


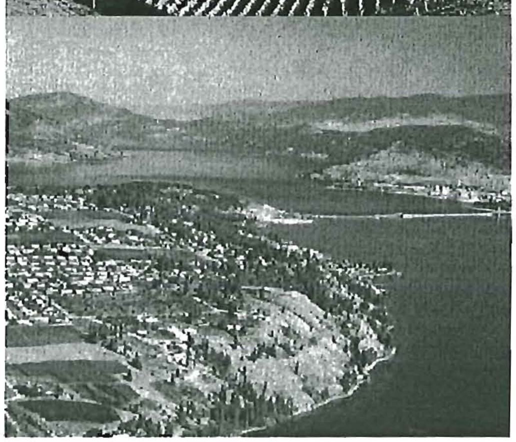

Climate Change and Mission Creek, BC

FINAL REPORT

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Executive Summary

Mission Creek supplies about one-third of all of the water that reaches Okanagan Lake each year. The creek is a designated community watershed supplying drinking water to the city of Kelowna. There are 154 water withdrawal licenses on the creek, accounting for as much as one-third of the total flow during a dry year (MWLAP, 2001a). Mission Creek contains a variety of fish species, including kokanee, rainbow trout, redside shiners and longnose dace. Okanagan Lake kokanee have seen considerable decline in recent decades, and in Mission Creek, spawners have declined from over 350,000 in 1971 to about 13,650 in 2003.

Ongoing concern over decreasing kokanee salmon populations has led to the Okanagan Lake Action Plan, aimed at restoring kokanee populations in Okanagan Lake. This Action Plan is considered to be a long-term strategy for lake restoration. For this Action Plan to be effective, it must consider the impacts of natural climate cycle (*e.g.*, El Niño-Southern Oscillation, ENSO; Pacific Decadal Oscillation, PDO) and anthropogenic climate change. Without these considerations, any restoration works are likely to be effective only in the short term at best.

The objective of this study was to estimate the impacts of climate change on Mission Creek kokanee salmon and rainbow trout. To do this, we focused on three questions:

1. How has climate changed in and near Kelowna, and how will it change in the future?

2. How do natural climatic cycles such as ENSO and PDO affect Mission Creek flows and stream temperatures?

3. How have historical stream temperatures affected Mission Creek kokanee and rainbow trout, and what will be the impact of anthropogenic climate change?

In addressing these issues, we took a relatively novel approach, using high-frequency (*i.e.*, daily or hourly) data to estimate climatic trends and exposure risks. We also compared our results to other studies using more conventional approaches.

As a side project, we also examined the relation between trends in Mission Creek flows and nutrients. *The nutrient-focused portion of the study was completed as a separate report, and is provided in* ***Appendix 1***.

Our results suggest that climate in the Mission Creek area has become significantly warmer and wetter over the past century. Mean daily air temperatures have increased by approximately 4°C during winter, 3.5°C during spring, and 2.5°C during summer and fall. These increases are substantial and are nearly double those estimated for the BC southern interior by other researchers. Much of the difference appears related to the "heat island effect" from rapid population growth in the City of Kelowna, which occupies part of the watershed. Total annual precipitation appears to have increased by approximately 80 mm or 25%, with almost all of the change occurring during spring and summer. Downscaled climate change simulations suggest that summertime mean air temperatures in the Mission Creek area will increase by about 1.4°C by the 2020s, 2.3 – 2.6°C by the 2050s, and 2.8 – 4.1°C by the 2080s.

During El Niño years in the Okanagan, precipitation is somewhat lower, and air temperature is substantially higher from February through June. Mission Creek streamflow is lower during El Niño summers. During in-phase El Niño years, when El Niño events coincide with the warm phase of the Pacific Decadal Oscillation, precipitation appears to be higher than average during spring, and Mission Creek streamflows are higher than average during March and April, and lower during May to September (though only significant in June). Cold-phase ENSO (*i.e.*, La Niña) impacts are roughly the opposite.

Historically, summer stream temperatures in Mission Creek are generally in the 20-24°C range and were found to be about 4-6°C below lethal (acute) exposures for kokanee and rainbow trout. They were, however, estimated to cause sublethal (chronic) risks of ~20% during 1998, as measured by total growth risk (*TGR*). Climate change simulations, coupled with a site-specific air temperature-water temperature model, suggest that Mission Creek mean summer water temperatures may increase by approximately 1.0°C by the 2020s (with a 4% increase in the amplitude of the daily cycle), 1.6-1.8°C by the 2050s (and 8% increase in diurnal), and 2.0-2.9°C by the 2080s (and 10% increase in diurnal). Though acute impacts appear to remain unlikely, projections suggest that chronic growth risks could nearly double by the 2020s and approach 100% (zero yearly growth) by the 2080s during warm years. Detailed projections of climate change impacts upon Mission Creek thermal risks to fish depend upon the particular greenhouse gas forcing scenario used, and whether a historically warm or cool year is employed as the basis for predictions. However, under every combination considered, substantial increases in chronic thermal risk are observed.

Climate variability and change impacts upon water resources and fisheries in Mission Creek must be incorporated into watershed management and planning. Several suggestions for additional monitoring and analysis are presented. These focus upon acquisition of continuous Mission Creek temperature data, analyses of local groundwater responses to climatic cycles, further investigation of the urban heat island effect and its implications for Mission Creek salmonids, and development of a Mission Creek watershed model. Specific recommendations regarding mitigation of climate change impacts upon the water quality and ecological health of Mission Creek are also made.

Introduction

Keeping a watershed healthy while accommodating economic growth can be difficult. Land development activities such as logging, agriculture, cattle grazing, 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) and climate change, which can be on a scale larger than that of local interventions. For example, coastal summertime maximum stream temperatures can be more than 7°C warmer during an El Niño year (Quilty *et al.*, 2004c), and climate change is estimated to have increased stream temperatures by 1-2°C (MWLAP, 2001b; Quilty *et al.* 2004a). Making permanent development decisions without climate information is akin to signing a lifelong employment contract without any consideration for inflation.

Mission Creek is a tributary to Okanagan Lake (**Figure 1**), running through Kelowna, BC, and is a designated community watershed supplying drinking water to the city of Kelowna. The creek is a significant tributary to Okanagan Lake, carrying about one-third of all of the water that reaches Okanagan Lake each year (MWLAP, 2001a). A total of 154 water withdrawal licenses have been issued for Mission Creek, accounting for as much as one-third of the total flow during a dry year (MWLAP, 2001a). Mission Creek contains a variety of fish species, including kokanee, rainbow trout, redside shiners and longnose dace. It is a major site for viewing spawning kokanee, second only to the Adams River sockeye run (MWLAP, 2001a). Mission Creek was projected to have an equivalent clearcut area (ECA) of 21.8% by 2003 (Dobson Engineering, 1998). By 1997, approximately one-fifth of the entire stream-length had been logged to the stream bank. Grazing licences allow for several hundred cows in the watershed, depending on the time of year (MWLAP, 2001a).

Okanagan Lake kokanee salmon, a landlocked population of sockeye salmon, have seen considerable decline in recent decades. In Mission Creek, spawners have declined from over 350,000 in 1971 to about 13,650 in 2003. Spawning area destruction, both in Mission Creek and along the Okanagan lakeshore, and the introduction of freshwater shrimp (*Mysis relicta*) have been cited as the potential causes for kokanee population decline (Andrusak *et al.*, 2002). A spawning channel was established in 1988 in Mission Creek and was rebuilt in 1995 to compensate for loss of kokanee spawning habitat due to diking and sedimentation. The spawning channel is 1km long and located 7km upstream from the mouth. It augments spawning areas with 28 spawning reaches separated by 30cm weirs (Kokanee Salmon Heritage Project, 2005). Ongoing concern over decreasing kokanee salmon populations has led to the Okanagan Lake Action Plan, aimed at restoring kokanee populations in Okanagan Lake. This Action Plan is considered to be a long-term strategy for stream restoration. Annual progress reports have been published as part of the Plan (see Andrusak *et al.*, 2002).

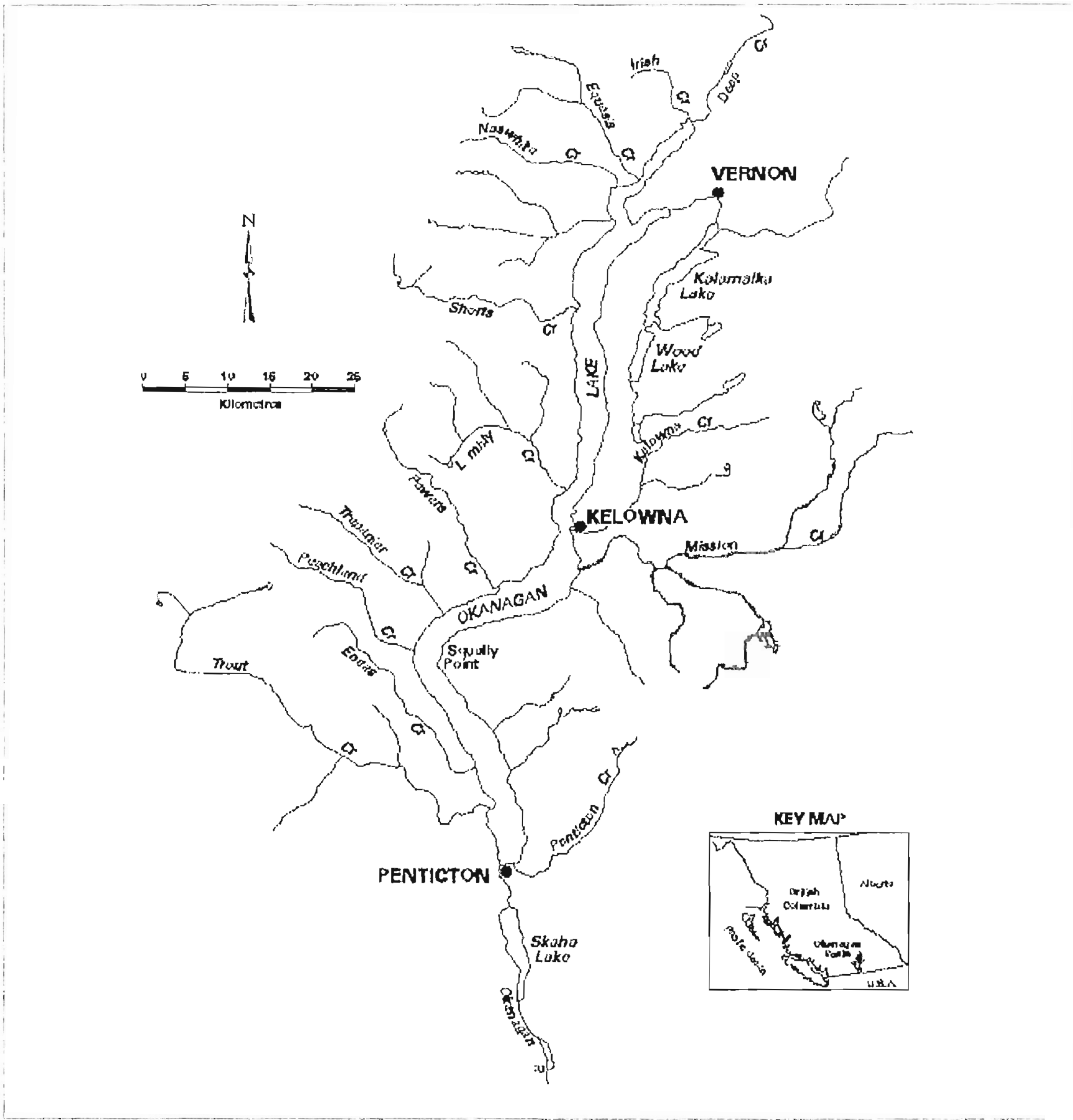


Figure 1. Okanagan Lake and its tributaries. Mission Creek is highlighted in blue. Adapted from Andrusak *et al.* (2002).

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 several tens of thousands of years (EPICA, 2004; Petit *et al.*, 1999). During this time, global average temperatures have changed by as much as 12°C between glacial–interglacial periods (**Figure 2 - 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 conditions that, at different times, were warmer, cooler, wetter, or 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 (e.g., evaporation, oceanic CO_2 sequestering). Once in the atmosphere, these gasses absorb and retransmit 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 2: lines a, c**). CO_2, for example, has almost always been in a state of change during the past 420,000 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 step with temperature for hundreds of thousands of years (Petit *et al.*, 1999).

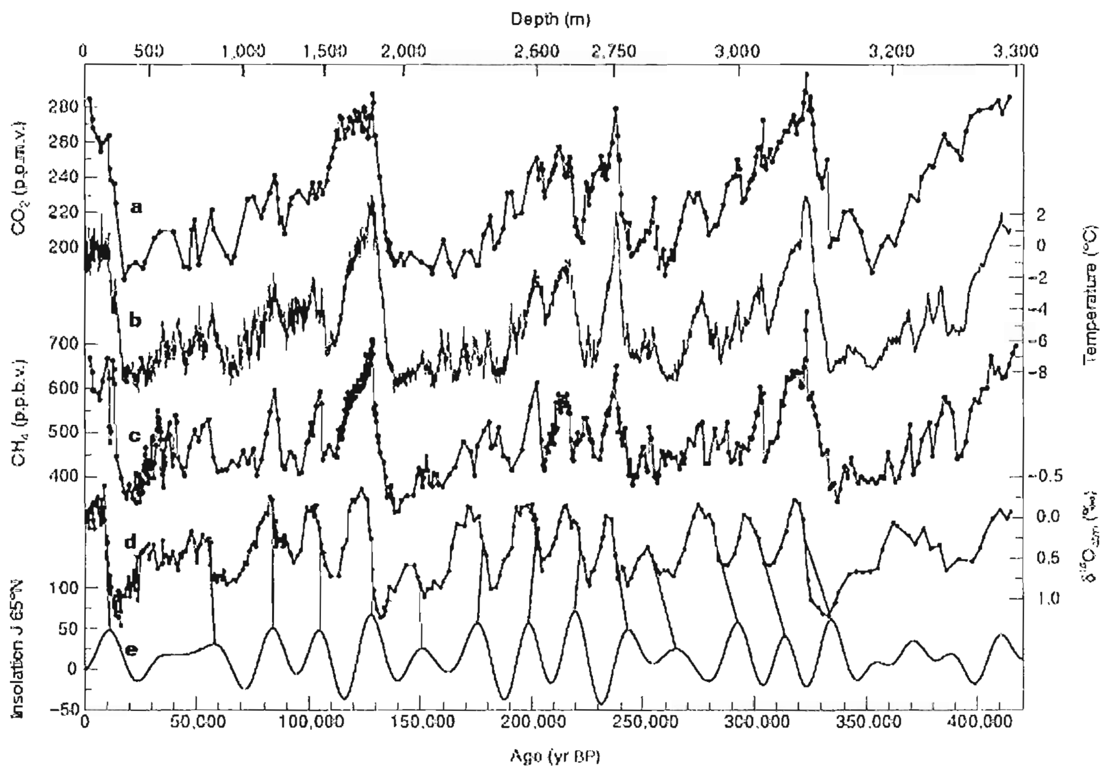


Figure 2. Changes in Earth's atmosphere and surface temperature during the past 420,000 years as estimated from ice-core drilling at Vostok, East Antarctica. Vostok time series for a) CO_2; b) isotopic temperature of the atmosphere; c) CH_4; d) $^{18}O_{atm}$; and e) mid-June insolation at 65° N (in 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 is associated with 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 Southern Oscillation. 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 cold phase, also known as La Niña, involves roughly opposite conditions.

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.

In general, ENSO events are stronger when they occur with the same phase as the PDO, and weaker when they are of opposite phase. This phenomenon is referred to as modulation. For example, a warm-phase ENSO (*i.e.*, El Niño) event tends to be reinforced when it occurs during a warm phase of the PDO, and damped when it occurs during a PDO cold phase (see Kiffney *et al.*, 2002 and references therein).

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°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 3**), 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).

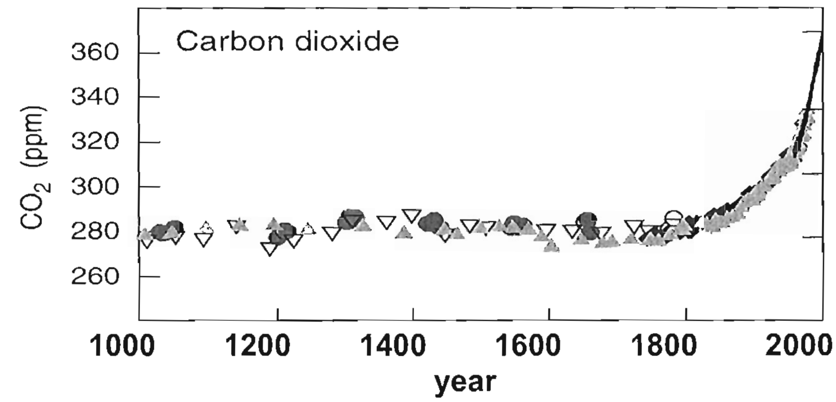


Figure 3. 1000-year record of past changes in atmospheric carbon dioxide. From IPCC (2001).

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 4**). For the Southern Interior, seasonal temperatures are estimated to have increased by 1.8°C in spring, 1.2°C in summer, 0.9°C in fall, and 0.8°C in winter (MWLAP, 2001b). There have been numerous related effects on climate, such as increased precipitation in southern BC, increased sea level and sea temperature along the coast, and glacial retreat (MWLAP, 2001b).

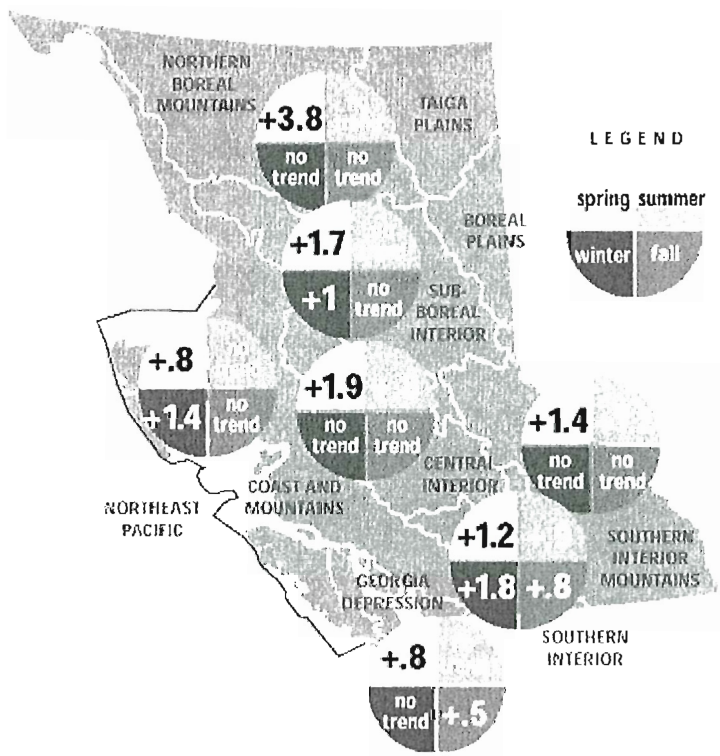


Figure 4. Change in seasonal temperature (°C per century) for regions in British Columbia between 1895 and 1995. From MWLAP (2001b).

Observed Impacts on Water Resources in the Okanagan

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 decreased winter precipitation, increased winter air temperature, 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.*, 2004c). 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°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, 2001; Whitfield and Cannon, 2000; Whitfield *et al.*, 2002; Cohen *et al.*, 2003). Cohen *et al.* (2003) predicted the Okanagan basin would receive 10~20% more precipitation by the 2080s. Furthermore, hydrology in Okanagan basin streams would be characterized by an earlier freshet and lower summer flows resulting from increased precipitation in spring and fall coupled with slight decreases in summer rainfall. 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 different eco-zones in Canada. Peak runoffs were predicted to occur up to 1 month earlier than is currently the case.

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). These models are based on physical laws represented by equations that are solved using a three-dimensional grid over the globe. The global models couple submodels that represent the atmosphere, ocean, land surface, cryosphere and bioshere (IPCC, 2001). The models are then run using various future greenhouse gas emission scenarios, such as the A1, A2, B1, and B2 scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (**Figure 5**). SRES scenarios prefixed with the letter 'A' represent futures in which 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 (A1T), 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 to 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°C between 1990 and 2100 (Albritton and Filho, 2001; IPCC, 2001).

