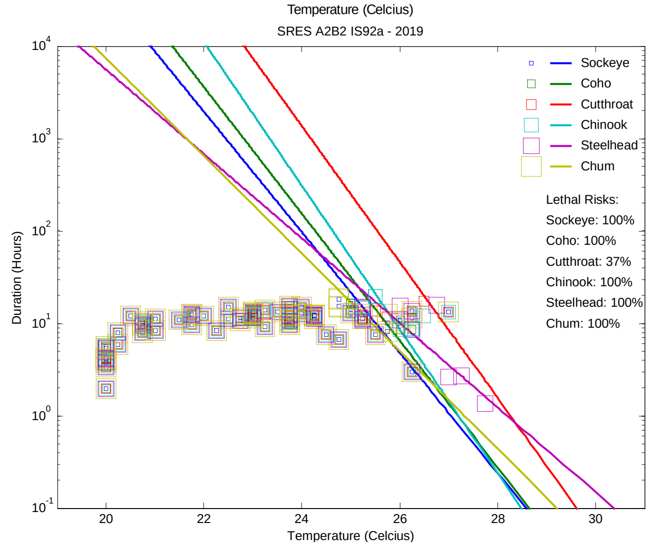
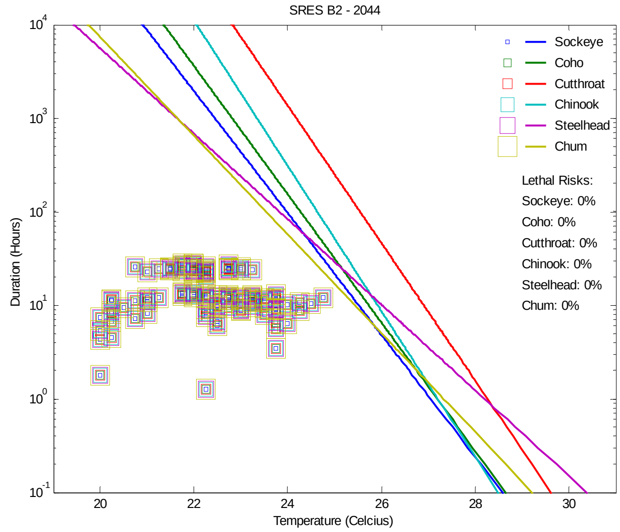


Figure 36. Forecasted salmonid mortalities in upper Lang Creek by the 2020s during a) a cool year and b) a warm year.

2040s

Forecasts for the 2040s are presented for the coolest (B2 cool) and warmest (A2 warm) scenarios (**Figure 37a** and **Figure 37b**). Predicted mortalities are presented in **Table 6**. During a cool year, temperatures may reach 25 – 27^{o}C and the model predicts 0 to 96% mortalities, depending on species and on the emissions scenario. Cutthroat are predicted to have no mortalities during a cool year, while Chum are predicted to have large mortalities. During a warm year, temperatures may approach 28^{o}C; mortalities are predicted to be near 100% for all species including cutthroat.

a.



b.

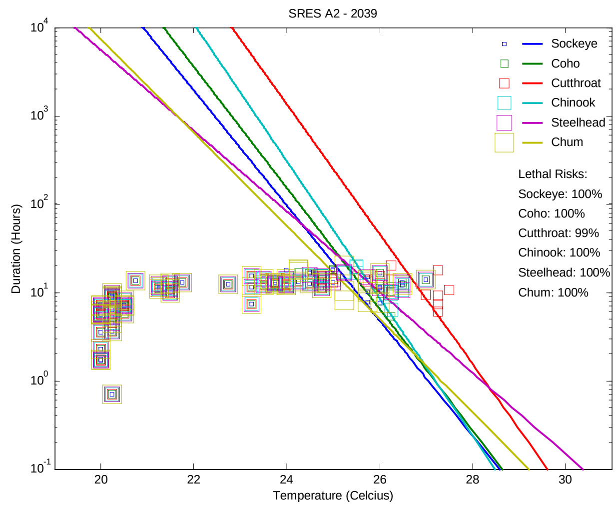
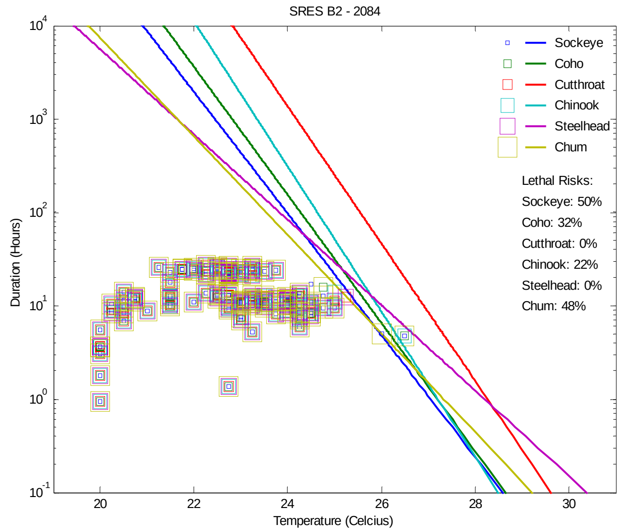


Figure 37. Forecasted salmonid mortalities in upper Lang Creek during the 2040s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

2080s

Forecasts for the 2080s are presented for the coolest and warmest scenarios (**Figure 38a** and **Figure 38b**). Predicted mortalities are presented in **Table 7**. During a cool year, the model predicts temperatures to exceed 28^{o}C and mortalities to range from 0 to 100%, depending on species and on the emissions scenario. Cutthroat are the only species predicted to not have large mortalities. During a warm year, temperatures may approach 30°C and mortalities are predicted be 100% for all species.

a.



b.

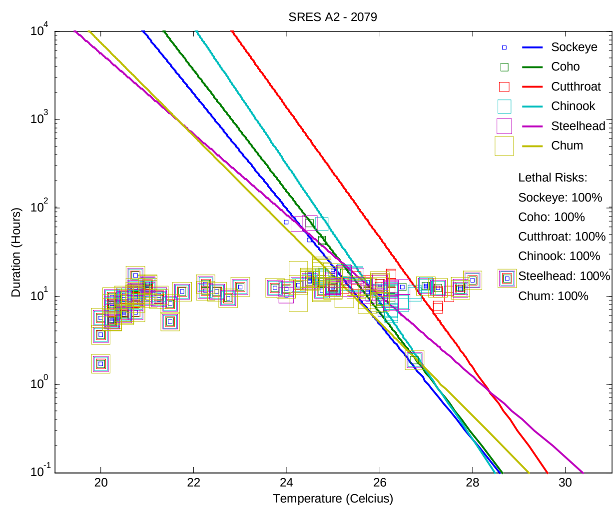


Figure 38. Forecasted salmonid mortalities in Upper Lang Creek during the 2080s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

Table 7. Forecasted potential mortalities to salmonids in Upper Lang Creek to 2080s.