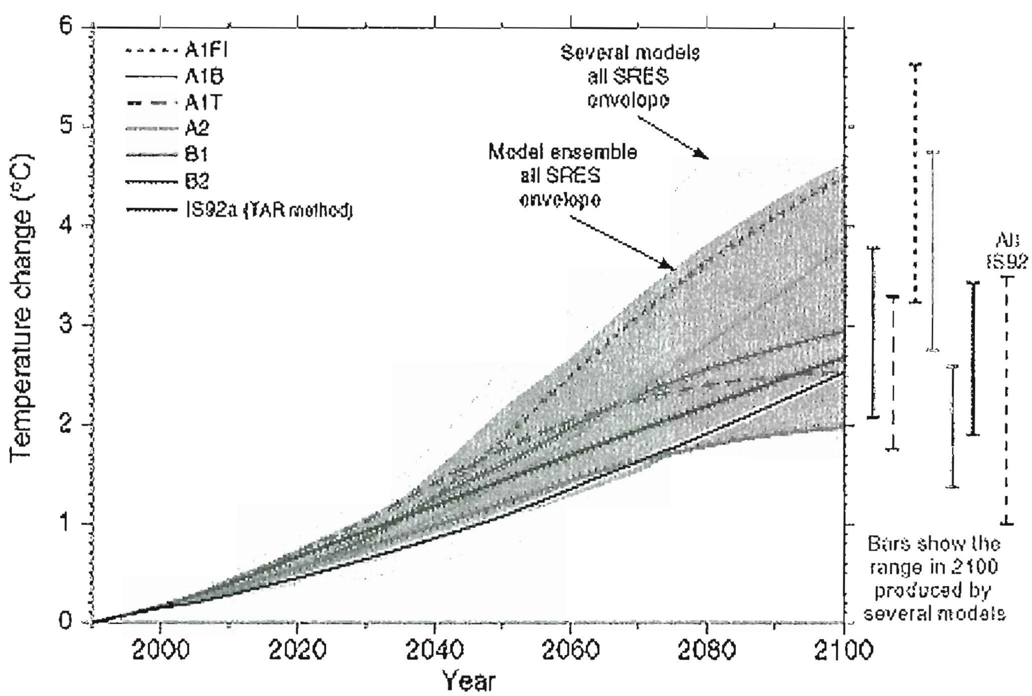


Figure 5. Predicted mean global temperature change between 1990 and 2100 resulting from seven emission scenarios. SRES scenarios are prefixed by A or B. IS92a scenario is older, but commonly used, IPCC base-case conceptualization. From IPCC (2001).

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 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 possibly above 20°C due to freezing and increased evaporation, respectively (Crisp and Howson, 1982; Mohseni and Stefan, 1999; Webb *et al.*, 2003). The relation may also 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 salmonid life (Brett, 1995). Adversely high temperatures 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°C may have lethal effects on certain salmon after only minutes, whereas exposure at 24°C will take several days to have the same lethal effect (**Figure 6**). 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°C lower than those acclimated to warmer waters.

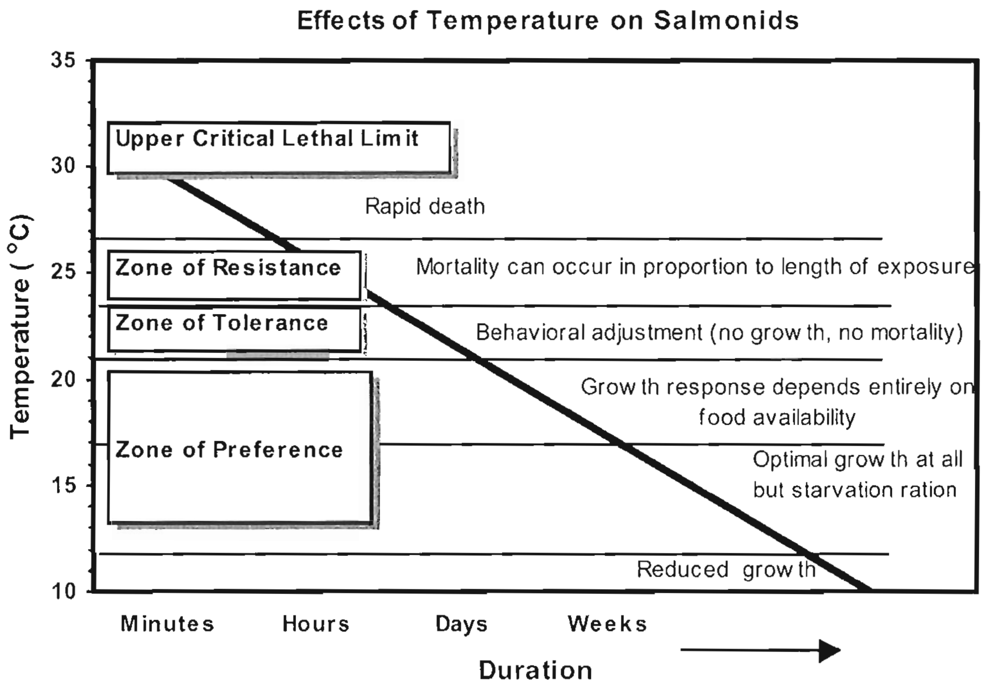


Figure 6. General biological effects of temperature on salmonids in relation to magnitude and duration of temperature. Taken from Sullivan *et al.* (2000).

Study Site

Mission Creek runs from several small marshy lakes between Jubilee Mountain and Buck Mountain, through the City of Kelowna, and into Okanagan Lake. Pearson Creek and Beligo Creek augment Mission Creek flows before runoff from Black Night Mountain, Hydraulic Creek, and Klo Creek enter several kilometres upstream of Okanagan Lake. Under the auspices of the Forest Renewal British Columbia (FRBC) program, a near-continuous water quality monitoring station was installed in Mission Creek in 1997 (**Figure 7**). The station was located about half way up the mainstem, upstream of the most urbanization.

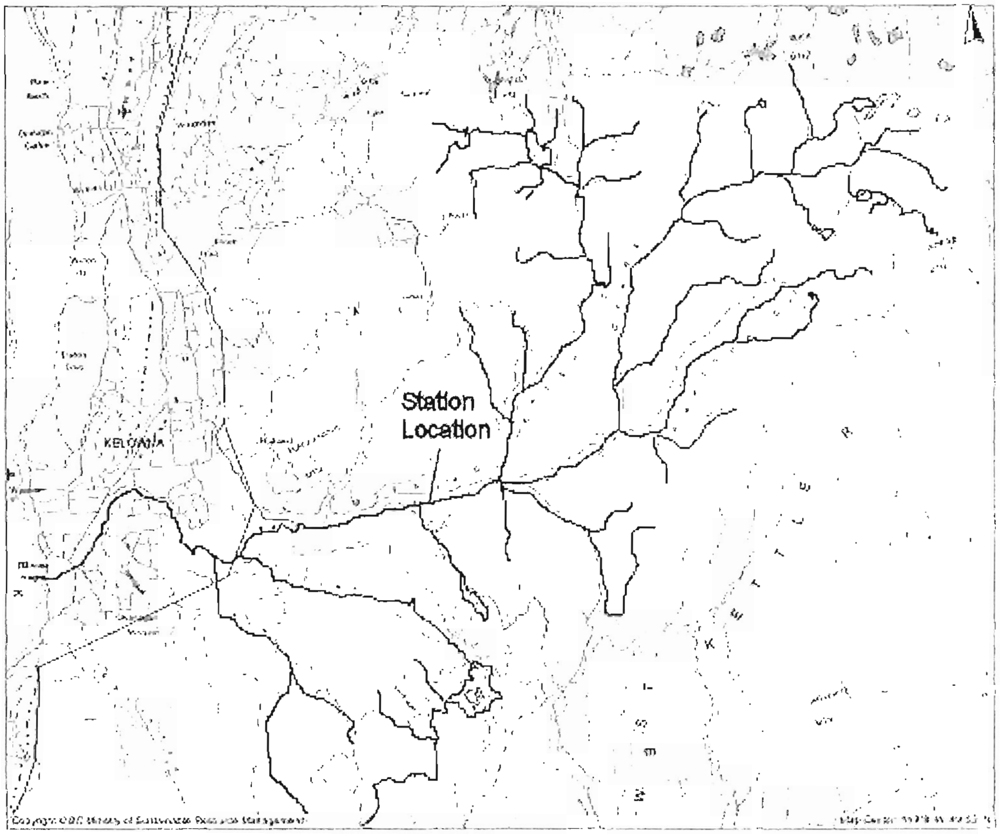


Figure 7 - Topographic map of the Mission Creek Drainage, with the location of the FRBC near-continuous water quality monitoring station labelled.

Figure 8 – Photo of the Buck Mtn. Irrigation District intake site, where the Mission Creek near-continuous water quality monitoring station was located.

Study Objectives

The objectives of this study are to:

1. Estimate climate change trends for Kelowna specifically, and at a high temporal resolution. Other studies have examined regional trends (*e.g.*, Okanagan Basin) and have focused on annual or monthly extremes. We examine trends within the City of Kelowna, and at a resolution varying from seasonal to daily.

2. Estimate trends in Mission Creek flows, including those from climate change and cycles (*e.g.*, El Niño). We also examine the relation between trends in Mission Creek flows and nutrients. *The nutrient-focused portion of the study was completed as a separate report, and is provided in* ***Appendix 1***.

3. Estimate recent impacts of exposure to high stream temperatures on Mission Creek kokanee and rainbow trout.

4. Forecast likely impacts of exposure to future stream temperatures on Mission Creek kokanee and rainbow trout.

Methods

Summary of Approach

Overall, our objective was to investigate what impacts recent water temperatures might be having on salmonids in Mission Creek, and to estimate the impacts of future water temperatures. To do this, we:

1. Estimate climate change in the Kelowna area over the past century using daily mean temperatures and precipitation. Our approach is different from approaches used by other researchers (*e.g.,* Brewer and Taylor, 2001; Taylor *et al.*, 2004), who have typically looked at *annual* daily maximum/minimum or *monthly* daily maximum/minimum. Analysis of data at a daily resolution may provide more insight into seasonal differences. Analysis of means rather than minima or maxima might allow for a more general approach when looking at exposures.

2. Estimate the effects of climatic cycles on the annual and seasonal hydrology of Mission Creek. The mean annual regimes of streamflow, air temperature, and precipitation are compared between El Niño, La Niña, and neutral years using monthly means. We also consider how the Pacific Decadal Oscillation may modulate the streamflow impacts of ENSO; there have been very few studies in Canada that have considered such potentially important details.

3. Estimate impacts to salmonids (kokanee salmon and rainbow trout) in Mission Creek from exposure to summer stream temperatures during recent years. Here our approach is again unique. We use near-continuous stream temperature data, collected automatically every 15 minutes, to determine the magnitude and duration (exposure) of high temperature events. We then relate these exposures to known lethal and sublethal exposure limits. Most studies have looked at daily mean or maximum temperatures and compared them to a static threshold, thereby considering only magnitude, and not duration, of exposure.

4. Forecast Mission Creek summer stream temperatures during the 2020s, 2050s, and 2080s, and estimate impacts to salmonids. Here our approach is to downscale air temperature forecasts from global climate models to the Kelowna area, and then use an empirical relationship between Kelowna air temperature and Mission Creek water temperature to forecast changes in Mission Creek. As was done above, we then estimate lethal and sublethal effects.

Estimating historical climate change in the Kelowna Area

Typically, for climate change studies, researchers use Historical Canadian Climate Database (HCCD) data provided by the Meteorological Service of Canada (see Mekis and Hogg, 1999; Vincent and Gullett, 1999). Daily data from the suite of stations selected for incorporation in the HCCD have been homogenized and corrected for non-climate related jumps caused by instrumentation changes and station relocations. Monthly HCCD data is available for sites near Vernon and Summerland. However, for the purposes of this portion of the study, we required daily data and preferred data closer to Mission Creek. Daily air temperature and precipitation data have been collected in or around Kelowna since 1899. Daily mean air temperatures from Environment Canada climate stations in Kelowna were therefore reconstructed into a single time series using **AQUARIUS**^{TM} time series software **(Figure 9)**. Kelowna stations used in reconstruction are listed in **Table 1.**

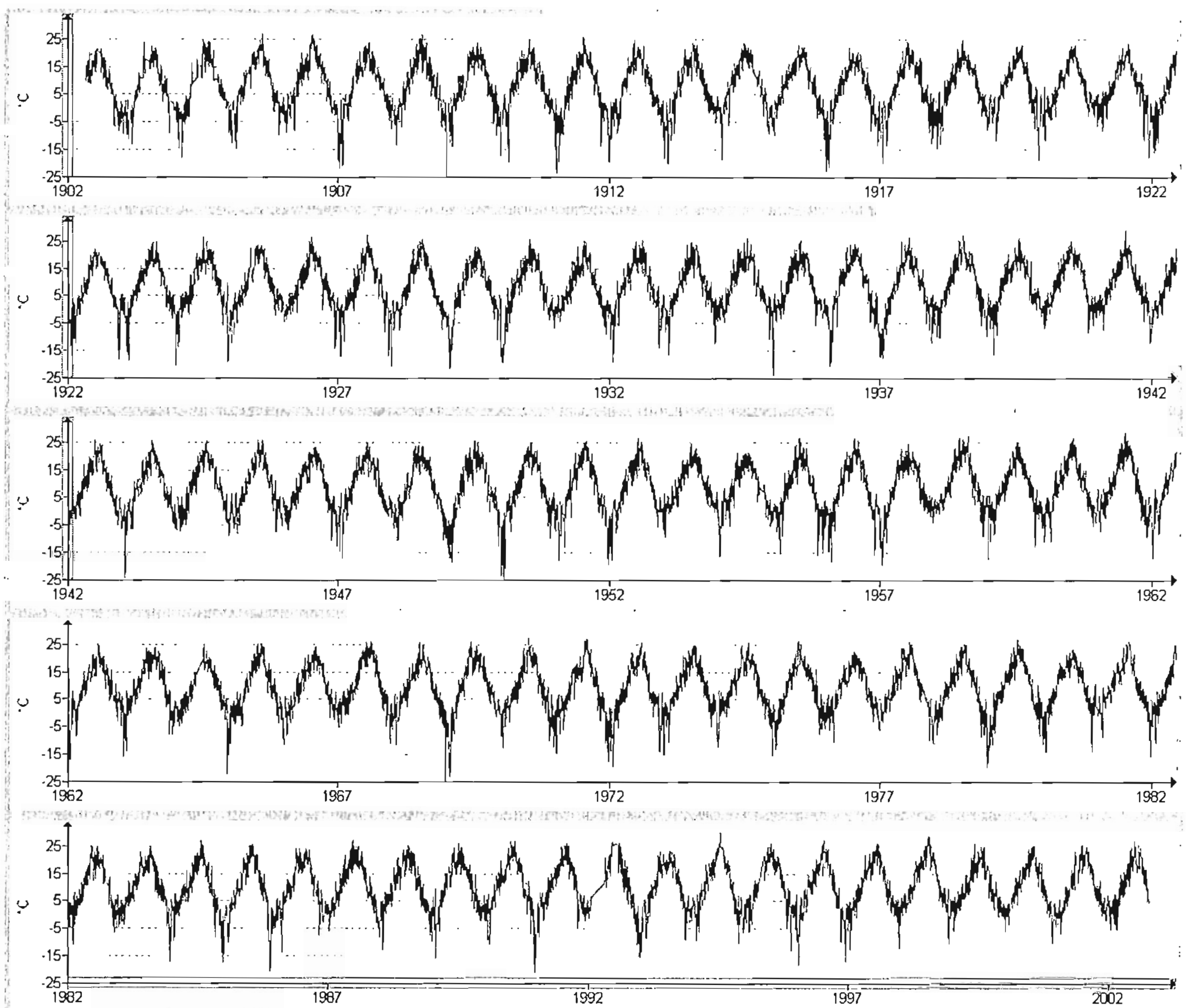


Figure 9. Time series of reconstructed daily mean air temperature data for Kelowna.

To detect trends in the Kelowna daily air temperature and precipitation data, the data were 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 robust, rank-based slope estimator of Theil (1950) and Sen (1968), and associated statistical confidence can be assessed using the nonparametric Mann-Kendall test for monotonic trend. The method used in this study expands on the seasonality of the seasonal Mann-Kendall test (four seasons) to more continuous resolution (compares on a daily level across years) to provide higher-resolution trend information.

Table 1. Environment Canada stations used to reconstruct Kelowna daily mean air temperature.

Station Name	Station Number	Record
Kelowna	1123930	1899-1962
Kelowna Airport	1123970	1968-2002
Kelowna Bankhead	1123972	1914-1931
Kelowna Bowes Street	1123970	1961-1969
Kelowna Bylands	1123977	1994-1995
Kelowna CDA	1123980	1950-1970
Kelowna Cedar Creek	1123981	1994-2002
Kelowna Dav-Spiers Road	1123982	1978-2002
Kelowna East	1123984	1980-2000
Kelowna Lakeview	1123990	1952-2000
Kelowna MWSO	11239R0	1994–2002
Kelowna N Glenmore	112C991	1984-1986
Kelowna PC Burnetts Nurs	1123992	1969-2002
Kelowna Quails Gate	1123993	1995-2002

Estimating the effects of climatic cycles on the hydrology of Mission Creek

We use climatological composite analysis to assess ENSO impacts upon Mission Creek hydrology and local surface meteorology. The mean annual regimes of streamflow, air temperature, and precipitation are compared between El Niño, La Niña, and neutral years. The analyses are posed in terms of anomalies from the hydroclimatic normal. The procedure is performed using (i) all ENSO events over the hydrometeorological period of record, and (ii) only those ENSO events which occur with the same phase as the PDO. Month-by-month significance testing for differences between the monthly means is accomplished using a Monte Carlo boostrapping method free of distributional assumptions. The results of the composite analyses are physically interpreted, and the discharge composite results are checked using a simpler but methodologically independent regression analysis. Some potential implications are identified, particularly with respect to Mission Creek fisheries health.

For the purposes of examining the effects of climatic cycles on hydrology, monthly means and totals were appropriate. Therefore, the following hydrometeorological data were sourced from the online Water Survey of Canada HYDAT database, and the online Meteorological Service of Canada HCCD database:

- Mean monthly streamflow, Mission Creek near East Kelowna, 1967-2003 (WSC ID 08MN116);
- Monthly total precipitation, Vernon Coldstream Ranch, 1900-1996 (MSC ID 1128580);
- Monthly mean temperature, Vernon Coldstream Ranch, 1900-2002 (MSC ID 1128581);
- Monthly total precipitation, Penticton Airport, 1908-2003 (MSC ID 1126150);
- Monthly mean temperature, Summerland, 1907-2002 (MSC ID 112G8L1).

We employed the list of ENSO event years developed by Kiffney *et al.* (2002), which is summarized below in **Table 2**. The canonical ENSO event typically spans two calendar years, often reaching its peak during the winter. ENSO events are thus often identified as, for example, the 1982-1983 El Niño. The calendar year of event onset is typically denoted in the climatological literature as year [0], and the following year as year [+1].

Table 2. ENSO event years, adapted from Kiffney *et al.* (2002). For each ENSO event, concurrent PDO phase is also shown. W = warm phase and C = cold phase. ENSO in-phase warm events are shaded orange. ENSO in-phase cold events are shaded blue.

Year	ENSO	PDO
1949-1950	C	C
1950-1951	C	C
1951-1952	W	C
1953-1954	W	C
1954-1955	C	C
1955-1956	C	C
1957-1958	W	C
1963-1964	W	C
1964-1965	C	C
1965-1966	W	C
1968-1969	W	C
1969-1970	W	C
1970-1971	C	C
1972-1973	W	C
1973-1974	C	C
1975-1976	C	C
1976-1977	W	W
1982-1983	W	W
1986-1987	W	W
1987-1988	W	W
1988-1989	C	W
1991-1992	W	W
1994-1995	W	W
1995-1996	C	W
1997-1998	W	W
1998-1999	C	C
1999-2000	C	C

Because a reliable list of ENSO event years is available only over 1949-2000 (Table 2), we truncated the foregoing hydrometeorological time series at those start and end dates, where applicable. Given the melt freshet-dominated nature of the Mission Creek hydrograph, we leave the data parsed into calendar years as downloaded, rather than rearranging into water (Oct – Sep) years. We make no attempt to adjust the observational hydrometric data for total water withdrawals, because reliable 1967-2000 monthly records of actual abstraction (as opposed to annual licenced maxima) do not appear to be available, and because we wish to determine the net effect of ENSO upon Mission Creek hydrology, including any interactions that may occur with local anthropogenic activities (see results and discussion section). For each time series, the mean annual cycle was removed and a month-by-month standardization to zero mean and unit variance was performed. For example, the standardized value of total monthly precipitation for the i^{th} January of a *N*-year January precipitation record was found by first subtracting the climatological average January precipitation (over all years) from the observed value for the i^{th} year, and then dividing the difference by the standard deviation of all January monthly precipitation observations. The same was done for each month, for each hydrometeorological record. The result consists of an anomaly time series giving the number of standard deviations away from the hydroclimatic normal. Using the same example, a yearly value of -1.0 would indicate a January total precipitation value for that year which is one standard deviation below the long-term average for that month.

Composite analysis consists of separating data into disjoint subsets on the basis of some external constraint, and then comparing the characteristics (typically, the means) of the two or more subsets. Here, the external constraint is ENSO state. Considering the historical monthly Mission Creek discharge record, for instance, we separate the standardized data into three subsets: one containing flow data for years during which an El Niño occurred, one containing flow data during La Niña years, and one containing discharge data for years during which no ENSO event occurred (the neutral case). This is done separately for each month of the year. For a given month of the year (say, June), the mean El Niño streamflow, mean La Niña streamflow, and mean neutral streamflow are then all calculated. Finally, whether these means are significantly different from each other is assessed using a Monte Carlo bootstrap procedure (resampling with replacement). An annual time series (of, say, June discharge) is constructed by drawing observations from the historical June record at random; the three composites are constructed; and the differences between the means are evaluated and stored. This procedure is repeated a large number of times (we use 10^4 here). For each comparison pair (e.g., mean El Niño June discharge versus mean neutral June discharge), an empirical cumulative distribution function of the absolute values of the differences between the means is constructed. If the absolute value of the difference between the means as found from the actual data is greater than the 95^{th} percentile value of the bootstrapped distribution, the observed difference is significant at $P < 0.05$. This testing method avoids distributional assumptions, and may offer some other technical advantages (see Edgington, 1995; Manly, 1997). The entire procedure is repeated for each month, then for each of the other environmental time series. All the foregoing steps are then repeated considering only those ENSO events which occurred in phase with the PDO, with out-of-phase ENSO events placed in the neutral subset.

As noted above, ENSO impacts are generally thought to peak during the winter, about December [0] through February [+1]. However, significant impacts can also occur later in the

[+1] year. Moreover, the typical cold-regions hydrograph (like that of Mission Creek) is such that wintertime hydroclimatic information content is, in effect, typically "stored" until the spring/summer snowmelt freshet. As a result, [+1] year hydrometeorological data are considered in this analysis. For example, we search the 1983 Mission Creek discharge data for evidence of hydrological impacts from the 1982-1983 El Niño.

Estimating summer temperature impacts to fish: present and future

As noted previously, near-continuous water temperature readings were recorded at mid-Mission Creek during 1998 and 1999 as part of a Forest Renewal BC project (**Figure 10**). For the purposes of this study, 5 to 10 years of data would have been optimal; however, by chance these two years capture a strong El Niño / La Niña swing (a warm and cool year) and therefore are sufficient at least for a cursory assessment.

To forecast impacts of climate change on Mission Creek salmonids, a coupled General Circulation Model (GCM) is downscaled to the Kelowna weather station, and then the relation between Kelowna air temperature and Mission Creek water temperature was used to forecast changes to stream temperatures, and hence impacts to fish. The Canadian Global Coupled Model 2 (C-GCM2) was statistically downscaled from the computational cell centred at 50.0995N 120.0000W to a Kelowna 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, 2050s, 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 a range of potential change. Time series results of forecasts from various emissions can be accessed through the Canadian Climate Impacts and Scenarios Project (www.cics.uvic.ca).

Although Webb and Nobilis (1997) point out that the relationship between air temperature and water temperature may not be one of cause and effect, despite the valid exchange of heat energy between water and air, a 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 Mission Creek summer water temperatures in the 2020s, 2050s, and 2080s, local air temperature forecasts were applied to Mission Creek water temperatures using the air temperature – water temperature (AT-WT) relationship. Since the relationship between air temperature and water temperature tends to flatten at very low and very high water temperatures, only water temperatures above 15°C were considered. These were linearly regressed against air temperature 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.

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°C during the day and decreased by 2°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 acute 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 amplifier centred at the diurnal frequency band.

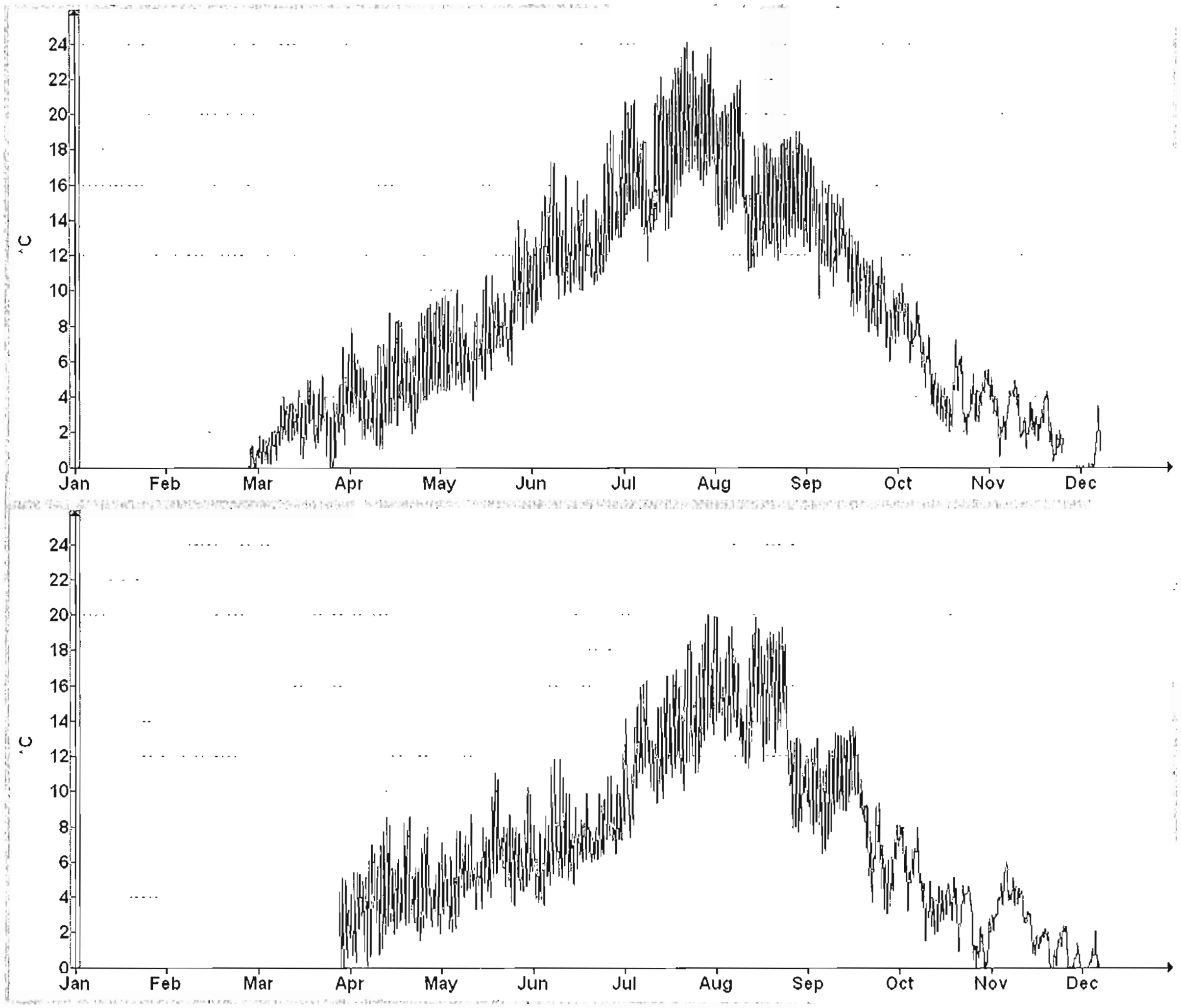


Figure 10. Observed Mission Creek stream temperatures during 1998 (top) and 1999 (bottom).

Environmental Risk Assessment for Lethal (Acute) Effects

Environmental risk assessment is designed to combine the information from biological studies with an analysis of a population's exposure to quantified effects. Risk occurs when the magnitude, frequency, and duration of environmental stress exceed the ability of the organism 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 (anadromous rainbow trout) can tolerate short durations (minutes to seconds) of very high temperatures (above 28°C) better than other salmonids; however, they are not as tolerant to long durations (weeks to months) in warm temperatures (20-24°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 were taken from Brett (1952), Alabaster and Downing (1956), Craigie (1963), and 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 not consider local populations' behavioural or evolutionary adaptations to warmer temperatures.

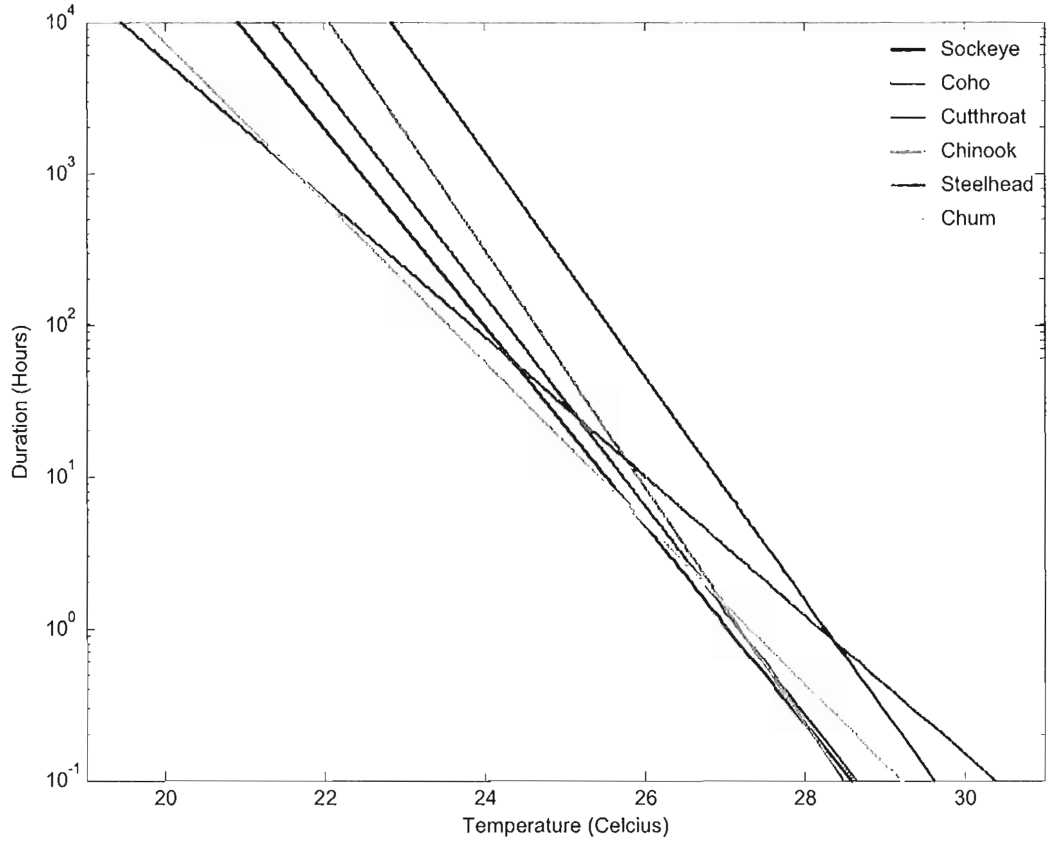


Figure 11. Temperature LT10 exposure curves for salmonids. Mortalities increase exponentially to the top-right of the curves.

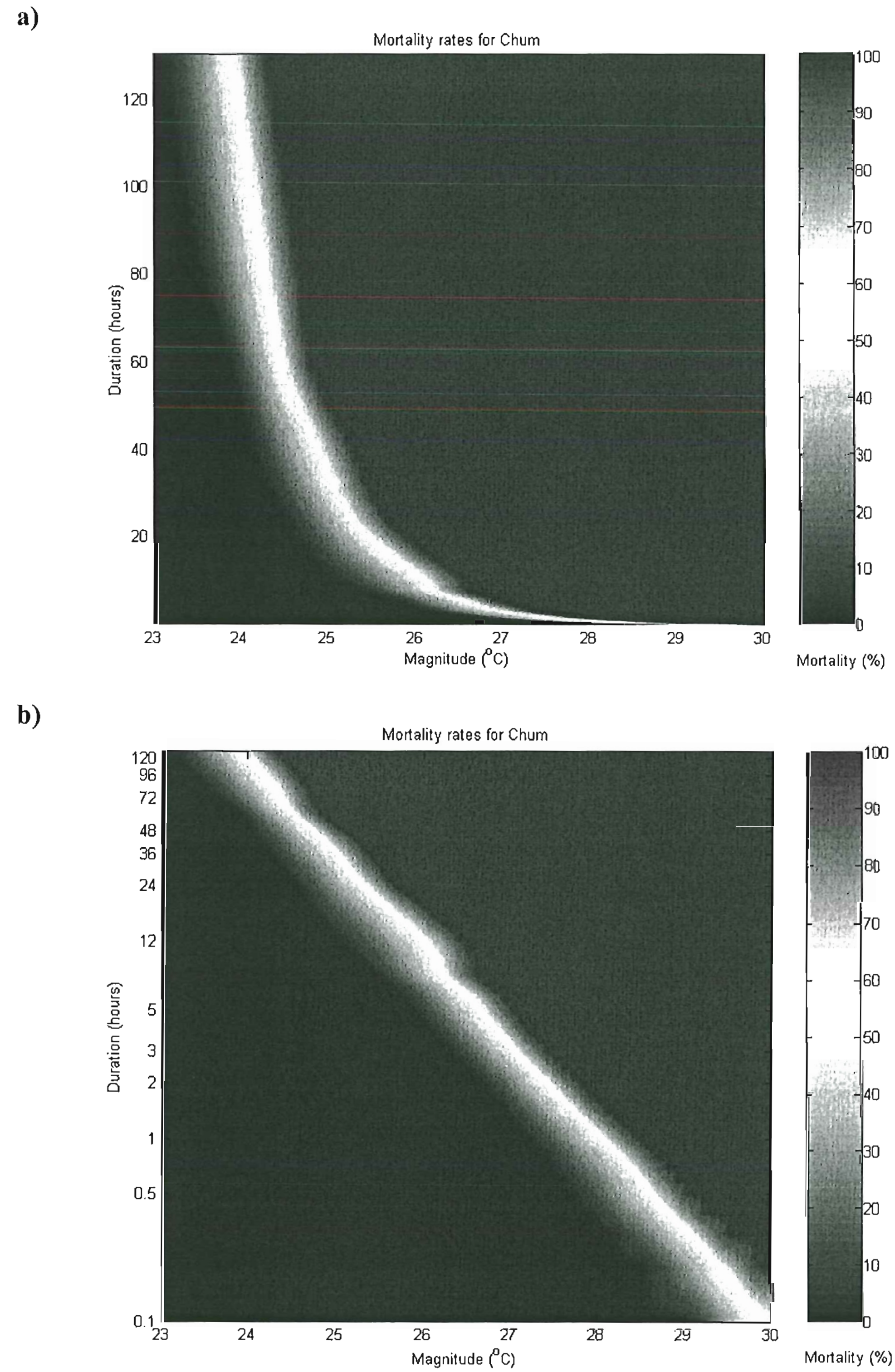


Figure 12. Interpolated lethal exposure times for chum salmon, a) linear scale, and b) log scale. An illustration of how mortality increases at a near-exponential rate above the LT10.

The magnitude and duration of all temperature events in Mission Creek greater than 20°C were determined using an Automated Risk Assessment script developed by Aquatic Informatics Inc., and previously used to assess increases in acute thermal risks to British Columbia salmonids under potential climatic changes (Quilty *et al.*, 2004d). 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.

Environmental Risk Assessment for Sublethal (Chronic) Effects

In this section, we consider increases in sublethal or chronic (cumulative) temperature risks to salmonids in Mission Creek under various climatic change scenarios. In contrast to acute risks, which are defined in terms of immediate fish mortality, chronic risks consist of sub-lethal temperature impacts which can compromise the overall viability of salmonid populations. Note that chronic impacts are incurred at considerably lower water temperatures than acute risks. Acute risks to salmonids generally start at roughly 24°C, whereas (for example) sub-optimal steelhead/rainbow trout growth rates begin to be experienced at about 14°C. Like acute risks, however, the emphasis lies upon the summer period (approximately June to September), when British Columbia stream temperatures are highest and potentially in the range at which acute risks or chronic growth risks occur.

The same historical and potential future temperature regimes considered in the foregoing acute risk assessment were used here (see below). 1998, warm year; 1999, cool year; 1998 and 1999 temperature regimes forecast to 2020, 2050, and 2080 under A2 and B2 scenarios. Thus, similar caveats apply to the chronic risk results: we have limited historical data from which to project potential future thermal regimes for Mission Creek, and the water temperature forecasts omit the potential effects of changes in streamflow. The assessment must therefore be considered a tentative, albeit instructive, exploration of potential climatic change impacts upon Mission Creek fisheries resources.

The chronic risk assessment uses the magnitude-duration method introduced and explained in detail by Fleming *et al.* (2004) and Fleming and Quilty (in review). Readers should refer to those publications for a full explanation of the method. In summary, the approach has the following general properties. (i) It uses temperature impacts on growth as a measure of chronic temperature risk. Chronic risks are quantified as total growth risk (*TGR*), the loss in percent yearly growth due specifically to high daily mean water temperatures, relative to the growth that would have occurred if days of temperature exceedance had instead shown optimal mean temperatures. (ii) It explicitly incorporates the effects of both magnitude and cumulative duration of high daily mean water temperatures. (iii) It adjusts the result for local watershed conditions, so that a naturally warm system is much less likely to be identified as being thermally polluted, and a naturally cool system is more closely monitored for ecologically harmful changes in thermal regime. (iv) The method expresses the net result both graphically and as a risk quotient, closely analogous to that used in toxicological risk assessments, leading to a simple but robust and rigorous decision rule for watershed managers. Specifically, a yearly risk quotient, *RQ*, greater than 1 indicates abnormally high chronic temperature risk, and cause for environmental management concern and potentially corrective action. In contrast, a risk quotient less than or equal to 1 indicates that there is no immediate cause for management concern.

However, *RQ* calculation requires a reasonably substantial historical temperature record, which is not available for Mission Creek. In the current application, then, we present our results primarily in terms of *TGR*, which does not explicitly adjust for the natural variability in thermal regime between river basins. Nevertheless, we also calculate a risk amplification factor, *f*, which is the ratio of future *TGR* under climatic warming to historically observed *TGR* for each of 1998 and 1999. This factor is closely analogous to *RQ*.

Results and Discussion

Observed Air Temperature Trends in Kelowna (1902 – 2002)

Reconstructed daily mean air temperature data from Kelowna is displayed as a 3D surface plot in **Figure 13**. Each year, starting in 1902, is stacked one after another showing seasonal and annual variation throughout the record. The same plot is shown viewed directly from above in **Figure 14**. Mean daily temperatures generally approach 25°C in summer and less than –15°C in winter. Trends in the data are examined using asymmetric 2D wavelet smoothing (see Quilty *et al.*, 2004a for details). This is a low-pass filter which increases the signal-to-noise ratio of the data, where (in this context) the signal is long-term monotonic trend, and all other time series components are taken to be noise. **Figure 15** shows the Kelowna air temperature data smoothed at the 4th level (2^4 or 32 days) across days, and the 2nd level (4 years) across years. A general warming trend is observed during summers and winters, and summers appear to be becoming longer. **Figure 16** shows the same data smoothed further (32 days and 64 years), and shows a similar trend.

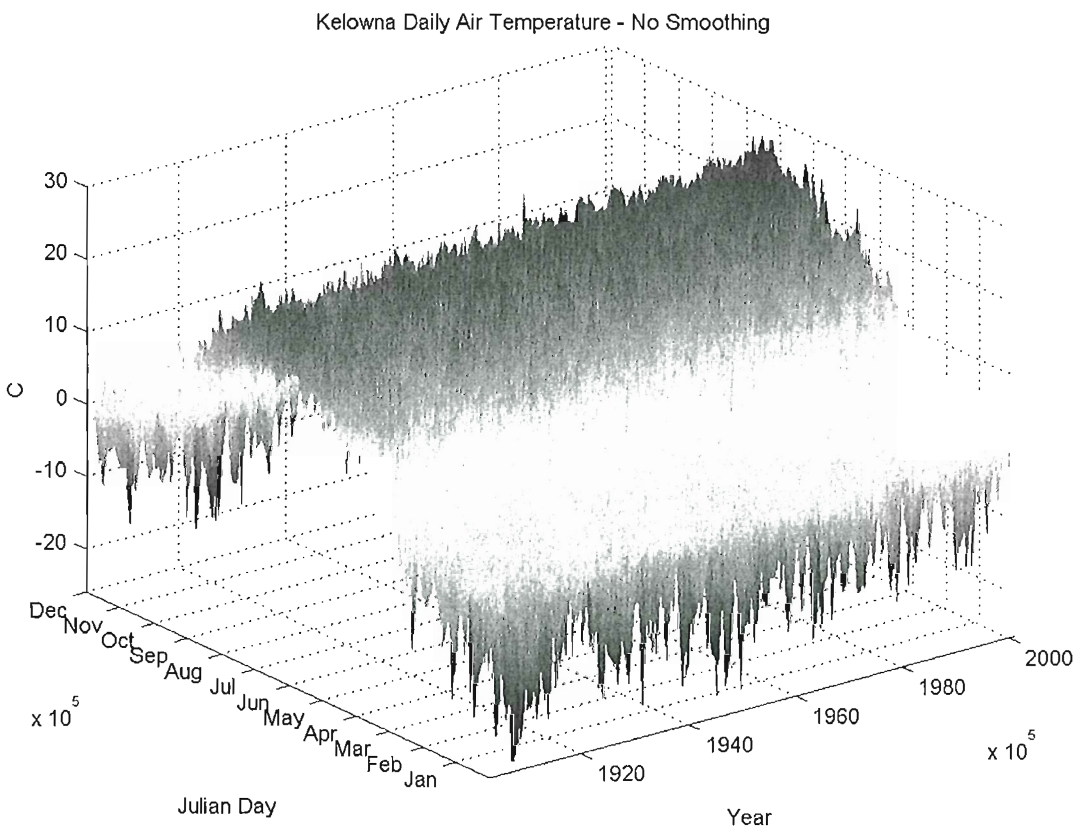


Figure 13. Surface plot of yearly profiles of Kelowna daily mean air temperature (°C).