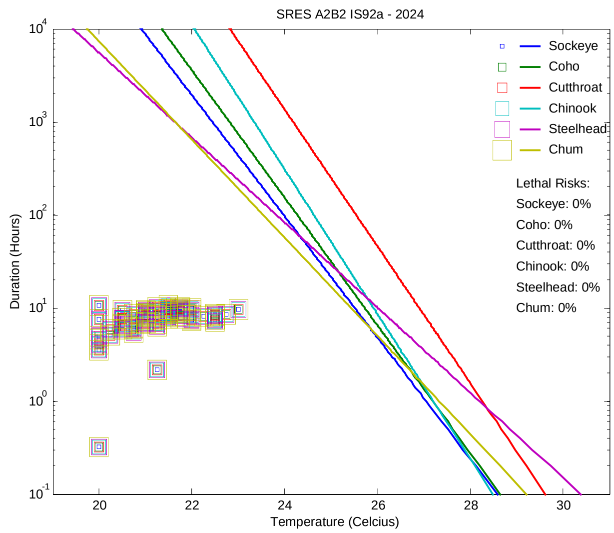
	2000 cool	2000 warm	2020 cool	2020 warm	2040 cool	2040 warm	2080 cool	2080 warm
Coho	0%	**66%**	0%	**100%**	**0 - 62%**	**100%**	**95 - 100%**	**100%**
Cutthroat	0%	0%	0%	**100%**	0%	**100%**	**0 - 84%**	**100%**
Chinook	0%	**52%**	0%	**100%**	**0 - 35%**	**100%**	**82 - 100%**	**100%**
Sockeye	0%	**89%**	0%	**100%**	**38 - 90%**	**100%**	**100%**	**100%**
Chum	0%	**97%**	0%	**100%**	**53 - 96%**	**100%**	**100%**	**100%**
Steelhead	0%	**41%**	0%	**100%**	0%	**100%**	**67 - 100%**	**100%**

Risk Assessment in Mid Lang Creek Under Climate Change Scenarios

2020s

In both cool and warm years during the 2020s, the model predicts no mortalities, though temperatures are forecasted to approach lethal limits (**Figure 39**). Forecasted mortalities for all years are presented in **Table 9**.

a.



b.

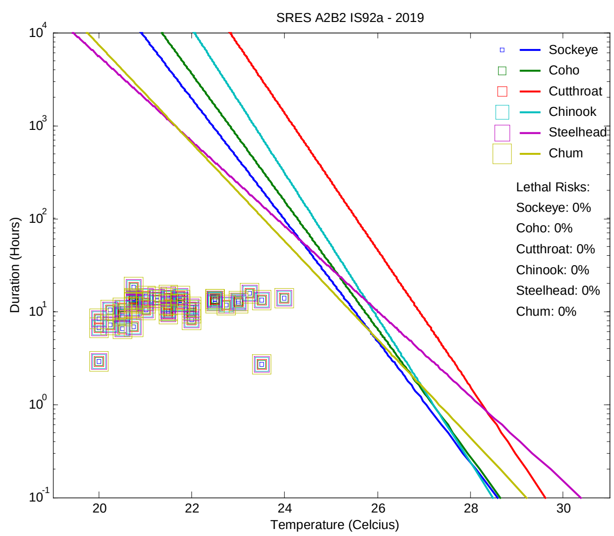
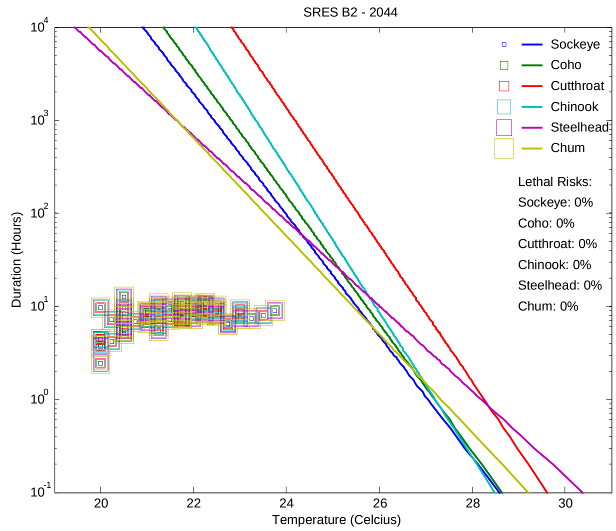


Figure 39. Forecasted salmonid mortalities in mid Lang Creek during the 2020s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

2040s

Forecasts for the 2040s are presented for the coolest and warmest scenarios (**Figure 40a** and **Figure 40b**). During cool years, temperatures are forecasted to remain below 24°C, and during are at the edge of lethal thresholds. Forecasted mortalities are presented in **Table 9**.

a.



b.

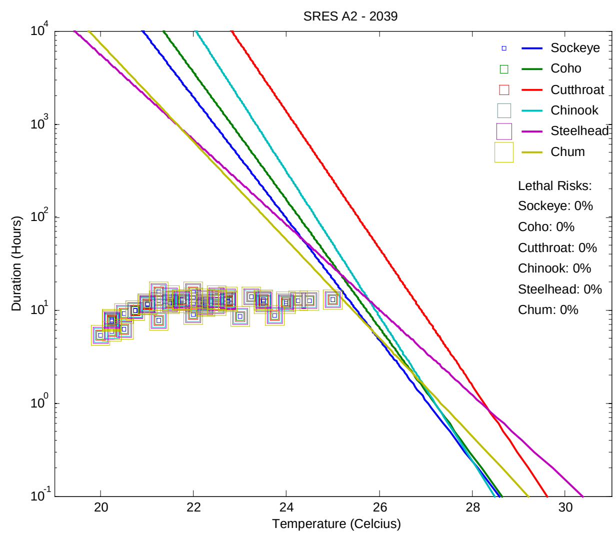
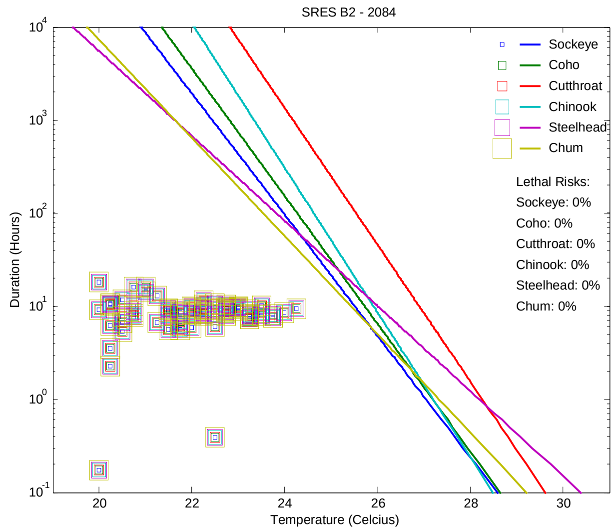