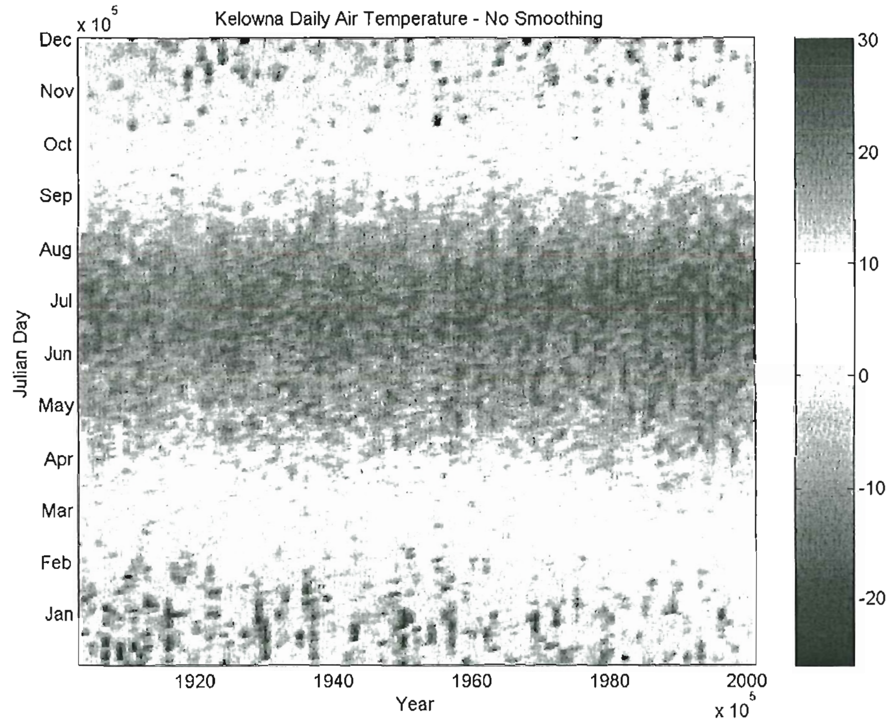


Figure 14. Colour map of Kelowna daily mean air temperature (°C).

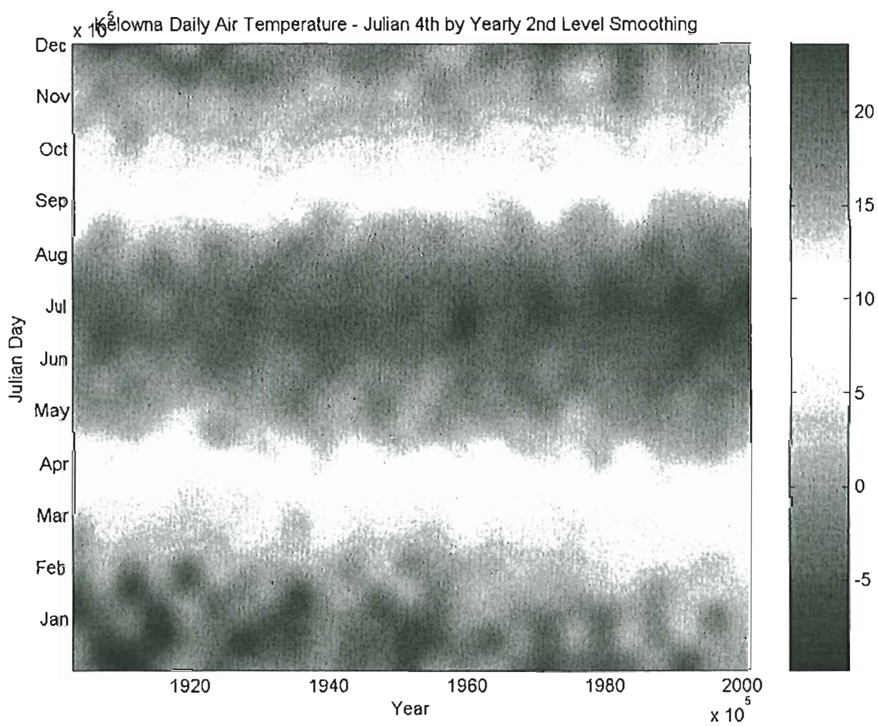


Figure 15. Wavelet smoothing (4th and 2nd levels) of Kelowna daily mean air temperature (°C).

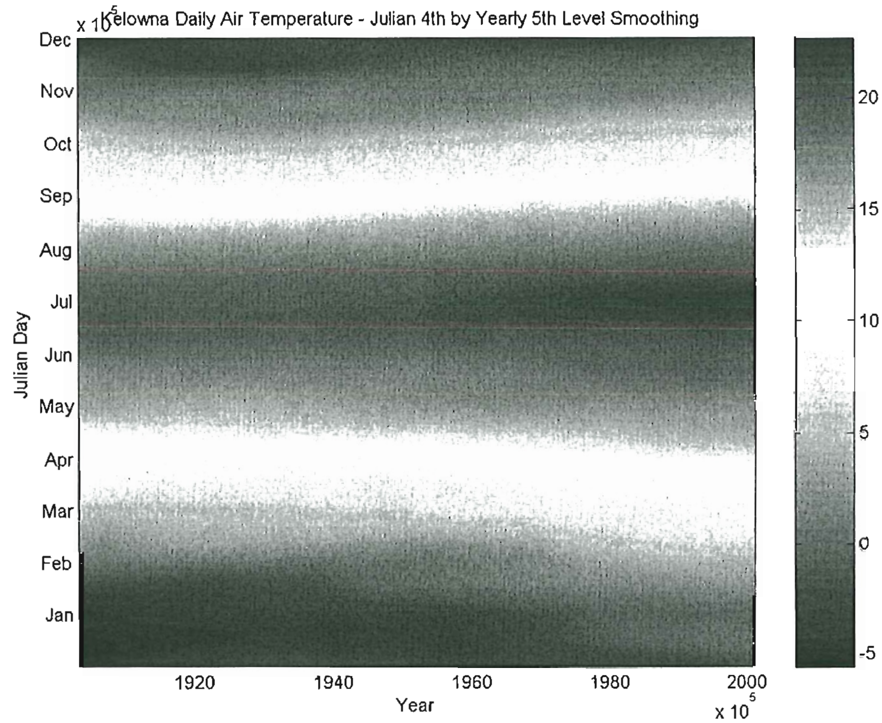


Figure 16. Wavelet smoothing (4th and 5th level) of daily mean air temperature (°C).

The Mann-Kendall statistic and the Theil-Sen slope estimator were used to quantify the trends at high temporal resolutions (seasonal, monthly, and daily). Results are shown in **Figure 17**, **Figure 18**, and **Figure 19**, and summarized in **Table 3**. Seasonal trend analysis suggest that between 1902 and 2002, mean daily temperatures in Kelowna increased by about 4°C during winter, 3.4°C during spring, 2.4°C during summer, and 2.6°C during fall (**Figure 17**). All but the winter trends are strongly significant. Results for trends at a monthly resolution are quite variable, even within seasons (**Figure 18**). For example, trends for December, January, and February were estimated to be 1.7°C, 3.9°C, and 5.6°C respectively. However, none of the estimates of trends across months were statistically significant at $P < 0.05$ (1-tailed test). Trends for April, August, September, and October were significant at $P < 0.10$. Trends within months (daily) were even more variable, and none were significant at $P < 0.10$ (**Figure 19**).

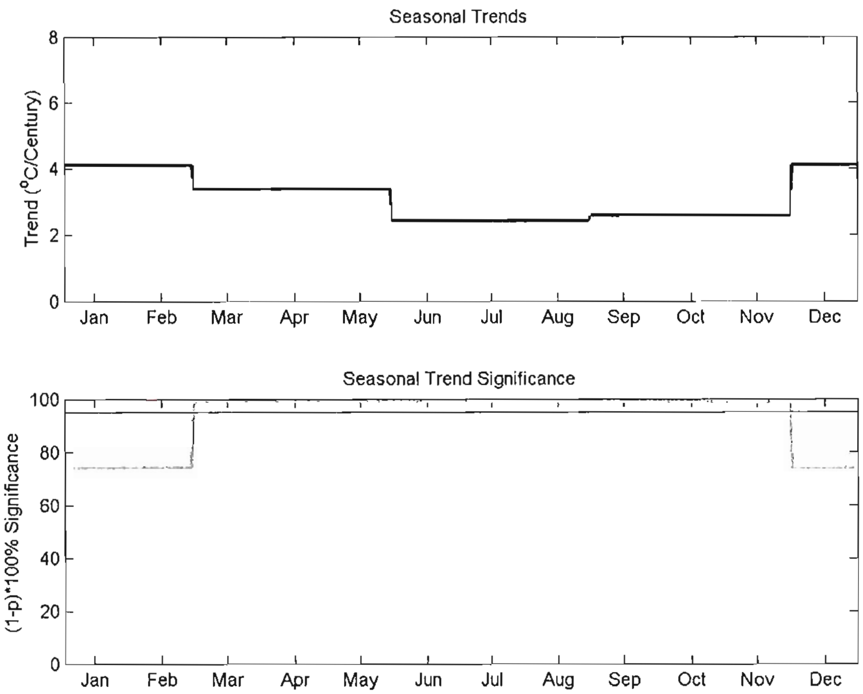


Figure 17. Seasonal trends in Kelowna mean daily air temperature (top) and statistical significance of the trends (bottom). $P = 0.05$ is marked with a grey line (~95% confidence).

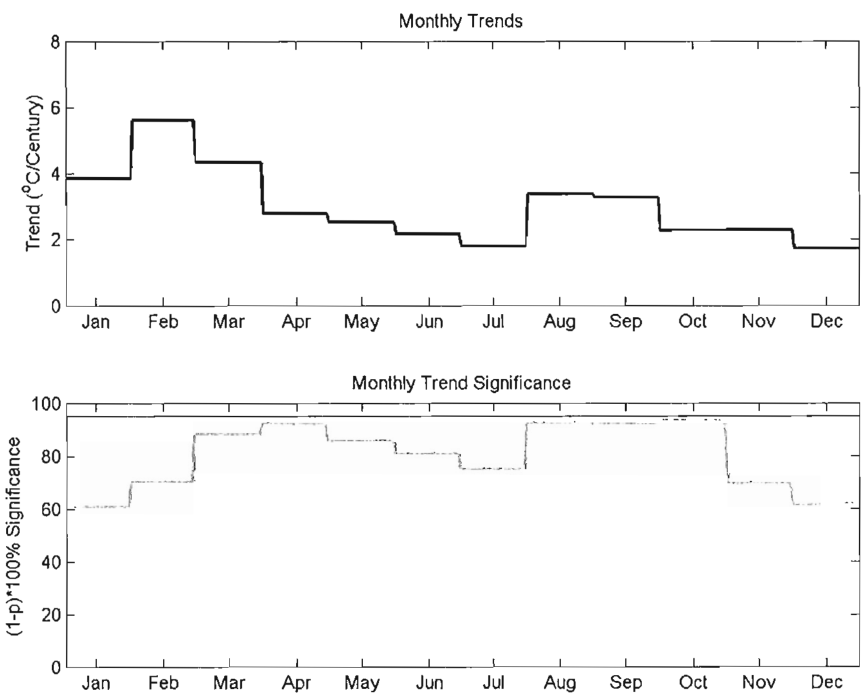


Figure 18. Monthly trends in Kelowna mean daily air temperature (top) and the statistical significance of the trend (bottom). $P = 0.05$ is marked with a grey line (~95% confidence).

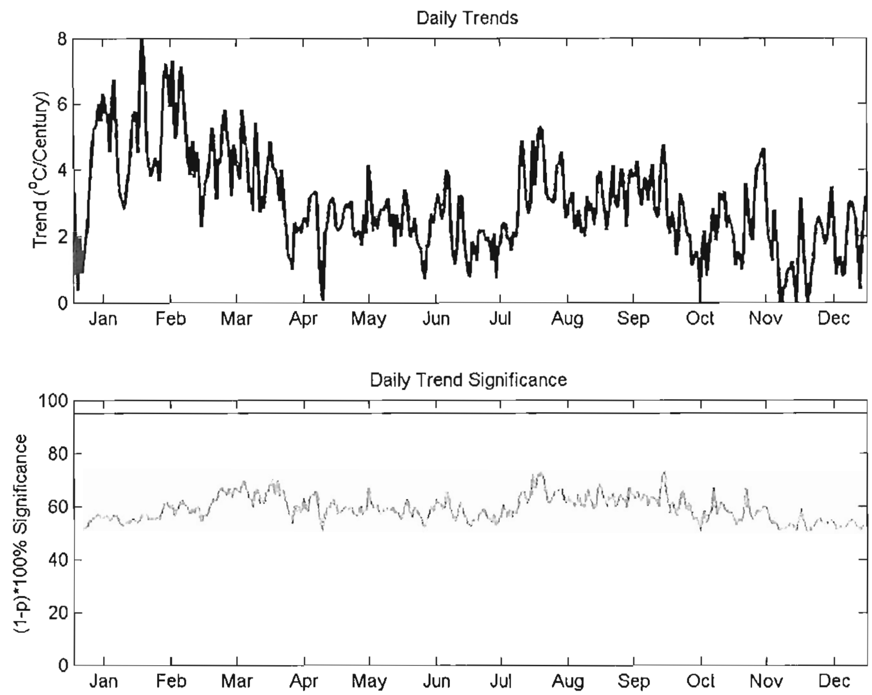


Figure 19. Daily trends in Kelowna mean daily air temperature (top) and statistical significance (bottom). $P = 0.05$ is marked with a grey line (~95% confidence).

Table 3. Seasonal and monthly increases in mean air temperature in Kelowna, 1902-2002. * denotes statistical significance at $P = 0.05$.

Season	Increase (°C) over 1902-2002	Month	Increase (°C) over 1902-2002
Winter	4.1	December	1.7
		January	3.9
		February	5.6
Spring	*3.4	March	4.3
		April	2.8
		May	2.5
Summer	*2.4	June	2.2
		July	1.8
		August	3.4
Fall	*2.6	September	3.4
		October	2.3
		November	2.3

Results from our trend analysis (at seasonal resolution) are compared to results from other studies in **Table 4**. In general, our trend estimates for Kelowna are approximately double those found for the Southern Interior (MWLAP, 2001b) and for Summerland (Taylor, 2005). Our results could be different for several reasons: (i) we used daily mean air temperatures while others have used annual daily extremes; (ii) we used 2D wavelet smoothing while others used decimation; and (iii) we used reconstructed, not homogenized, data. To examine these differences further, we compared our reconstructed Kelowna air temperature data to the homogenized Summerland data used by Taylor (2005). There was a noticeable upward trend in the difference between these two time series, accounting for nearly 1.5°C of additional warming in Kelowna. We felt this might be due to the "heat island effect" (i.e. the heating influence of localized urban sprawl), so we binned and linearly interpolated the residual to dates in which population estimates (BC Stats.) were available for the City of Kelowna (**Figure 20**). There appears to be an approximate correlation between population growth and increased warming in reconstructed Kelowna data, which supports our interpretation of a more local heat island effect in addition to the regional climate warming.

Table 4. Comparison of climate change trend estimates (past century) from various studies.

Study: Study Area: Measure	This report Kelowna Daily Mean AT (°C)	Taylor (2005) Summerland Annual Daily Min AT (°C)	MWLAP (2001b) Southern Interior Not reported (°C)
Winter	4.1	3.6	1.8
Spring	3.4	1.4	1.2
Summer	2.4	0.6	0.9
Fall	2.6	0.8	0.8

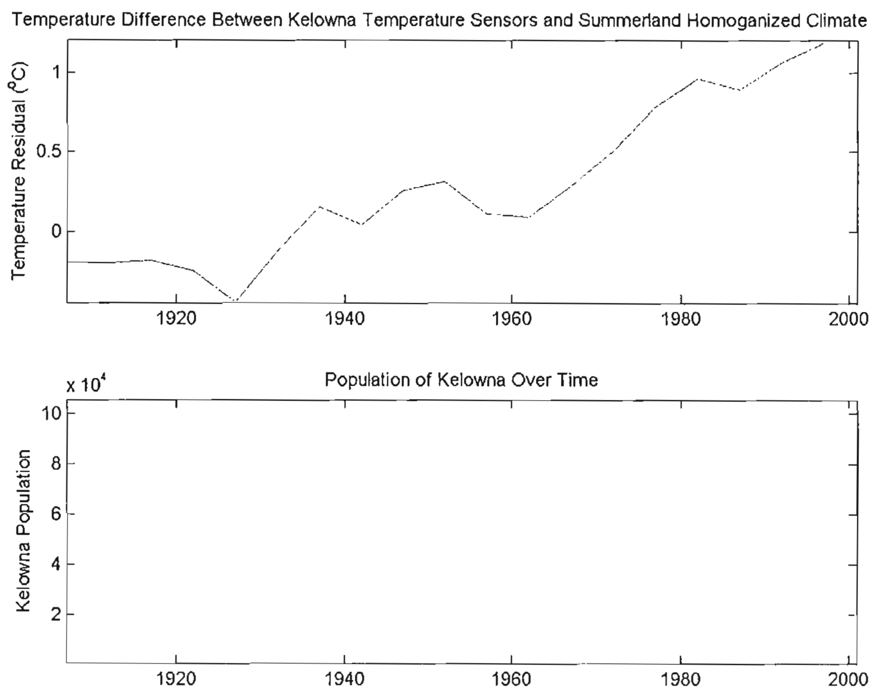


Figure 20. Trends in increased warming in Kelowna reconstructed data over Summerland homogenized data (top) and population growth in the City of Kelowna (bottom).

Important Findings:

1. Over the last century, mean daily air temperature in Kelowna appears to have:
   a. Increased by more than 4°C during winter.
   b. Increased by more than 3.4°C during spring.
   c. Increased by more than 2.4°C during summer.
   d. Increased by more than 2.6°C during fall.
2. In general, these trends in Kelowna air temperature are nearly double those estimated by other researchers for the southern interior and for Summerland. A difference of as much as 1.5°C appears to be due to a heat island effect associated with population growth in the City of Kelowna.

Observed Precipitation Trends in Kelowna (1902 – 2002)

Daily precipitation records for Kelowna were reconstructed and organized much the same way as was done for air temperature. For visualization of the data, wavelet smoothing was performed at level 4 across days (16 days) and level 5 across years (32 years) (**Figure 21**). This figure suggests that precipitation has been increasing during spring and summer in recent years. To estimate the trends, 30-day averaging across days was completed, and the Mann-Kendall trend statistic was evaluated (**Figure 22**). Results are reported in **Table 5**. These results suggest that precipitation has increased by approximately 80 mm in Kelowna since 1902, with most of the increase coming during spring and summer. The total increase is similar to that found by Cohen and Kulkami (2001), who estimated it to be about 125 mm.

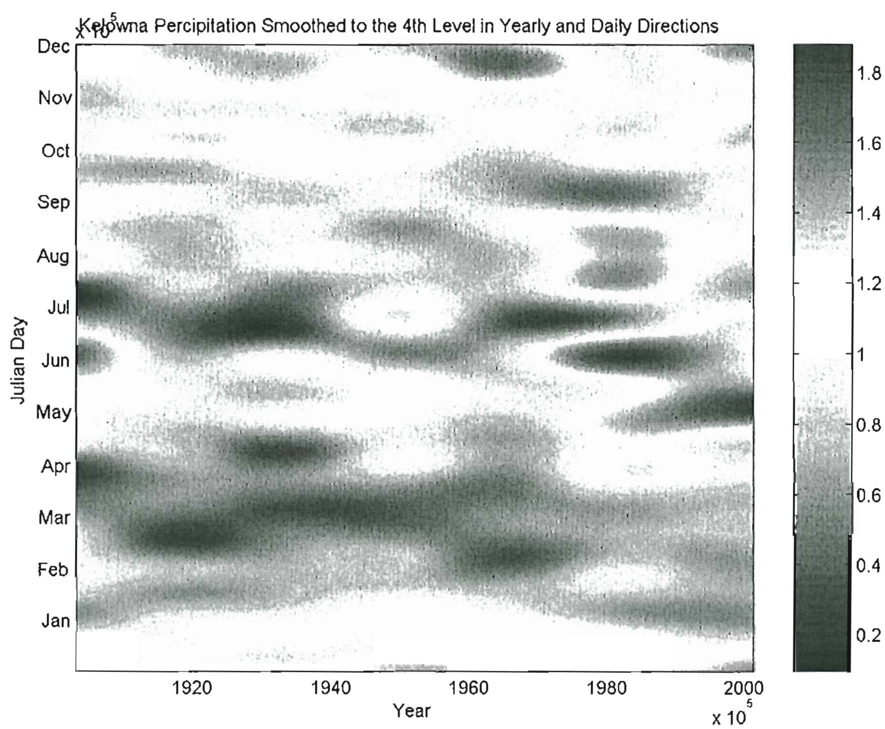


Figure 21. Wavelet-smoothed (4th level) Kelowna precipitation (mm/day), 1902-2002.

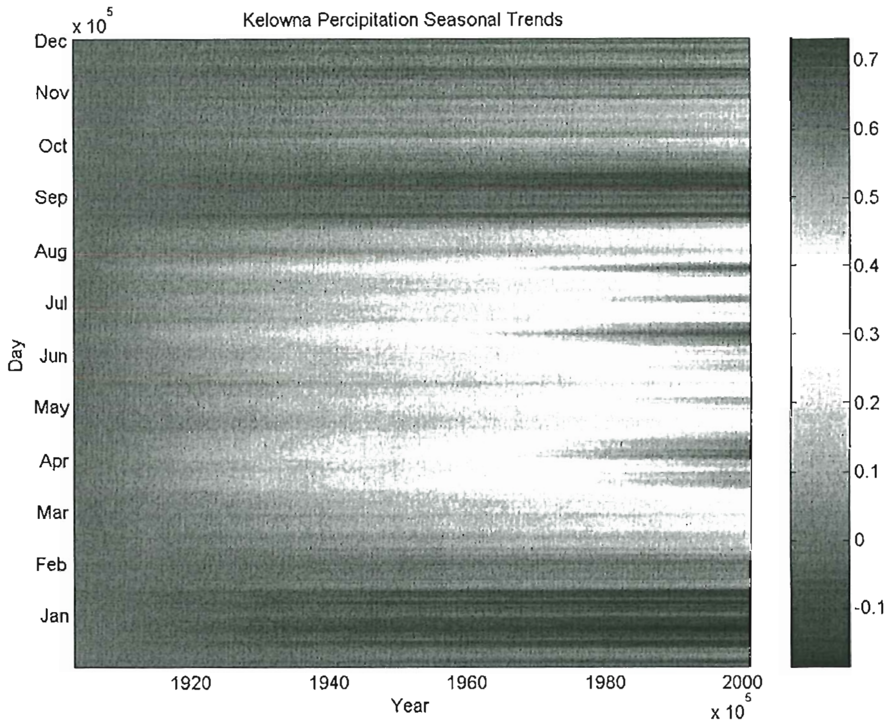


Figure 22. Precipitation trends (mm/day) for Kelowna.

Table 5. Annual, seasonal, and monthly increases in daily precipitation in Kelowna, 1902-2002. Results that are marked * are significant at $P = 0.10$.

Increase In Precip. (mm) 1902-2002	Season	Increase In Precip. (mm) 1902-2002	Month	Increase In Precip. (mm) 1902-2002
77	Winter	0	December	0
			January	0
			February	0
	Spring	34.8	March	6.0*
			April	14.1*
			May	14.7*
	Summer	33.6	June	9.6*
			July	13.2
			August	10.8
	Fall	8.1	September	8.1
			October	0
			November	0

Important Findings:
3. Over the last century, yearly total precipitation in Kelowna appears to have increased by approximately 80 mm (25%), most coming during spring and summer.

Observed Effects of Climatic Cycles on the Hydrology of Mission Creek

All ENSO Events

Results of composite analyses considering the effects of all 1949-2000 ENSO events, without regard to PDO phase, are shown in **Figure 23**, **Figure 24**, and **Figure 25**. The red line shows the average value during a warm-phase (El Niño) event, the blue line denotes the average value during a cold-phase (La Niña) event, and the black line indicates the average value during neutral years. Red, blue, and green circles indicates monthly means which are different at $P < 0.05$ between, respectively, El Niño and neutral years; La Niña and neutral years; and El Niño and La Niña years. Recall that the annual cycle was removed from the data prior to construction of the composites.

We focus our discussion upon El Niño impacts. During a warm-phase ENSO year, Mission Creek shows, on average, lower streamflow over about June through September. Precipitation does not show as strong or consistent a signal, but judging from the significance test results, it may be generally somewhat lower. Temperature is clearly and substantially higher from about February through June.

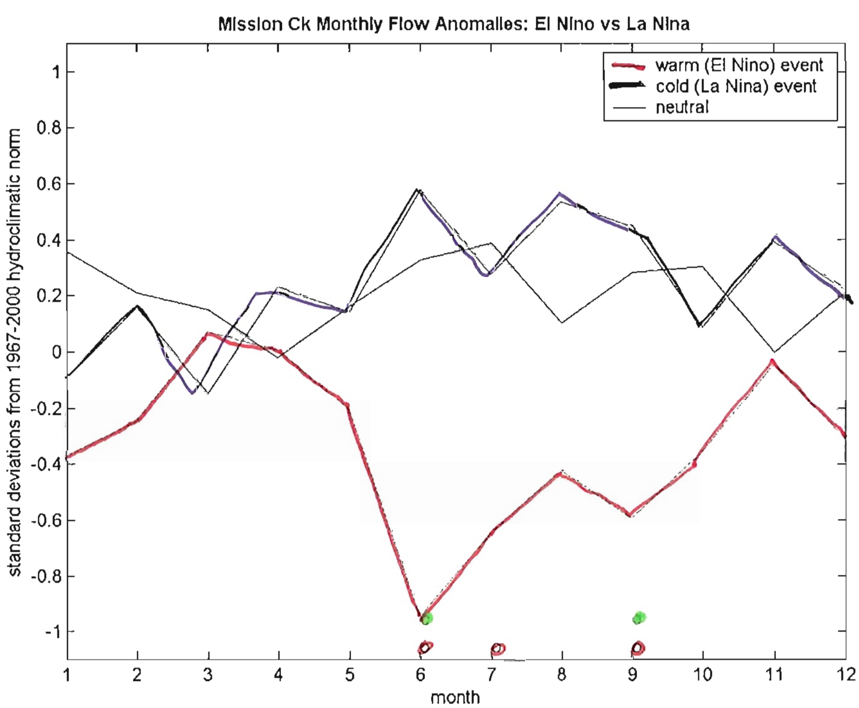
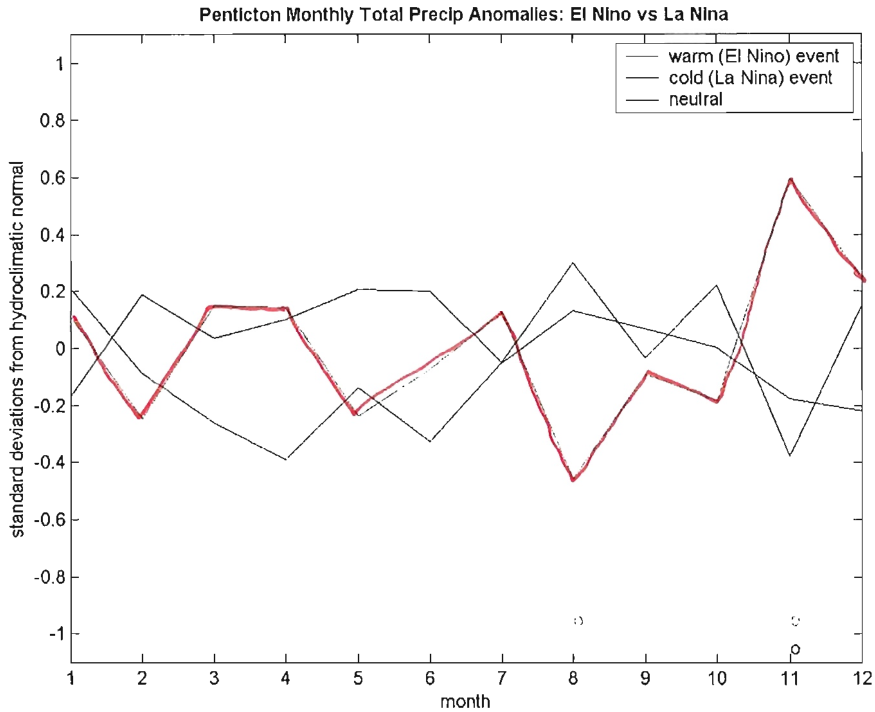
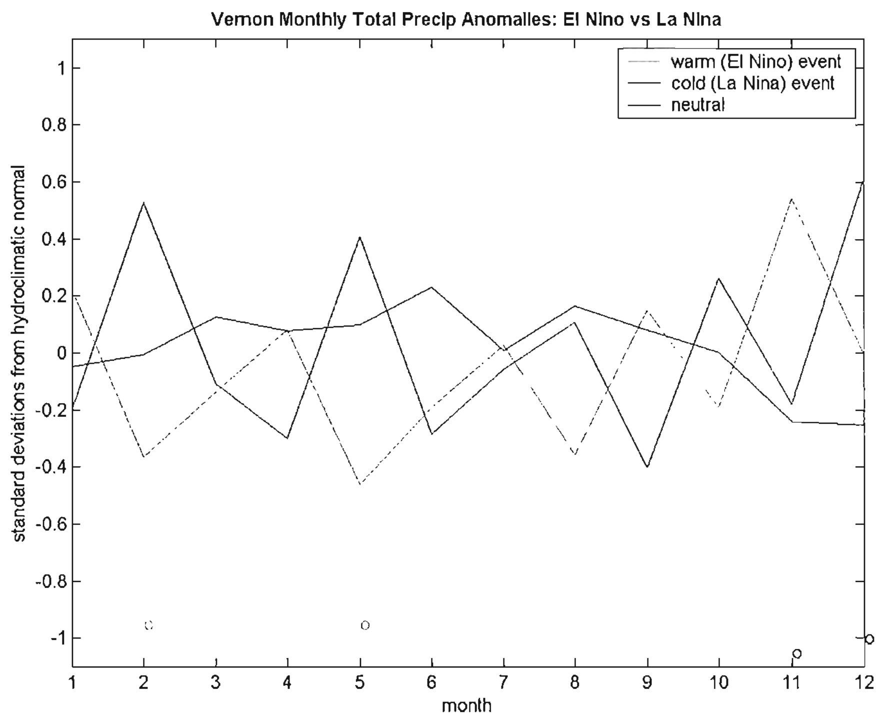


Figure 23. Comparison of Mission Creek monthly flow anomalies for all 1949-2000 ENSO events. See text for explanation of red, blue, and green circles.



(a)



(b)

Figure 24. Comparison of a) Penticton and b) Vernon monthly total precipitation anomalies for all 1949-2000 ENSO events. See text for explanation of red, blue, and green circles.

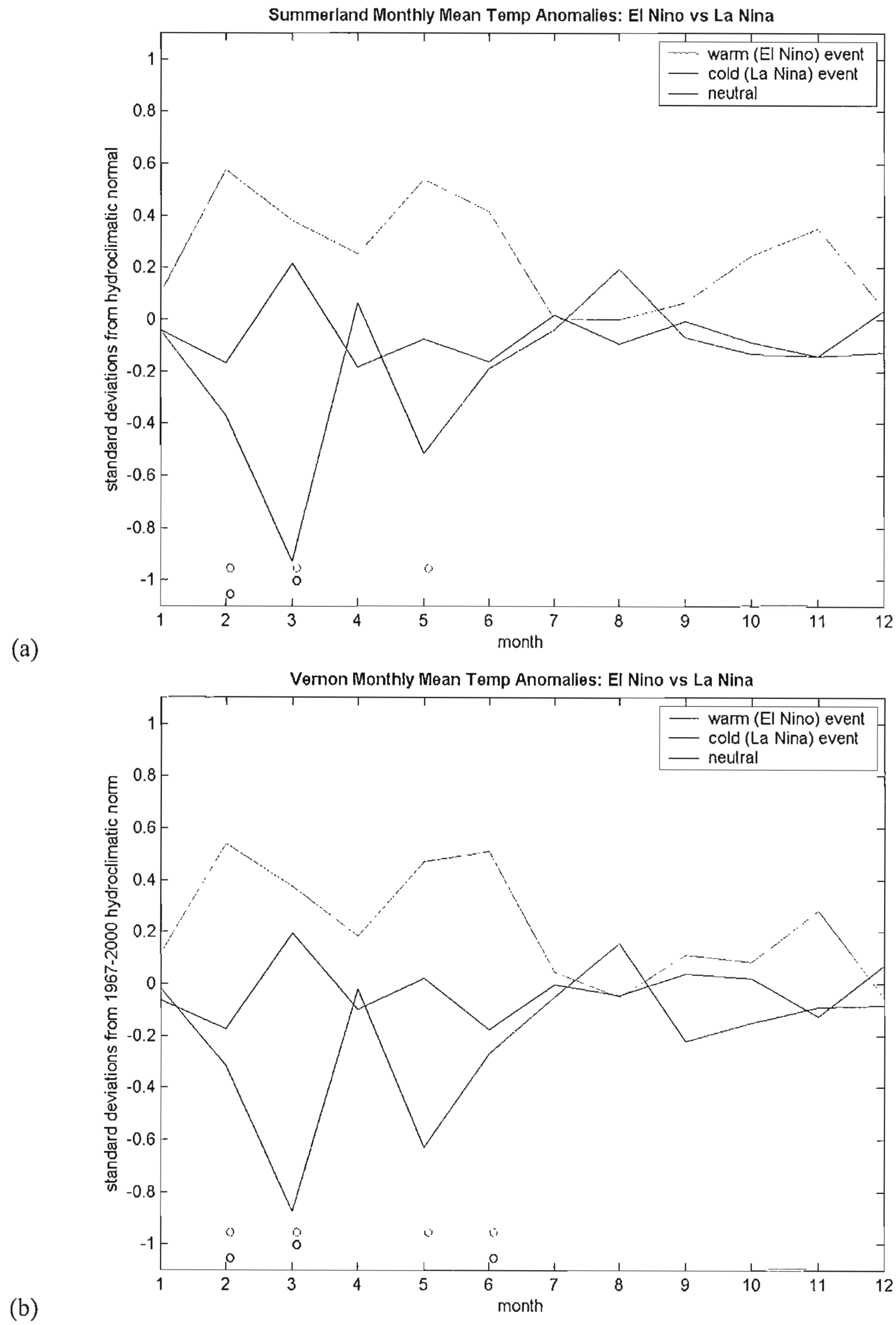


Figure 25. Comparison of s) Summerland and b) Vernon monthly mean air temperature anomalies for all 1949-2000 ENSO events. See text for explanation of red, blue, and green circles.

We interpret these results as follows. Higher spring temperatures could conceivably give an earlier freshet and, therefore, a positive streamflow anomaly in spring. However, possibly slightly lower spring precipitation may balance this effect, explaining the lack of an observed positive discharge anomaly. The dominant hydrologic effect, however, is the June through October negative streamflow anomaly, which we interpret to arise from slightly lower precipitation and, in particular, substantially higher temperature. The latter may raise evapotranspiration losses during the spring and early summer, reducing both discharge over this period and the stored (aquifer) water available for late summer and fall baseflow. Increased water withdrawals from Mission Creek for irrigation or livestock watering, for example, in response to the increased summer air temperatures associated with El Niño could also play a role. Inspection of the Land and Water British Columbia online water license database revealed a total of 154 current or pending licenses for water withdrawals from Mission Creek. Considering only current licenses, total authorized withdrawals come to an average of 1.1 m^3/s, a substantial proportion of the annual mean 1967-2000 streamflow of 6.4 m^3/s, although of course observed discharges in turn reflect historical water withdrawals. It is also unclear how much of the licensed capacity is actually used, although MWLAP (2001a) suggest that these withdrawals may account for up to one-third of total flow, depending on the year. Water withdrawals from Mission Creek certainly occur to some degree, and these may be greater during El Niño years due to higher summer air temperatures, potentially helping to explain associated negative discharge anomalies.

Important Findings:

4. During El Niño years:
   a. Mission Creek streamflow is lower from June to September.
   b. Precipitation in the Okanagan is generally somewhat lower.
   c. Air temperature in the Okanagan is substantially higher from February through June.

PDO-Modulated ENSO Events

Results of composite analyses considering only those ENSO events with the same phase as the PDO are shown in **Figure 26**, **Figure 27**, and **Figure 28**. The colour scheme is the same as that for the previous section. We again focus on El Niño effects. Streamflow anomalies associated with in-phase warm events consist of somewhat higher-than-average spring discharge, and substantially lower flows over about May through September. However, the difference is significant at $P < 0.05$ only for June. Associated precipitation anomalies are somewhat inconsistent and weak, but higher precipitation does appear to occur in spring (particularly April). Temperature shows a very strong and consistent positive anomaly, especially over February through June.

Our interpretation of the composites is that, in spring, slight rainfall increases combine with higher temperatures (and therefore increased early snowmelt) to give a moderate positive discharge anomaly. However, continued very high temperatures (almost a full standard deviation greater than the 1949-2000 climatic normal) lead to substantial evapotranspiration losses and decreases in summer discharge. As noted in the previous section, potentially higher water withdrawals for agricultural and other purposes, in response to the much higher early summer air temperatures associated with warm-phase events, might conceivably further contribute to the observed negative discharge anomaly.

Important Findings:

5. During in-phase (warm PDO regime) El Niño years:
    a. Mission Creek streamflows are higher during March and April, and lower during May to September (though only significant in June).
    b. Precipitation in the Okanagan appears to be higher during spring.
    c. Air temperature in the Okanagan is substantially higher from February through June.

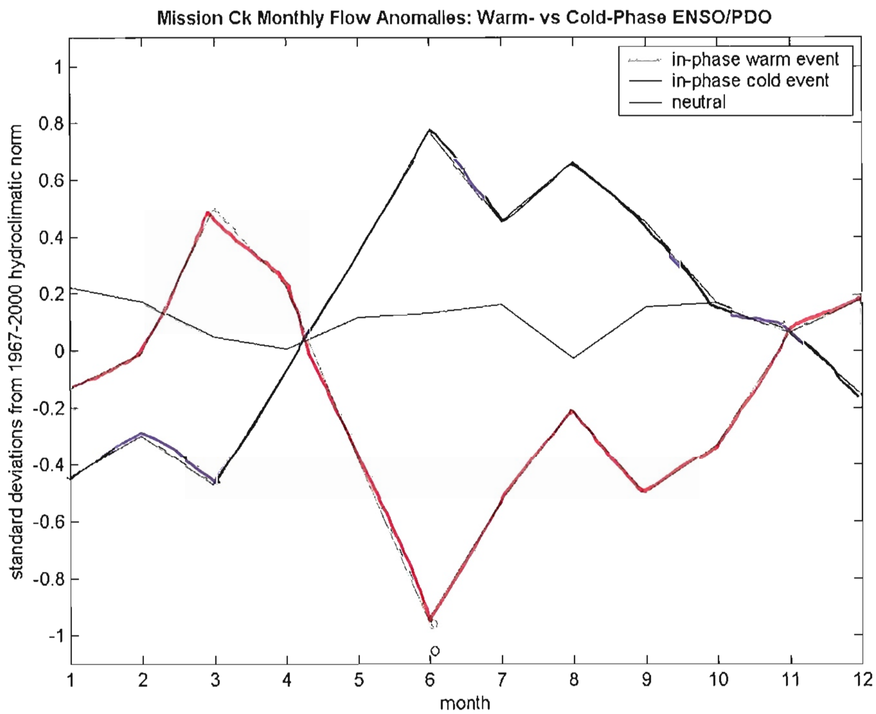
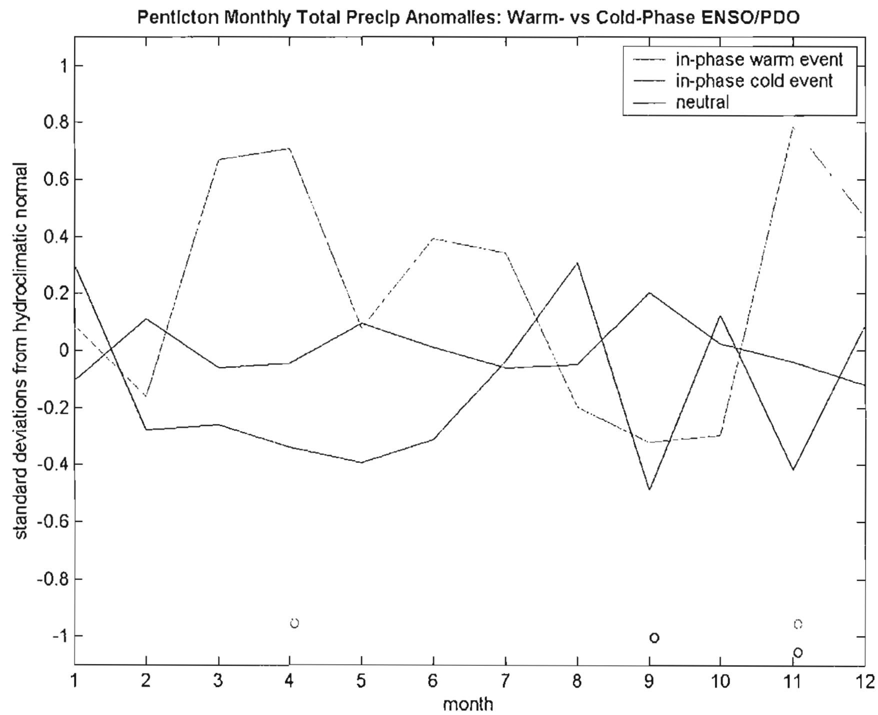
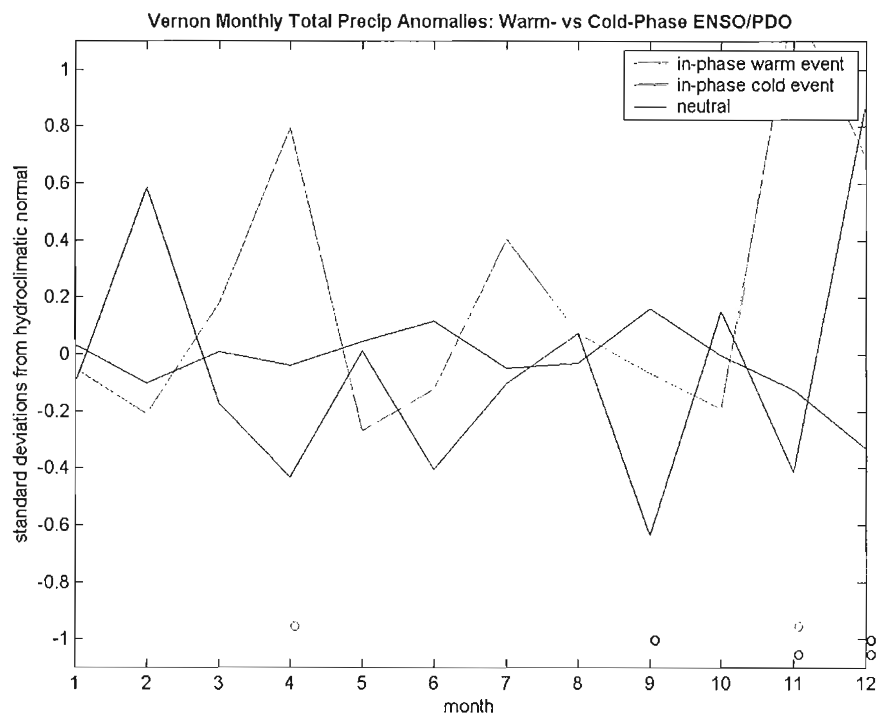


Figure 26. Comparison of Mission Creek flow anomalies for all in-phase 1949-2000 ENSO events.