Figure 40. Forecasted salmonid mortalities in mid Lang Creek by the 2040s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

2080s

Results from forward modeling to the 2080s are presented for the coolest and warmest scenarios (**Figure 41a** and **Figure 41b**). During cool years, temperatures are forecasted to reach thresholds, with mortalities ranging from 0 to 46%, depending on the species and the scenario. During warm years, mortalities are forecasted reach as high as 100% for some species (**Table 9**).

a.



b.

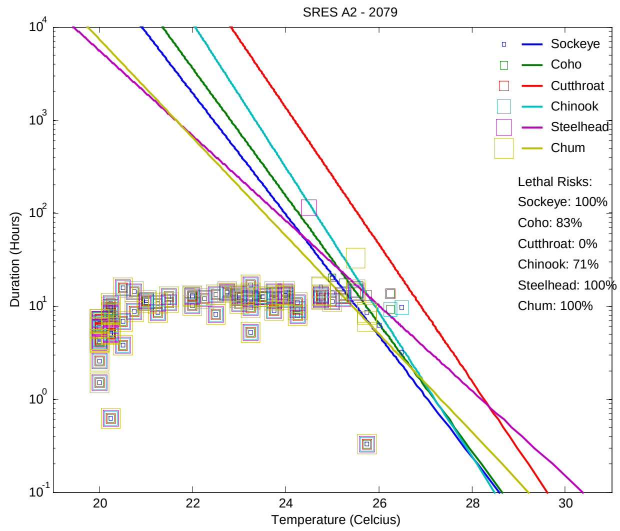


Figure 41. Forecasted salmonid mortalities in mid Lang Creek by 2080s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

Table 8. Forecasted potential mortalities to salmonids in mid Lang Creek to 2080s.

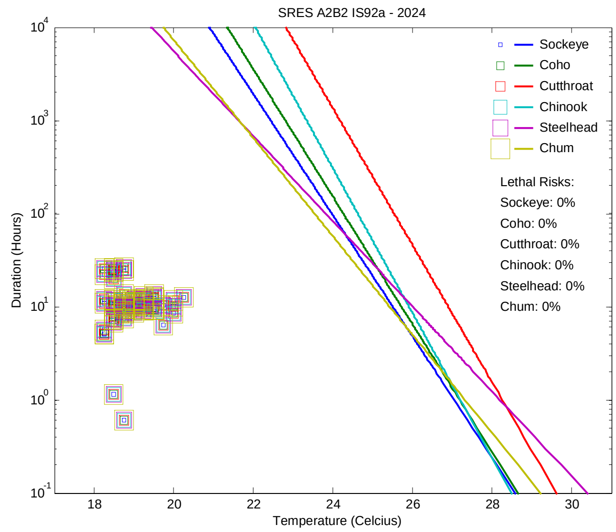
	2000 cool	**2000 warm**	**2020 cool**	**2020 warm**	**2040 cool**	**2040 warm**	2080 cool	2080 warm
Coho	0%	0%	0%	0%	0%	0%	0 - 27%	0 - 83%
Cutthroat	0%	0%	0%	0%	0%	0%	0%	0%
Chinook	0%	0%	0%	0%	0%	0%	**0 - 18%**	**0 - 71%**
Sockeye	0%	0%	0%	0%	0%	0%	**0 - 46%**	**0 - 100%**
Chum	0%	0%	0%	0%	0%	0%	**0 - 36%**	**18 - 100%**
Steelhead	0%	0%	0%	0%	0%	0%	0%	**0 - 100%**

Risk Assessment in Lower Lang Creek Under Climate Change Scenarios

2020s

During both cool and warm years during the 2020s, the model predicts no mortalities, as temperatures are forecasted to remain below 21 - 23°C (**Figure 42**). Forecasted mortalities are presented in **Table 9**.

a.



b.

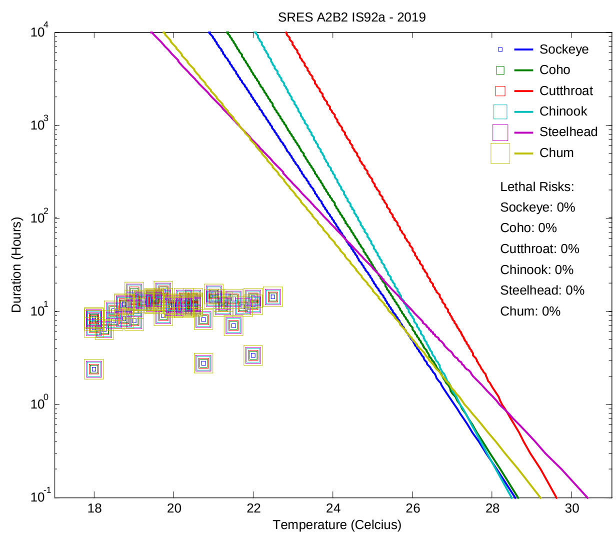
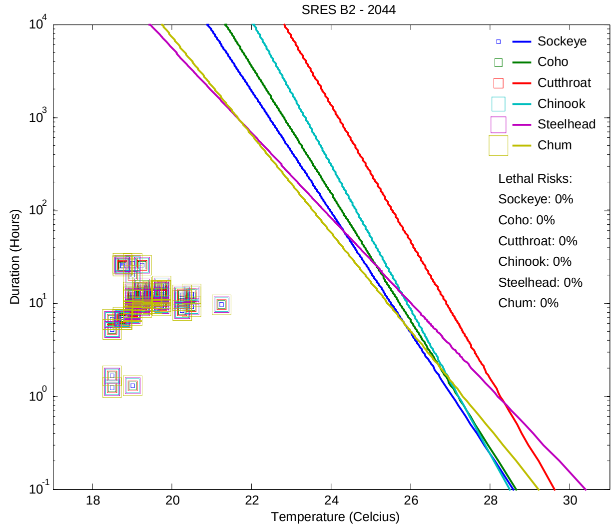


Figure 42. Forecasted salmonid mortalities in Lower Lang Creek during the 2020s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

2040s

Forecasts for the 2040s are presented for the coolest and warmest scenarios (**Figure 43a** and **Figure 43b**). During cool years, temperatures are forecasted to remain below 22°C, and during warm years below 24°C. No mortalities are predicted **Table 9**.

a.



b.