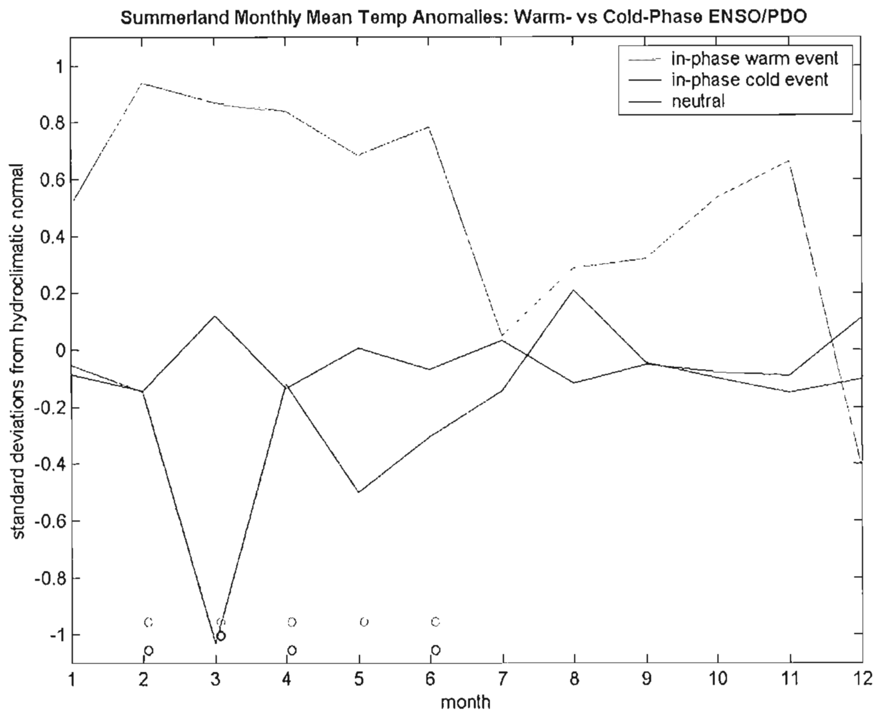


(a)

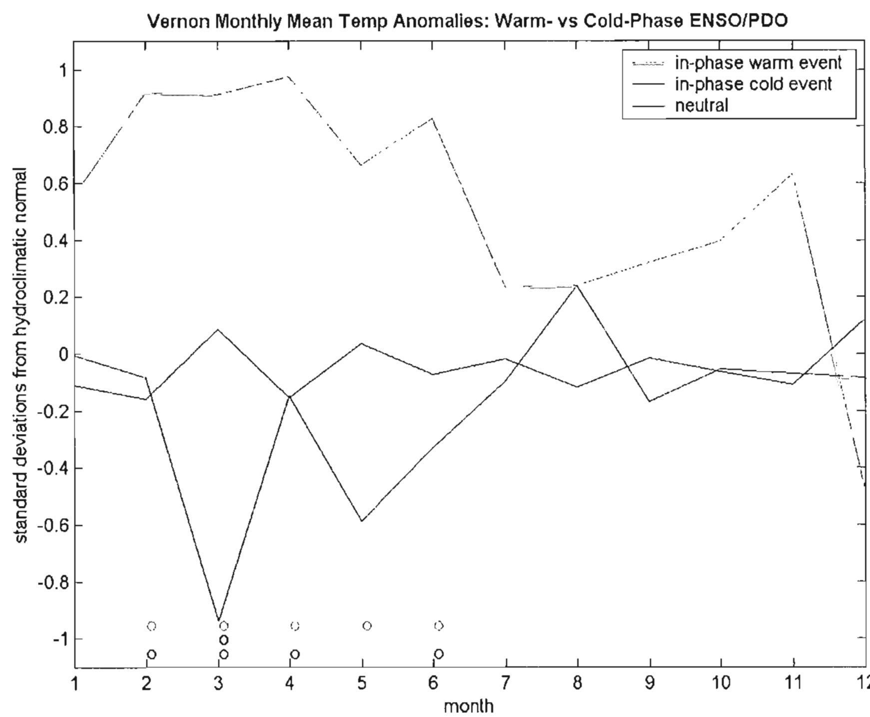


(b)

Figure 27. Comparison of a) Penticton and b) Vernon monthly total precipitation anomalies for all in-phase 1949-2000 ENSO events.



(a)



(b)

Figure 28. Comparison of Summerland monthly mean temperature anomalies for all in-phase 1949-2000 ENSO events.

ENSO / PDO Impacts on Hydrology: Discussion and Additional Analysis

While the cold- and warm-phase ENSO responses are seen to be rough opposites of each other, local hydrometeorological impacts of El Niño appear to be substantially greater than those associated with La Niña. This likely reflects the well-recognized nonlinearity of extratropical ENSO teleconnections (*e.g.*, Hoerling *et al.*, 1997). It is also interesting to note that composites considering all 1949-2000 ENSO events suggest local hydrometeorological impacts which are somewhat different not only in degree, but also in nature, from those constructed using only those ENSO events in phase with the PDO. This is particularly for precipitation. Nevertheless, temperature effects are similar between the two approaches. Most importantly for our present purposes, the net hydrological impacts are also generally similar.

We took a second look at discharge impacts by regressing annual mean Mission Creek discharge against the annual mean December through February (DJF) Southern Oscillation Index (*SOI*), and the average of the DJF PDO index and –*SOI*, which we refer to here as the modulated Pacific index (*MPI*). The negative of the *SOI* is used so that climate index anomalies reflecting warm ENSO and PDO phase are of like sign; otherwise, the PDO index and *SOI* would mutually cancel in the average. The *MPI* incorporates, in an approximate way, the mutually reinforcing or mutually cancelling effects of in-phase and out-of-phase events. This seems a more appropriate approach for our present purposes than a multiple linear regression between discharge and the ENSO and PDO indices. Note that negative *SOI* values (the standardized difference in SLP between Tahiti and Darwin) indicate warm-phase conditions, whereas negative *MPI* values indicate cold-phase conditions. Consistent with the approach outlined previously, DJF index values are assigned to the JF (i.e., [+1]) year and compared with [+1] annual mean discharge. The regression procedure assumes linearity. This is not strictly satisfied for ENSO impacts (see composites and Hoerling *et al.*, 1997); failure to fully meet this assumption will obscure relationships. Gaussian data distributions are also assumed. This is readily checked for the three time series considered in the regression analyses, and was found to be reasonable. Results are shown below in **Table 6**.

Table 6. Results for simple linear regressions between indices of large-scale ocean-atmosphere circulation and annual mean Mission Creek streamflow.

Model	**Slope**	**Intercept**	***R***	***P***
Discharge = f (*SOI*)	0.289	6.32	0.31	0.06
Discharge = f (*MPI*)	-0.548	6.32	-0.38	0.02

The regression results suggest that streamflow is more strongly controlled by the combination of ENSO and PDO (strongly significant, $P < 0.02$) than by ENSO alone (marginal, $P < 0.06$), which contrasts somewhat with the significance testing results from the composite analysis. A potential explanation is that, judging by the degree to which the various composites reveal La Niña and El Niño discharge effects to be simple mutual opposites, Mission Creek streamflow responses to PDO-reinforced ENSO events are considerably more linear relative to those associated with all ENSO events regardless of PDO phase. For example, mean June discharge anomalies associated with all El Niño events approach –1 standard deviation from the hydroclimatic normal, whereas those associated with all La Niña events average only +0.5 above the norm; the in-phase responses, in contrast, are much more symmetric (see composites). Thus, the relationship between discharge and *MPI* may better satisfy the monotonicity and linearity requirements for regression, relative to the relationship between discharge and *SOI*. Overall, however, the regression analysis strongly supports the overall impressions of ENSO impacts on Mission Creek streamflow obtained from the composite analyses. Given the monthly streamflow anomalies revealed by the composites, we would expect annual mean streamflow to be lower during warm-phase events, and vice versa. This is borne out by both the regressions.

Moreover, our Mission Creek ENSO results are consistent with findings from geographically broader studies. In southern British Columbia, and indeed throughout much of southwestern Canada, El Niño events tend to be associated with lower precipitation, higher temperature, and lower streamflow (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Woo and Thorne, 2003). La Niña impacts are roughly opposite. However, our study is more temporally detailed insofar as we considered the full annual regime on a month-by-month basis, whereas the studies cited above tend to be more seasonally-oriented.

The lower summer discharges evidently associated with El Niño events, regardless of whether we consider all ENSO events or only those in phase with the PDO, may have substantial habitat implications for resident salmonids in Mission Creek, such as rainbow trout. Potential effects include habitat quantity reduction, and water quality deterioration through (for instance) higher water temperatures and lower dissolved oxygen concentrations. Water temperature effects might be exacerbated in early summer by coincident positive air temperature anomalies. Additionally, El Niño-related negative September discharge anomalies ($P < 0.04$, all events considered, for warm-phase versus both neutral and cold-phase) may have potentially serious repercussions for the success of stream-spawning Lake Okanagan kokanee through similar habitat mechanisms. Note, however, that the positive air temperature anomalies associated with warm-phase events appear to largely vanish by September.

The results may also have important water resource forecasting implications. Due to the lag between ENSO and PDO signatures in wintertime Pacific sea surface temperature (SST) and sea level pressure (SLP) measurements, and the spring/summer freshet in Mission Creek, simply keeping track of Pacific ocean-atmosphere conditions could provide some predictive ability for streamflow. Moreover, ENSO forecasting has made substantial progress in the last few years. Combined with the aforementioned lag, ENSO impacts upon Mission Creek summer streamflow might be predicted up to about a year ahead of time.

Forecasted Increases to Kelowna AT and Mission Creek WT

The CGCM2 model was used to predict changes to mean summer temperature for the 2020s, 2050s, and 2080s. This model predicts that summer air temperatures in the southern interior of British Columbia will warm by approximately 1.2°C by 2020s under both the A2 and B2 scenarios. The region is expected to warm by about 2.0 - 2.2°C by the 2050s, and by about 2.4 - 3.5°C by the 2080s (B2 and A2 scenarios respectively). The resolution of this model is quite coarse and therefore statistical downscaling was conducted to forecast trends for Kelowna. Baseline (1961-1990) monthly mean air temperatures at Kelowna were regressed against CGCM2 monthly mean temperatures from the regional cell, resulting in a regression slope of 1.1708 (or 0.8541 inversed) ($R = 0.97$, 94% of variance explained). This suggests that temperatures in Kelowna will warm more quickly than temperatures in the general for the region

(1.2°C in Kelowna for every 1°C in the region). Hence, Kelowna is predicted to warm by approximately 1.4°C by 2020s, by about 2.3 - 2.6°C by the 2050s, and by about 2.8 – 4.1°C by the 2080s (**Table 7**).

Kelowna mean daily summer air temperature (1998-1999) was then regressed against Mission Creek mean summer daily water temperature (1998-1999), giving a regression slope of 0.7044 (R = 0.93, 87% of variance explained). Since nested regressions are linear, it is possible to downscale in one step by using both regression coefficients as shown in the following:

$$\frac{MissionCr}{Kelowna} = 0.7044$$

$$\frac{CGCM2}{Kelowna} = 0.8541$$

$$\therefore \frac{MissonCr}{CGCM2} = \frac{Kelowna}{CGCM2} \times \frac{MissionCr}{Kelowna} = \frac{1}{0.8541} \times \frac{0.7044}{1} = 0.8247$$

That is, for every 1°C increase in CGCM2 cell temperature, summer water temperatures in Mission Creek are predicted to increase by about 0.83°C (**Table 7**). Note that the very high correlation coefficient between local air temperature and Mission Creek summer water temperature (for >15°C; see methods section of report) suggests that the effects of streamflow variation upon water temperature is minor at this locality.

We include changes to the diurnal temperature oscillations in our forecasts, as these are ecologically very important yet not accounted for when analyzing changes to mean temperatures. The CGCM2 can be used to predict changes to daily oscillations. For southern BC, diurnal air temperature oscillations averaged about 8°C during summers for the period 1961-1990 (Quilty *et al.*, 2004d). Forecasts suggest the amplitude of the diurnal cycle will increase by 4% by the 2020s, by 8% by 2040s, and by 10% by the 2080s (**Table 7**). As described in Quilty *et al.* (2004d), this relative increase in air temperature oscillation can be applied to water temperature by using a band pass amplifier.

Table 7. Forecasted changes to summer water temperature under the A2 & B2 scenarios.

Decade	Emission Scenario	Forecasted Increases in Kelowna Mean AT	Forecasted Increases to Mission Creek Mean WT	Forecasted Increases to Daily Oscillations
2020s	A2/B2/IS92a	1.4°C	1.0°C	4%
2050s	B2	2.3°C	1.6°C	8%
2050s	A2	2.6°C	1.8°C	8%
2080s	B2	2.8°C	2.0°C	10%
2080s	A2	4.1°C	2.9°C	10%

The apparent heat island effect from Kelowna (see section above, *Observed Air Temperature Trends in Kelowna*) is not incorporated into these GCM-based projections.

Moreover, the population of Kelowna is predicted to continue increasing rapidly, and its associated heat island will likely continue to grow as well. Consequently, the projections of Kelowna mean air temperature and Mission Creek mean water temperature listed in **Table 7** may be minimum estimates.

Important Findings:

6. Mean summer air temperatures in Kelowna are forecasted to increase by approximately:
    a. 1.4°C by the 2020s
    b. 2.3 – 2.6°C by the 2050s
    c. 2.8 – 4.1°C by the 2080s
7. Mission Creek mean summer water temperatures are forecasted to increase by approximately:
    a. 1.0°C by the 2020s (and 4% increase in diurnal oscillation)
    b. 1.6 – 1.8°C by the 2050s (and 8% increase in diurnal oscillation)
    c. 2.0 - 2.9°C by the 2080s (and 10% increase in diurnal oscillation)

Assessment of Lethal Risks to Mission Creek Salmonids: Present and Future

Risk assessment for lethal effects on salmonids was completed for Mission Creek stream temperatures during 1998 and 1999, and under forecasted increases to stream temperatures. Although 1998-1999 represents a relatively short period for assessing the thermal regime in Mission Creek, it does characterize years with a strong El Niño / La Niña swing, thereby incorporating a substantial amount of variability. Risk assessment was completed using biological data for steelhead and sockeye salmon, which are rainbow trout and kokanee (respectively) with different migratory characteristics. Although kokanee salmon are not in Mission Creek during summer months when temperatures peak, risk analysis is presented here for the sake of completeness. Results for 1998-1999 are shown in **Figure 29.** During 1998, the strong El Niño year, maximum stream temperatures were approximately 22°C, and generally lasted for less than 10 hours. At this duration, stream temperatures were more than 4°C below lethal thresholds for kokanee, and almost 6°C below lethal thresholds for rainbow trout. During 1999, maximum stream temperatures were approximately 20°C, and therefore even further below lethal thresholds.

For forecasting impacts in the future, 1998 and 1999 were used as baseline warm and cool years, upon which predicted increases in mean summer water temperature (**Table 7**)were linearly superimposed. Results suggest that under all scenarios, including a warm year under the warm scenario, Mission Creek temperatures will be below lethal exposure thresholds (**Figure 30** and **Figure 31**).

Important Findings:

8. Stream temperatures in Mission Creek are currently at least 4-6°C below lethal exposures for kokanee and rainbow trout.
9. Forecasts suggest that stream temperatures in Mission Creek will remain at least 2°C below lethal exposures for kokanee and rainbow trout, even during an El Niño type year and a high climate warming scenario.

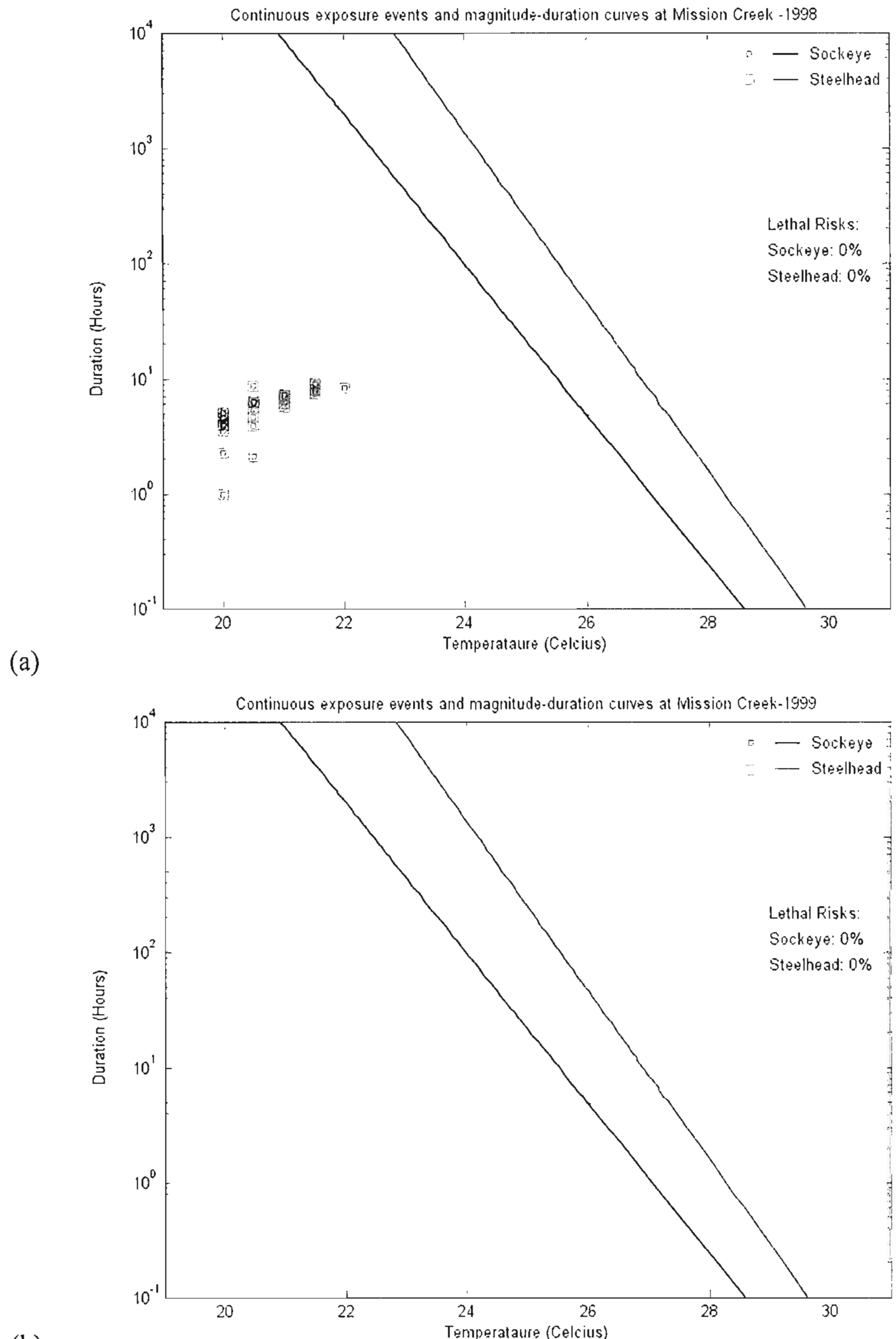


Figure 29. Risk assessment for lethal exposure of rainbow trout (steelhead) and kokanee salmon (sockeye) to high stream temperatures in Mission Creek during a) 1998 and b) 1999.