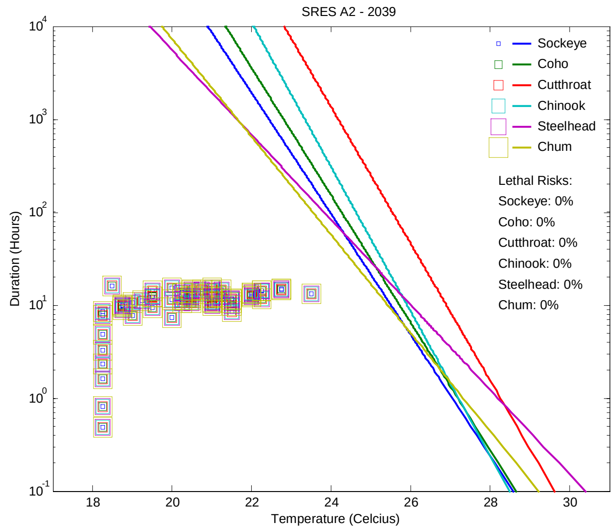
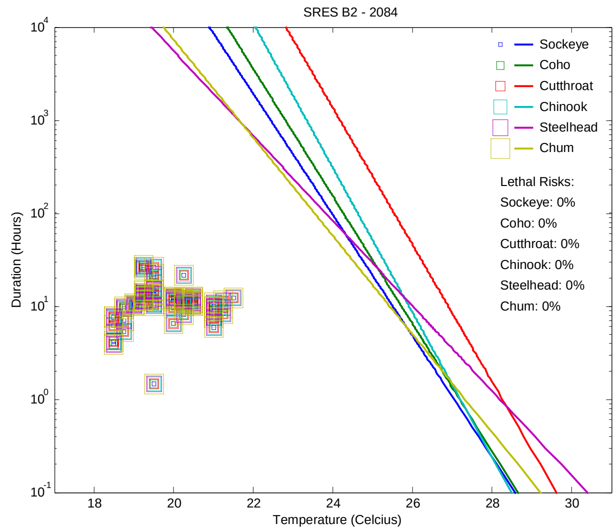


Figure 43. Forecasted salmonid mortalities in Upper Lang Creek by the 2040s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

2080s

Results from forward modeling to the 2080s are presented for the coolest and warmest scenarios (**Figure 44a** and **Figure 44b**). During cool years, temperatures are forecasted to remain below 23°C, and during warm years below 27°C. No mortalities are predicted, though during warm years temperatures will be approaching lethal levels (**Table 9**).

a.



b.

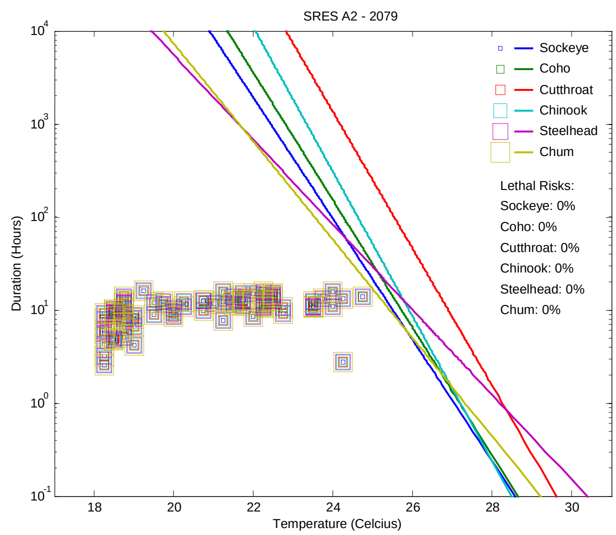


Figure 44. Forecasted salmonid mortalities in Upper Lang Creek by 2080s under cool B2 emission scenario (a.) and under warm A2 emission scenario (b).

Table 9. Forecasted potential mortalities to salmonids in Lower Lang Creek to 2080s.

	2000 cool	2000 warm	2020 cool	2020 warm	2040 cool	2040 warm	2080 cool	2080 warm
Coho	0%	0%	0%	0%	0%	0%	0%	0%
Cutthroat	0%	0%	0%	0%	0%	0%	0%	0%
Chinook	0%	0%	0%	0%	0%	0%	0%	0%
Sockeye	0%	0%	0%	0%	0%	0%	0%	0%
Chum	0%	0%	0%	0%	0%	0%	0%	0%
Steelhead	0%	0%	0%	0%	0%	0%	0%	0%

Discussion

The Earth's climate continually changes, with glacial periods cycling about every 100,000 years causing global mean temperatures to change by as much as 12°C. Currently, the Earth is in a warm interglacial period that has been relatively stable for approximately the last 20,000 years. Climate change is now, however, occurring at an unprecedented rate and temperatures are projected to be warmer than any other period in at least the last 700,000 years, and likely in the last 2 million years. Globally, average temperatures have increased by approximately 0.6°C during the last century, and are projected to increase by an additional 1.4 ~ 5.4°C over the next century.

Within B.C., impacts from climate change vary from region to region. For the Georgia Basin, over the last century temperatures are estimated to have increased by 0.8°C in spring, 0.5°C in the fall, and to have had no change in summer and winter (MWLAP, 2001). No trends in precipitation were etected for the Georgia Basin (MWLAP, 2001). For Powell River, our results suggest atmospheric warming of approximately 0.8°C in winter and 0.3°C in spring over the past 80 years. Summer and fall appear not to have been affected. Precipitation has increased throughout the year, with highest increases during winter (~1.2 mm/day) and spring (~0.8 mm/day), and modest increases during summer and fall (~0.5 mm/day). Differences in results are likely due to differences in resolution of the studies. We looked at one site specifically, while the MWLAP study examined a network of stations within a larger cell (Georgia Depression).

Projections from the Canadian Global Coupled Model 2 suggest that summer temperatures in the South Coast region of B.C. will warm by approximately 1°C by the 2020s, by 1.6 - 1.9°C by the 2040s, and by 2.2 - 3.2°C by the 2080s. Spring and fall temperatures are projected to have larger increases. These results were downscaled to the Powell River area using Powell River air temperature data recorded during the base condition (1961-1990). We estimated the Powell River area to be warming by 10% more than the average for the South Coast. According to this downscaled model, the Powell River area is expected to warm by approximately 1.1°C by 2020, by 1.8 - 2.1°C by the 2040s, and by 2.4 - 3.5°C by the 2080s. Similarly, precipitation is forecasted to increase by 5% annually by the 2020s, by 6 - 7% by the 2040s, and by 8 - 12% by the 2080s. These increases are expected to increase Lang Creek flows.