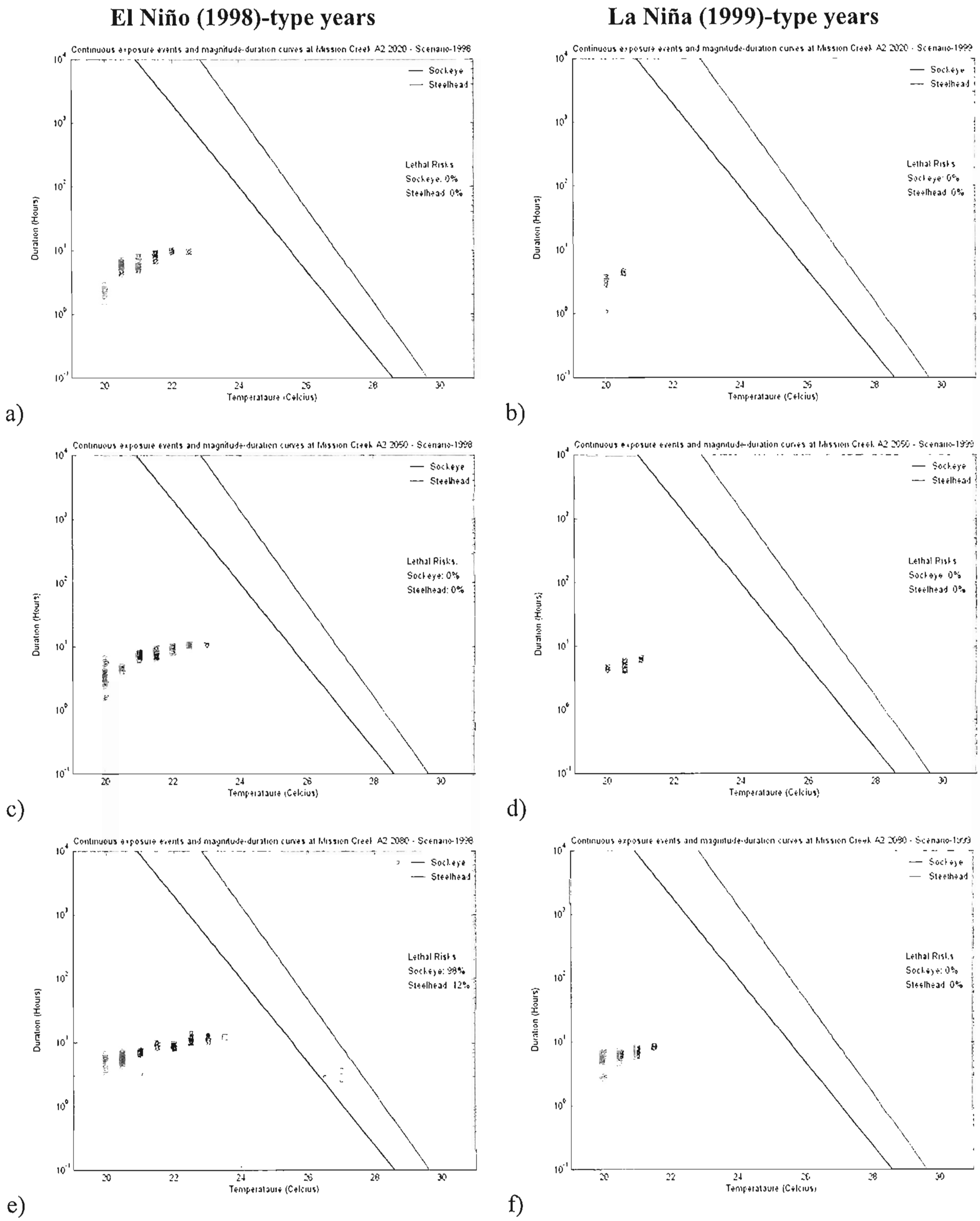


Figure 30. Forecasted risks to sockeye (kokanee) and steelhead (rainbow trout) under an A2 emissions scenario during El Niño (1998) and La Niña (1999) type years in the 2020s [a) and b)], in the 2050s [c) and d)], and in the 2080s [e) and f)].

El Niño (1998)-type years **La Niña (1999)-type years**

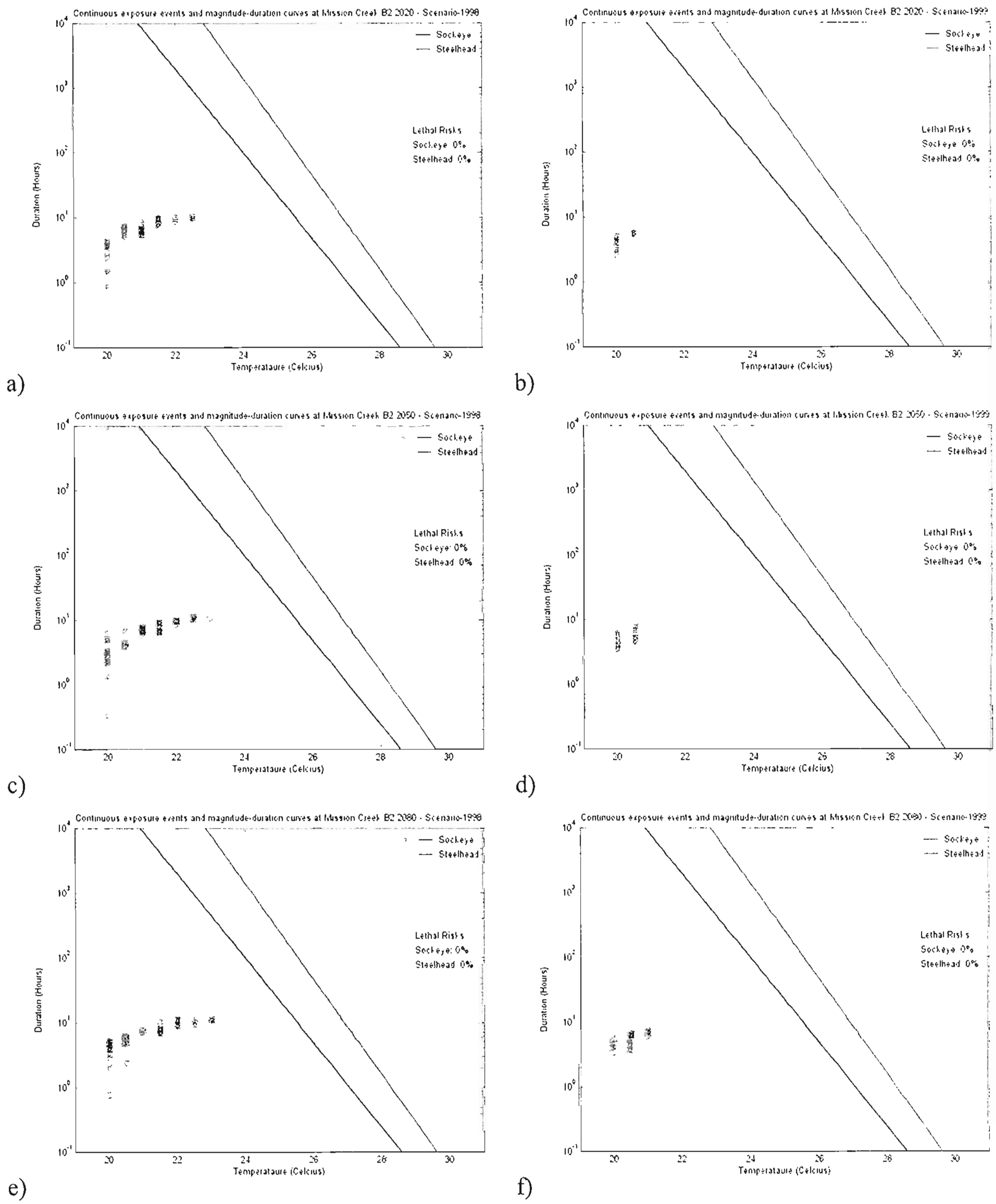


Figure 31. Forecasted risks to kokanee (sockeye) and rainbow trout (steelhead) under an B2 emissions scenario during El Niño (1998) and La Niña (1999) type years in the 2020s [a) and b)], in the 2050s [c) and d)], and in the 2080s [e) and f)].

Assessment of Sublethal Risks to Mission Creek Salmonids: Present and Future

The results of chronic risk assessment are species-dependent (but see Fleming *et al.*, 2004 and Fleming and Quilty, in review). The primary management focus for Mission Creek is on salmonids. While the temperature tolerance range for rainbow is broader than that for kokanee, the optimal growth temperature for kokanee is 15°C (both juveniles and adults), whereas the optimal growth temperature for rainbow trout is about 10-14°C (see Ford *et al.*, 1995). We therefore conservatively select rainbow trout as the target species for assessing chronic temperature risks (as this should also be generally protective of kokanee). Note, however, that juvenile kokanee may spend little time in the stream environment before escaping to rearing grounds in the lake (*e.g.*, Ford et al., 1995), and that brook trout are an introduced species and therefore of relatively low management concern. These considerations also point to rainbow trout an appropriate target species for assessing chronic temperature impacts in Mission Creek. A relationship between daily mean water temperature and rainbow/steelhead specific growth rate, defined specifically for temperatures exceeding the optimum (14°C for this species), was presented in Fleming *et al.* (2004) and Fleming and Quilty (in review), and is applied here for assessing potential growth losses.

Examples of the corresponding magnitude – cumulative duration curves are provided for the observed 1998 daily mean temperature data (**Figure 32**), and under the 1998 thermal regime projected to 2050 under scenario A2 (**Figure 33**). These figures illustrate the cumulative number of days in the year (vertical axis) having daily mean temperatures larger than the corresponding values on the horizontal axis. Percent daily growth risk, *DGR*, is also illustrated, and gives the percent loss in fish growth on a daily basis for a given daily mean temperature. Thus, data points lying to the right of the zero daily growth risk line (*DGR* = 0%) indicate days for which the mean temperature was sufficiently high to incur growth risk, and thus contribute to the cumulative yearly total growth risk (*TGR*). Note that growth is a nonlinear function of temperature.

Results for assessment of sublethal risks to historical (1998 and 1999) and forecasted (2020s, 2050s, 2080s) thermal regimes in Mission Creek are summarized **Table 8**. The number of days having sub-optimally high temperatures is N_{exc}; the average temperature over all such days of temperature exceedance is T_{exc} (°C); *TGR* is annual total growth risk (%); and f is the ratio of predicted *TGR* to historical *TGR*. *TGR* during a historical El Niño year (1998) and La Niña year (1999) were estimated to be about 18% and 16%, respectively. These are set as baseline impacts ($f = 1$). Under the A2 climate change scenario, *TGR* is estimated to increase to 33% by the 2020s, 50% by the 2050s, and 83% by the 2080s during an El Niño-type year; *TGR* is estimated to go up to 20% by the 2080s during a La Niña year under this scenario. Under a B2 scenario, *TGR*s are forecasted to be lower relative to the A2 scenario, reaching about 56% by the 2080s during an El Niño year and 12% during a La Niña year. f-ratios are expected to be greater than 1 during all years, reflective of increasing impacts under climatic change.

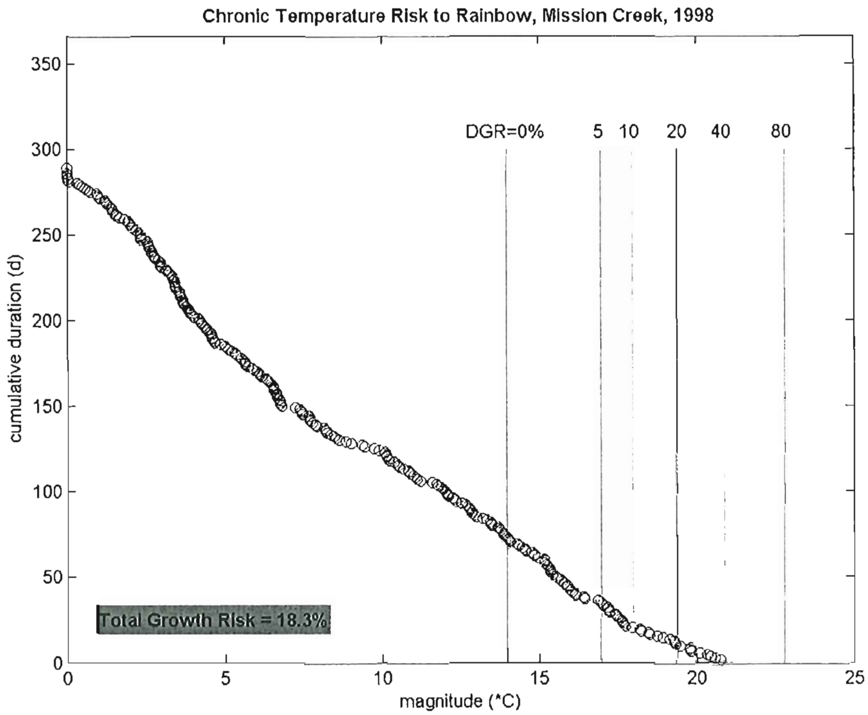


Figure 32. Sublethal (chronic) risk to rainbow trout in Mission Creek, 1998 (warm year).

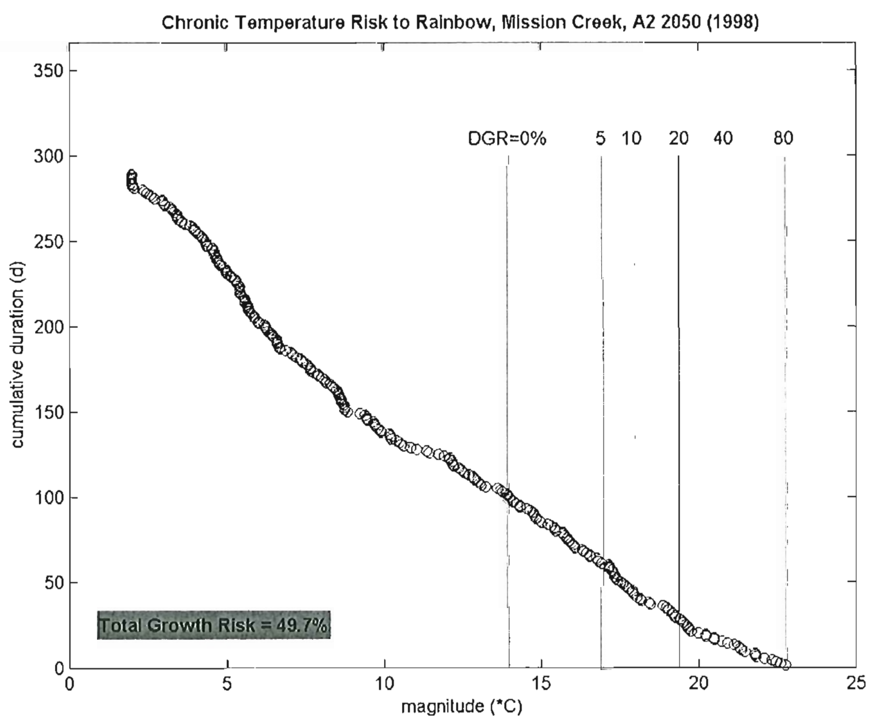


Figure 33. Forecasted warm-year chronic risks to Mission Creek rainbow, 2050, A2 scenario.

Table 8. Preliminary chronic risk estimates, Mission Creek.

	1998				1999			
	N_{exc}	T_{exc}	*TGR*	*f*	N_{exc}	T_{exc}	*TGR*	*f*
Historical	72	16.9	18.3	1	30	15.9	2.5	1
A2 2020	86	17.4	32.5	1.8	44	16.3	5.7	2.3
A2 2050	99	17.8	49.7	2.7	51	16.8	10.2	4.1
A2 2080	112	18.5	82.7	4.5	64	17.3	20.3	8.1
B2 2020	92	17.5	36.8	2.0	46	16.4	6.8	2.7
B2 2050	96	17.8	46.5	2.5	50	16.7	9.3	3.7
B2 2080	103	17.9	56.1	3.1	52	17.0	12.0	4.8

The results for chromic risk assessment (see table and figures above) suggest that increases in growth risk under climatic warming may occur much more quickly than increases in acute risk, reflecting in part the lower threshold temperatures for chronic impacts. Progressive increases in risk over time arise from both the larger number of days contributing to total growth risk (N_{exc}) and the higher temperatures on days of temperature exceedance (T_{exc}). Projection of the warm observed thermal regime of 1998 to a climatically altered future yields very high total growth risks to rainbow trout, nearing 100% (*i.e.*, zero yearly growth) for 2080 under scenario A2. Similar projection of the cool 1999 thermal regime obviously yields lower risks relative to the 1998-based prediction, but the rate of risk increase (*f*) is in fact somewhat higher.

Regardless of the scenario used or the starting point for the projections, the results suggest that a general doubling of chronic growth losses due to sub-optimally high water temperature could occur by 2020, with very large proportional increases by 2050 or 2080. Although the details remain tentative, our analysis strongly suggests that climatic change may have serious negative impacts upon fisheries resources in Mission Creek via substantial increases in growth loss from higher water temperatures.

Important Findings:

10. Sublethal thermal impacts to Mission Creek salmonids, as measured by total growth risk (*TGR*), are forecasted to nearly double to 30-40% by the 2020s and approach 100% (zero yearly growth) by the 2080s during a warm year.

Conclusions

Climate change in Kelowna

- Kelowna's climate has become significantly warmer and wetter over the past century. Mean daily air temperatures have increased by approximately 4°C during winter, 3.5°C during spring, and 2.5°C during summer and fall. These increases are substantial and are nearly double those estimated for the southern interior. Much of the difference appears related to a heat island effect associated with rapid population growth in the City of Kelowna.

- Total annual precipitation appears to have increased by approximately 80 mm or 25%, with almost all the increase occurring during spring and summer.

- Forecasts suggest that summertime mean air temperatures will increase by 1.4°C by the 2020s, 2.3 – 2.6°C by the 2050s, and 2.8 – 4.1°C by the 2080s.

- During El Niño years in the Okanagan, precipitation is somewhat lower and air temperature is substantially higher from February through June.

- During in-phase (warm PDO regime) El Niño years, precipitation in the Okanagan appears to be higher during spring, and air temperature is substantially higher from February through June.

Effects on Mission Creek hydrology

- During El Niño years, Mission Creek streamflow is lower than average from June to September.

- During in-phase (warm PDO regime) El Niño years, Mission Creek streamflows are somewhat higher during March and April, and considerably lower during May to September (though only statistically significant in June).

- Mission Creek mean summer water temperatures are forecasted to increase by approximately 1.0°C by the 2020s (with a 4% increase in the amplitude of the diurnal cycle), 1.6 – 1.8°C by the 2050s (and 8% increase in diurnal), and 2.0 - 2.9°C by the 2080s (and 10% increase in diurnal).

Effects on Mission Creek Kokanee and rainbow trout

- Stream temperatures in Mission Creek are currently 4-6°C below lethal (acute) exposures for kokanee and rainbow trout. Forecasts to the 2080s suggest that stream temperatures in Mission Creek will remain at least 2°C below lethal exposures, even during a warm year.

- Stream temperatures in Mission Creek are estimated to cause sublethal impacts of ~20% to kokanee and rainbow trout, as measured by total growth risk (*TGR*), during a warm year. Forecasts suggest these impacts will nearly double to by the 2020s and approach 100% (zero yearly growth) by the 2080s during warm years.

Recommendations

- Given the short record of continuous historical summer temperature data for Mission Creek, the preliminary estimates for future acute effects on salmonids must be considered as a first estimate only. ***Additional years of continuous summer temperature records are necessary*** to obtain a better understanding of the thermal conditions during warm and cool years, and thus better facilitate accurate predictions of future aquatic thermal regimes. Thermistors are relatively inexpensive (~$150 each), and an effective temperature monitoring program could be initiated for $1000 or less.

- Though lethal impacts to kokanee and rainbow trout from high stream temperatures in Mission Creek are unlikely, sublethal (chronic) effects such as reduced growth, reduced resistance to disease, and changes to behaviour will become more substantial. ***Mitigation and remediation projects should be designed and implemented.*** For example, rehabilitating riparian corridors, and restoring associated stream shading to more natural levels, is a win-win approach which would render Mission Creek far more robust to climatically induced temperature changes and have other ecological and aesthetic benefits, at relatively modest initial capital expenditures with few ongoing maintenance or operation costs. Alternatively, Dill (2005) recommends increasing discharge during September in Mission Creek to help negate the migratory delays coupled with high water temperatures. Upgrades to control on a daily basis the discharge in Mission Creek using Hydraulic Creek are estimated to be between $150,000 and $200,000, although the ecological impacts of such engineered solutions upon Hydraulic Creek would need to be evaluated.