Haslam Lake and Lang Creek, located near Powell River, are within a multiple-use community watershed that currently provides drinking water for approximately 20,000 people of Powell River and Brew Bay. The system is a substantial fisheries resource, with 2003 returns of approximately 1800 Coho, 1800 Chinook, 1000 Pink, 10,000 Chum, 500 Steelhead, and some Sockeye. The salmon are naturally restricted to the lower 10 km of the creek, whereby access above is blocked by a series of waterfalls. However, hundreds of thousands of hatchery fish are released upstream of the waterfalls in Duck Lake, Haslam Lake, and Blackwater Creek every spring. Water temperatures in Haslam Lake and upper Lang Creek are very warm during summer. The large lake and shallow ponds and marshes immediately downstream provide ample opportunity for solar warming. Temperatures are known to exceed 30°C in the marshy areas, though they cool downstream through contributions of cooler tributary water and groundwater. Within the observation record (1999-2004), summer water temperatures in upper Lang Creek routinely exceeded 24°C, and occasionally exceeded 26°C. In the mid and lower reaches, water temperature tended to be approximately 2 - 4^{o}C cooler respectively, thanks to cooler contributions from tributaries and groundwater, and from evaporation and riparian influences.

Magnitude and duration based risk assessment was conducted on stream temperatures in Lang Creek for the observation period. Results from upper Lang Creek suggest that salmonids faced lethal exposures during warm years (e.g. strong El Niño years), and approached lethal exposures even during cooler years. Mortalities would potentially range from 52% - 97%, depending on the species. In reality, however, high temperatures in the upper reaches are likely of minimal risk to fish as they are thought to exhibit avoidance behaviour by moving to cool waters in Blackwater Creek and in deeper waters in Haslam Lake and Mud Lake. Temperatures in mid and lower Lang Creek did not exceed lethal thresholds; however, they were high enough to cause chronic impacts such as reduced growth and increased disease.

Projections of the impacts of global warming on local air temperature were applied to water temperature in Lang Creek. The relation between Lang Creek mean daily water temperature and Powell River mean daily air temperature was approximately linear over the observation period, and accounted for 94% of the variability in water temperature. The slope of the relation tended to flatten off near 0^{o}C and above 20^{o}C, due to freezing and evaporation, respectively, so the summer relation was calculated separately from the rest of the year. Given this relation and the forecasted increases in air temperature for Powell River, Lang Creek mean stream temperatures are forecasted to increase by 0.9^{o}C during summers by the 2020s, by 1.6 - 1.9^{o}C, by the 2040s, and by 2.2 - 3.2^{o}C by the 2080s. Added to these increases, diurnal fluctuations are projected to increase by 4% (0.2^{o}C) by the 2020s, by 8% (~0.3^{o}C) by the 2040s, and 10% (~ 0.4^{o}C) by the 2080s. Combined forecasts are provided in the **Table 10**.

Table 10. Forecasted increases to Lang Creek water temperatures.

Decade	2020s	2040s	2080s
Forecasted Increases	1.0^{o}C	1.8 – 2.1^{o}C	2.4 – 3.4 ^{o}C

These forecasts suggest that future summer water temperatures in **upper Lang Creek** will cause very high mortalities to salmon populations exposed to them. By the 2020s, during a warm year (e.g. El Niño) mortalities are predicted to range from 85-94% for the salmon and approximately 19% for cutthroat. Chum salmon are the most sensitive to temperature increases. By the 2040s, mortalities are predicted to be near 100% for salmon during a warm year, and from 52 - 79% for cutthroat. By the 2080s, mortalities are predicted to be near 100% during warm years for all species, including cutthroat. For **mid Lang Creek**, temperatures are forecasted to approach lethal thresholds during warm years by the 2040s. By the 2080s, mortalities are forecasted to range from 0 – 100% during warm years. For **lower Lang Creek**, temperatures are projected to remain below lethal limits right into the 2080s, though they will approach lethal limits in warm years. **Figure 45**, **Figure 46**, and **Figure 47** illustrate how forecasted stream warming is likely to cause habitat exclusion for salmon in Lang Creek during summers by the 2020s, 2040s, and 2080s respectively. Fish are likely to avoid temperature extremes in these areas by seeking cooler refuge in tributaries and deep water in the lakes. The tributaries become mere trickles during summer and the lakes will only be accessible to fish upstream of the falls, therefore habitat will be severly limited. These projections consider lethal risks only, and do not consider the chronic impacts of such warm water, such as reduced growth and resistance to disease.

2020s

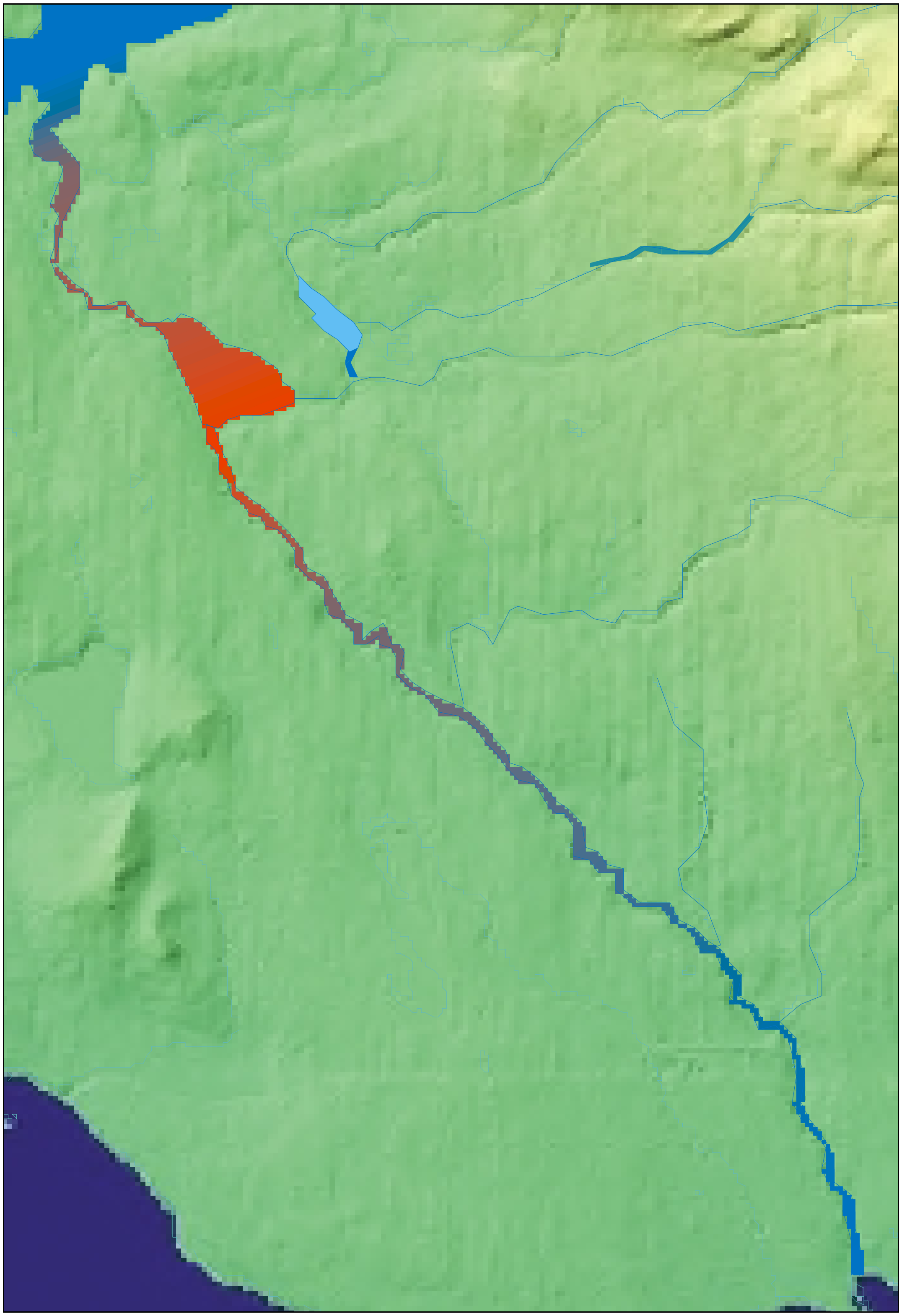


Figure 45. Forecasted summer habitat exclusion (red) in Lang Creek by the **2020s**.

2040s

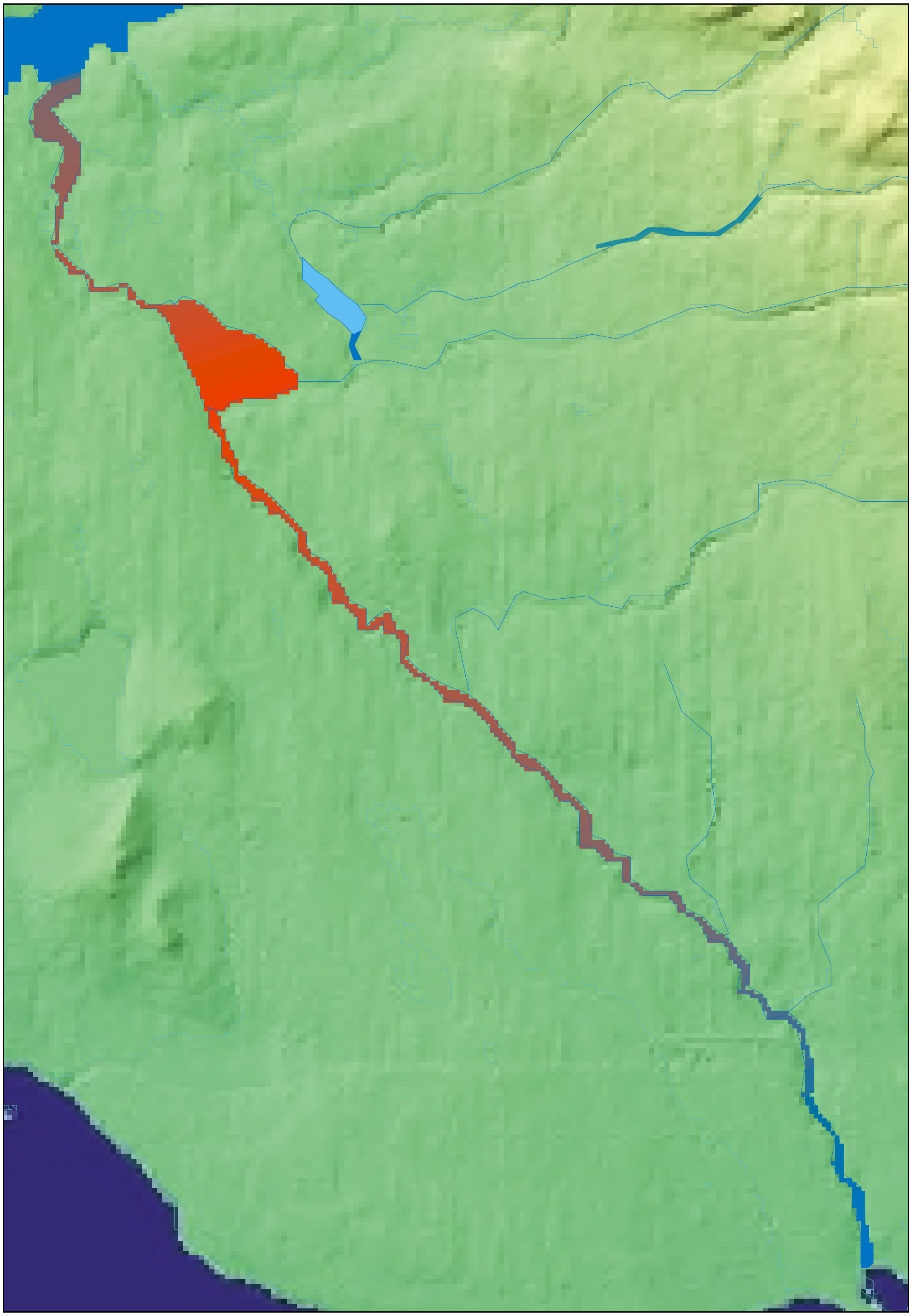


Figure 46. Forecasted summer habitat exclusion (red) in Lang Creek by the **2040s**.

2080s

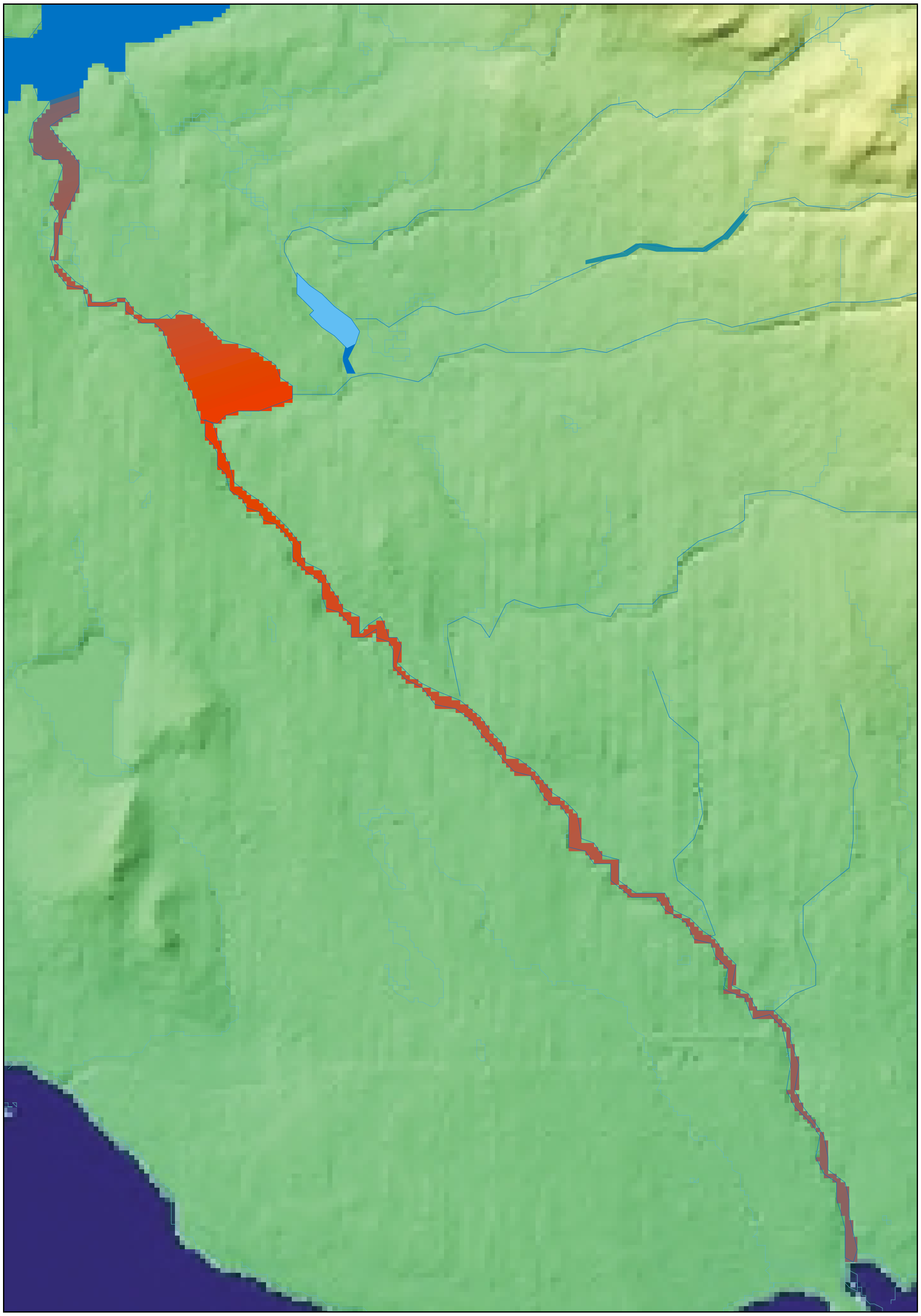


Figure 47. Forecasted summer habitat exclusion (red) in Lang Creek by the **2080s**.

Despite the strong relation between air temperature and water temperature, the above models do not consider the effect of potential future changes to the relative contributions of water from Haslam Lake, tributaries, and groundwater to Lang Creek flows. If more warm surface water from Haslam Lake was released during summer, downstream temperatures would increase significantly and forecasted mortalities in lower Lang Creek would be underestimated. Similarly, if riparian cover was removed from tributaries and subsequent warming occurred, mortalities would increase. Conversely, if cooler deep water from Mud Lake or Haslam Lake were diverted into Lang Creek during summers, then potential for mortalities would be substantially reduced. The above predictions also do not account for local populations abilities to adapt to warm temperatures, or for avoidance behaviou, nor do they consider other factors that effect salmon survival, such as habitat, fishing, or changes in nutrients, sediment loading, or flow regimes. Forecasted increases in annual precipitation for the area could provide increased flows during summer; however, this is likely also to be offset by increased water demand by population growth in Powell River and the surrounding areas.

Several studies have shown the water resource managers are generally complacent toward the impacts of climate change (Gleick, 2000). In a survey of American water resource stakeholder organizations, none indicated the intention to conduct future work regarding climate change, and all ranked the level of attention given to climate change as low (Seacrest et. al 2000). Canadian water resource managers have taken the lead in assessment of the potential impacts of climate change on hydrometric regimes. For example, water managers from the Grand River in southwestern Ontario have begun to develop contingency plans for future droughts (de Loe et al., 1999). The same approach should be considered when planning for the Haslam Lake and Lang Creek watershed. Development plans should consider the importance of tributaries and groundwater to cooling temperatures in lower Lang Creek. Riparian canopies should remain intact and road crossing minimized. Wet woodland areas should also be protected to prevent further warming to tributaries and overland seepage. Above all, management of flows over the Haslam Lake weir must be handled carefully. Prolonged flow or warmer surface water over the weir during the summer has the potential to create lethal conditions for fish downstream. On the other hand, minimum flow requirements must be maintained. It is recommended to reduce flows over the Haslam Lake weir during summers when flows downstream are sufficient for salmonid needs. One potential and economically feasible solution would be to have controlled diversion of cooler deepwater from Mud Lake or Haslam Lake. Such a change would likely create temperatures that are more optimal for fish, and for drinking water at Brew Bay; however, it would also substantially alter an ecosystem that has adapted to very warm summer stream temperatures. These impacts should be explored further before any deepwater diversion is seriously considered.

During summer months, temperatures in lower Lang Creek are consistently much higher than provincial guidelines for drinking water (15^{o}C). These objectives cannot be meet at the Brew Bay intake without diversion of cooler deepwater from Haslam Lake or Duck Lake. Temperatures are also higher than those optimal for rearing salmon or trout (**Table 11**). Watershed-specific objectives need to be developed that account for elevated temperatures caused by Haslam Lake discharge, and the marshy areas at the headwater of Lang Creek. Temperature objectives for drinking water must remain at 15^{o}C, though they will not be meet during summer. For aquatic life, it would be impractical to set temperature objectives that were meant to achieve optimum temperatures for salmonids. Summer water temperatures in Lang Creek are naturally much higher, even in the lower reaches where temperatures have cooled substantially. It is practical, however, to set objectives that prevent mortalities to any species throughout the Lang Creek system. Recommended water temperature objectives for upper Lang Creek at the outlet of Duck Lake are provided in **Table 12**. Achievement of these objectives should protect drinking water and fish.

Table 11. Optimum Temperature Ranges (^oC) of Specific Life History Stages of salmonids and Cutthroat trout (MWLAP, 2004).

Species	Incubation	Rearing	Migration	Spawning
Salmon				
Chinook	5.0-14.0	10.0-15.5	3.3-19.0	5.6-13.9
Chum	4.0-13.0	12.0-14.0	8.3-15.6	7.2-11.8
Coho	4.0-13.0	9.0-16.0	7.2-15.6	4.4-12.8
Pink	4.0-13.0	9.3-15.5	7.2-15.6	7.2-12.8
Sockeye	4.0-13.0	10.0-15.0	7.2-15.6	10.6-12.8
Trout				
Cutthroat	9.0-12.0	7.0-16.0	—	9.0-12.0

Table 12. Recommended water temperature objectives for Lang Creek.

Water Use	Monitoring Location	Monitoring Frequency	Magnitude (^oC)	Duration
Drinking Water	Brew Bay Intake	Continuous	15.0	Not to be exceeded
Aquatic Life	Duck Lake Outlet	Continuous	20.0	190 days
			20.5	100 days
			21.0	53 days
			21.5	28 days
			22.0	15 days
			22.5	8 days
			23.0	4 days
			23.5	2 days
			24.0	1 day
			24.5	15 hrs
			25.0	7 hrs
			25.5	4 hrs
			26.0	2 hrs
			26.5	1 hrs
			27.0	45 min
			27.5	30 min
			28.0	Not to be exceeded

Conclusions

1. For Powell River, our results suggest atmospheric warming over the past 80 years of approximately 0.8°C in winter and 0.3°C in spring. Summer and fall appear not to have been affected.
2. Precipitation was also shown to have increased over the last 80 years, with highest increases during winter (~1.2 mm/day) and spring (~0.8 mm/day), and modest increases during summer and fall (~0.5 mm/day). As a result, flows in Lang Creek have also been increasing.
3. Between 1998 and 2004, summer stream temperatures in upper Lang Creek were observed to routinely exceeded 24°C, and occasionally exceeded 26°C. Temperatures in mid and lower Lang Creek were 2 - 4°C cooler, due to groundwater and tributary contributions, evapotranspiration, and riparian cooling effects.
4. At present, salmonids in upper Lang Creek face lethal exposures during warm years (e.g. strong El Niño years). Mortalities would potentially range from 52% - 97%, depending on the species. However, it is thought that the fish avoid these temperatures by seeking refuge in the cooler deep waters in Mud Lake and Haslam Lake, and in tributaries such as Blackwater Creek. Temperatures in mid and lower Lang Creek do not reach acute thresholds, but are high enough to cause chronic impacts, such as reduced growth and increased disease.
5. According to our downscaled model, the Powell River area is expected to warm by approximately 10% more than the average for the South Coast. These forecasts suggest increases in air temperature of approximately 1.1°C by the 2020s, by 1.8 - 2.1°C by the 2040s, and by 2.4 - 3.5°C by the 2080s. Precipitation and Lang Creek flow are also expected to increase.
6. Lang Creek summer stream temperatures are forecasted to increase by 1.0°C by the 2020s, by 1.8 – 2.1°C by the 2040s, and by 2.4 - 3.4°C by the 2080s.
7. These forecasts suggest that even during cool years by the 2040s, summer water temperatures in upper Lang Creek will cause very high mortalities salmon. For mid Lang Creek, temperatures are predicted to approach lethal thresholds during warm years by the 2040s, and to have significant mortalities during all years by the 2080s. For lower Lang Creek, temperatures are projected to remain below lethal limits right to the 2080s, though they will approach lethal limits in warm years.
8. The cool tributaries and deeper lake water are vital for survival of Lang Creek salmon. Future land use decisions need to specifically mitigate the negative effects of increasing stream temperatures. In particular, wide riparian areas (> 30m) around all tributaries, including headwater streams, need to be preserved. Wet woodland areas should also be protected.
9. Steps should also be taken to cool Lang Creek temperatures during summer. Cooler water could be diverted from deeper waters of Mud Lake and Haslam Lake. Above all, management of flows over the Haslam Lake weir must be handled carefully. During summer, flows over the weir should be minimized provided downstream flow requirements are met.
10. Water temperature objectives have been proposed for Lang Creek. A drinking water objective of 15°C is recommended for the Brew Bay Intake, while magnitude-duration dependent objectives have been recommended for upper Lang Creek.

Recommendations

Given the forecasts provided in this report, management steps should be taken to protect water quality and aquatic life in Lang Creek. *The following recommendations should be considered*:

1. Continue the thermistor monitoring program in the watershed. Thermistors should be maintained at Haslam Lake, Blackwater Creek, Duck Lake Outlet, Lang Hatchery, mid Lang Creek, Anderson Creek, Coho Creeks, and lower Lang Creek (Channel). Hourly water temperature should be recorded at the lower hatchery, rather than daily averages.
2. Future land use decisions need to specifically mitigate the negative effects of increasing stream temperatures. Land development, such as forest harvesting, should be limited downstream of Haslam Lake. In particular, riparian areas around tributaries need to be protected. Where development takes place, riparian buffers greater than 30 meters should be maintained. Wet woodland areas should also be protected, to prevent warming of overland seepage.
3. During July and August, deep cooler water from Mud Lake or Haslam Lake should be diverted into Lang Creek. Temperature/depth profiles for Haslam Lake and Duck Lake are available (PRSES). It would likely be more economically feasible (shorter distance) to divert deep water flow Duck Lake because Haslam Lake is quite shallow on its south end. Temperature/depth profiles of Duck Lake should be collected first. Also, the environmental consequences of altering an ecosystem that has adapted to warm temperatures must be evaluated before any deepwater diversion is seriously considered.
4. Flows over the Haslam Lake weir should be reduced during summers when flows downstream are sufficient for downstream needs.
5. Water Temperature Objectives, as outlined in this report, should be set for Lang Creek. A drinking water objective of $15^{o}C$ is recommended for the Brew Bay Intake, while magnitude-duration dependent objectives have been recommended for upper Lang Creek.

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