- ***A groundwater variability study should be completed for the Mission Creek watershed.*** In general, groundwater plays an important role in summer low flows. However, little is known about the influence of climatic cycles, such as ENSO and PDO, on groundwater and on groundwater-surface water interactions. The Groundwater Assessment in the Okanagan Basin (GAOB) project includes a climate change component; however, it does not appear to explicitly target the effects of large-scale ocean-atmosphere circulation patterns, such as ENSO.

- ***Quantitative modelling and predictive tools for Mission Creek water resource and environmental management should be developed.*** For example, the ENSO effects on Mission Creek identified in this report could be used as the basis for average/above-average/below-average local hydrometeorological forecasts with a lead time of up to about a year. A physically based watershed model should be developed for Mission Creek to facilitate both medium-term (*e.g.*, ENSO) and long-term (climatic change) forecasts, as well as to develop a better understanding of the watershed and the potential effects of various watershed activities, land use changes, and remediation efforts.

- ***The apparent Kelowna heat island effect requires closer investigation.*** This local phenomenon, as suggested by historical temperature records, may have impacts on par with those from global climate change. The urban heat island effect could potentially have severe implications for Mission Creek fisheries health, that have not been incorporated into the forecasting portion of this study. Detailed analysis, verification, and quantification are required, and models of the effect should ultimately be incorporated into projections of Mission Creek climate change impacts.

- ***Climate variability and change impacts upon water resources and fisheries in Mission Creek must be incorporated into watershed management and planning***. For example, as noted in an earlier section of this report, making land use or fisheries management decisions without climate information is akin to signing a lifelong employment contract without any consideration for inflation. A variety of agencies and projects, at the municipal, regional, provincial, and federal levels, could gain additional context and insight from the results of this report, and from further analyses of Mission Creek water resource and fishery sensitivity to climatic variability and change. One example is the Mission Creek Watershed Plan currently under development.

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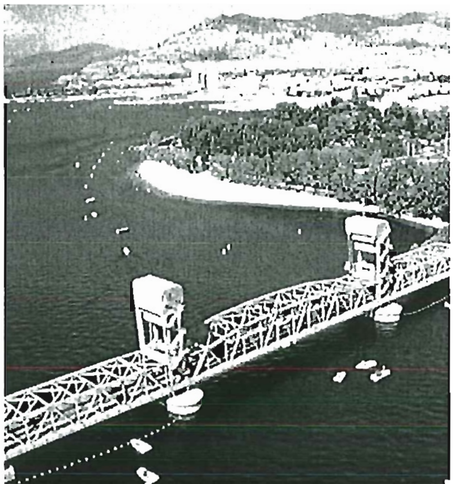
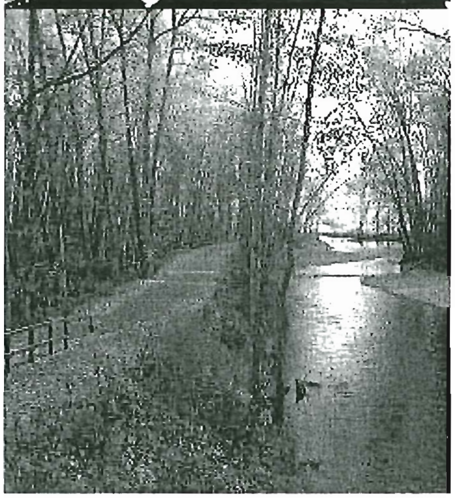
APPENDIX 1

Aquartic Informatics Inc. 2005. *An Initial Inspection of Nutrient Loadings, Mission Creek, 2002-2004. Draft Report.* Prepared for the Ministry of Water, Land, and Air Protection. Okanagan-Kootenay Region. February 2005.

Ministry of Water, Land & Air Protection

OKANAGAN-KOOTENAY REGION

DRAFT

An Initial Inspection of Nutrient Loadings, Mission Creek, 2002-2004

February 2005


Prepared for:

Environmental Quality Section
Environmental Protection Division
Okanagan-Kootenay Region
BC Ministry of Water, Land
& Air Protection

Prepared by:

Aquatic Informatics Inc.

Aquatic

ENVIRONMENTAL QUALITY

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Summary

This brief technical note presents a preliminary evaluation of nutrient trends in Mission Creek from 1972 to 2004, and approximate estimates of mean nutrient loadings for Mission Creek over the recent sampling period of 2002-2004. This work was a side project of a larger study on the effects of stream temperatures and climate change on salmonids in Mission Creek (Quilty *et al.* 2005). Statistical detection of temporal trends in nutrient loading could not be completed due to large gaps in the data from about 1983 to 1990, and 1993 to 2002, and because of low sampling frequency. In general, however, it appears that there has been no improvement in nutrient concentrations in Mission Creek. Recent mean annual loadings were roughly estimated. The values ranged from approximately 700 kg/yr for ortho-phoshate to 54,000 kg/yr for total nitrogen. Substantial further monitoring and analysis is required to obtain more reliable nutrient loading estimates for Mission Creek.

Data

Water quality grab sample results from Mission Creek at Lakeshore Road (EMS ID 500046) were downloaded and provided by V. Jensen of MWLAP. This location was chosen from the various sampling sites in the watershed because it is closest to Okanagan Lake and, therefore, likely provides the best available estimates of total Mission Creek nutrient loadings into the lake. Analysis focused on dissolved nitrate, dissolved nitrate plus nitrite, total nitrogen, dissolved ortho-phosphate, total phosphorus, and total dissolved phosphorus. Dissolved nitrogen–nitrite was not examined as there were few samples and available analytical results were low and contained a substantial number of non-detects (average was 0.0026 mg/L). In all cases, non-detects were assigned a value of one-half the listed detection limit. Nutrient loadings were estimated using flow data from the Water Survey of Canada gauge on Mission Creek near East Kelowna (WSC 08MN116), which were available to 2003.

Figure 1 below displays all sample results for the aforementioned water quality parameters. In general, large data gaps exist over about 1983 to 1990, and 1993 to 2002. Gaps are even larger for some parameters (e.g., ortho-phosphate). Qualitatively, there is little evidence for substantial improvement in these water quality parameters since the 1970s. We believe that the limited sample sizes, large gaps, and irregular sampling schedule currently preclude rigorous completion of more quantitative analyses of long-term trends in Mission Creek nutrient loadings.

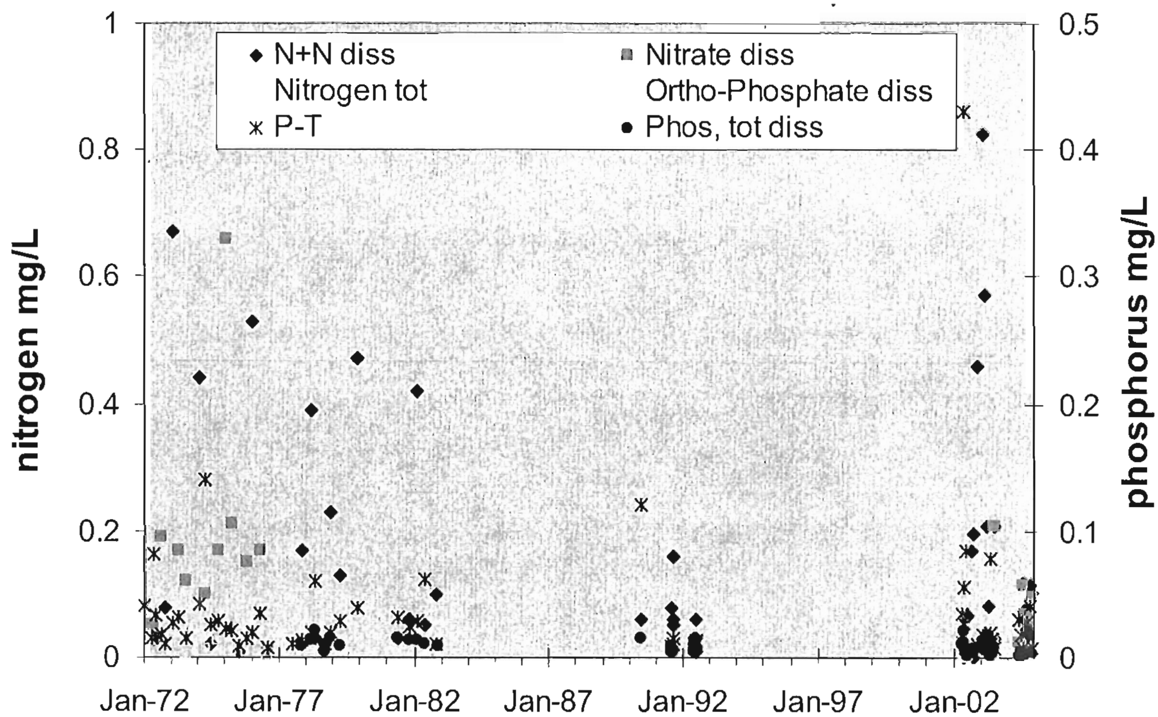

Figure 1. Mission Creek nutrient concentrations, full record.

Expanded views of recent (2002-2004) data are provided in **Figure 2**. Loading calculations focussed on these data, as they represent current conditions in the basin. However, the apparent absence of trends in concentration (**Figure 1**) suggests that current loadings may not be strongly different from historical nutrient inputs to Okanagan Lake from Mission Creek.

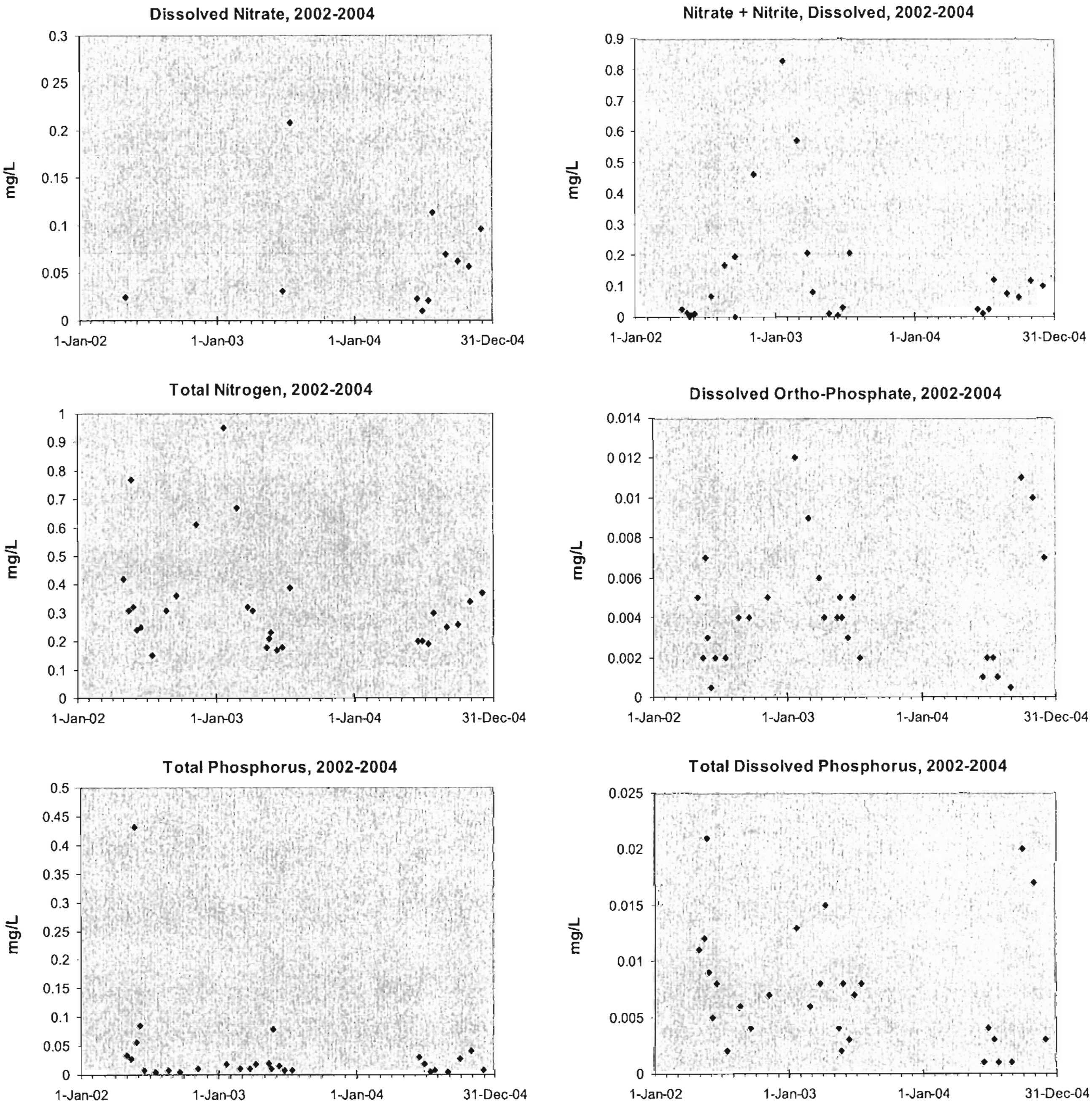

Figure 2. Mission Creek nutrient concentrations, 2002-2004.

Analysis

Some parameters show seasonality, over both the recent (2002-2004) period and earlier data, with lower values in summer than in winter. For example, concentrations of dissolved nitrate plus nitrite showed strong seasonality in the average (**Figure 3a**). Seasonality in the corresponding monthly average loadings, however, was observed to be substantially (but not completely) damped by an approximately opposite annual cycle in discharge, as shown in **Figures 3b** and **3c**.

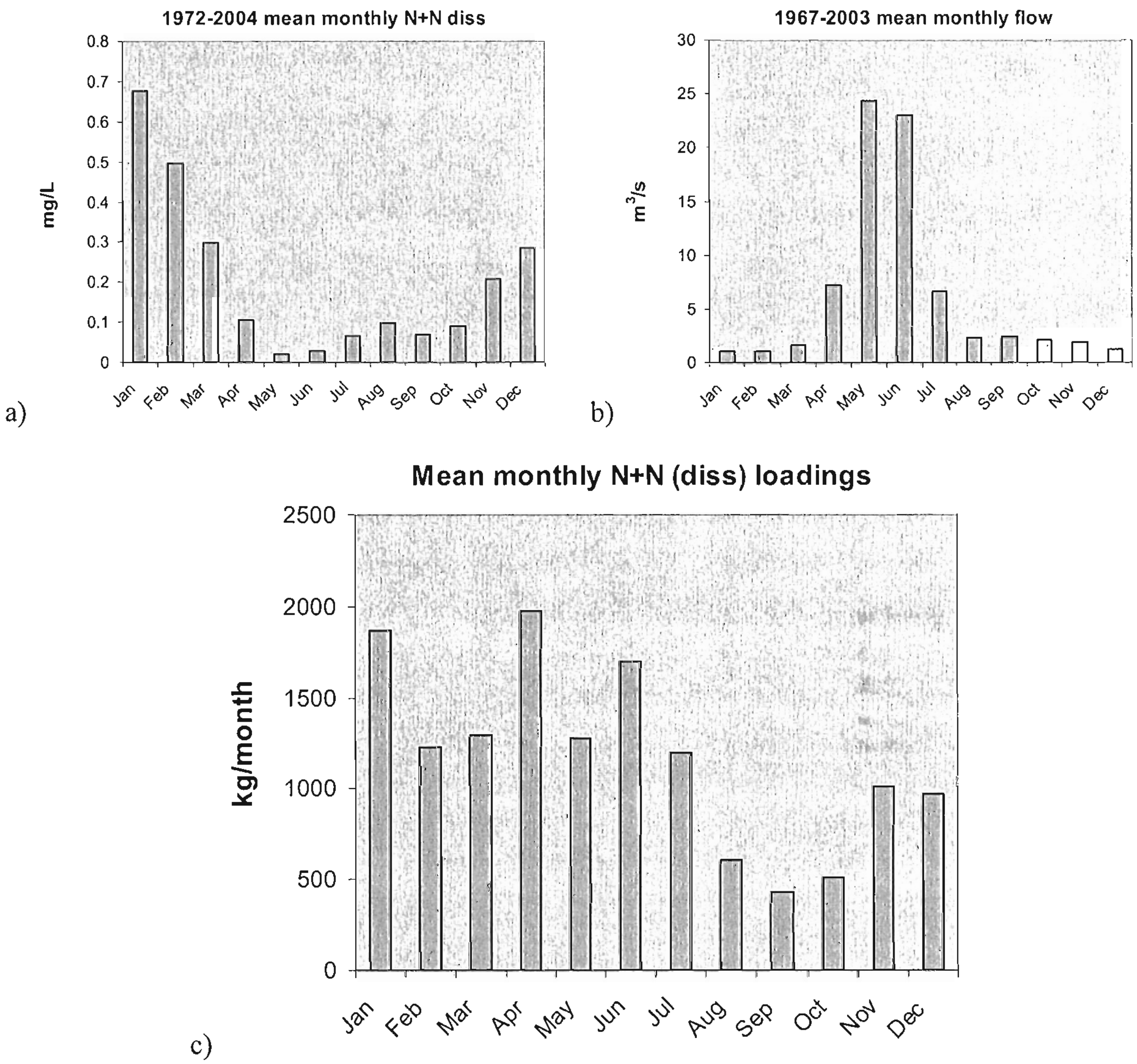

Figure 3. Mission Creek a) mean monthly nitrite+nitrate (N+N) concentrations, 1972-2004; b) mean monthly flow, 1967-2003; and c) mean monthly N+N loadings calculated from a) and b).

While mean seasonal patterns using all available data are relatively clear, the actual correlation between the available N+N (diss) data, and daily mean discharge (when available) on the days for which grab samples were obtained, was modest and explained only small proportions of the variance (16% for 1972-2003; 23% for recent period, 2002-2003; recall 2004 WSC Mission Creek discharge data were unavailable). Although discharge is used to calculate loading, correlations between mean daily discharge and mean daily loading (found from the product of grab sample concentration and mean daily discharge for days when both were available) were actually worse, giving $R^2 = 0.03$ over 2002-2003 for N+N (diss). This is presumably because the seasonal cycle is damped in the latter (see above). Moreover, seasonality is less clear or nonexistent in concentrations of some other parameters. The overall moderate to poor correspondence between discharge and concentration is illustrated for two water quality parameters in **Figure 4**.

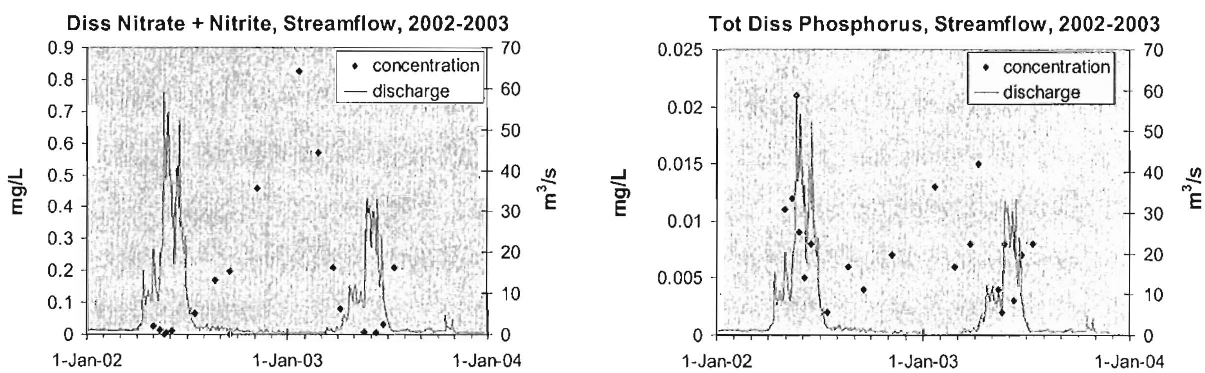

Figure 4. Mission Creek 2002-2003 streamflow and concentrations of a) dissolved nitrate plus nitrite, and b) total dissolved phosphorus.

Thus, little opportunity apparently exists for predicting concentration from discharge. In addition, concentration data are not available for all 12 months for each parameter for each year during the period 2002-2004, and 2004 discharge data are not publicly available for downloading for this streamgauge. The foregoing considerations, in combination, also currently preclude the use of a seasonal loading model.

The proportions of variance explained by cross-correlations between parameter concentrations over 2002-2004 are shown in **Table 1** below. Dissolved nitrate is omitted because the sample size for this parameter over this period was considerably smaller. Linear correlations between parameters range from essentially nil to $R^2 = 0.40$. For certain parameters, this may have implications for future data collection targets; for example, dissolved ortho-phosphate may give a usable indication of total nitrogen conditions, and vice versa. Likewise, it may thus be possible to make approximate concentration estimates for certain parameters on the basis of others. However, the currently small amount of data available, combined with the still-modest R^2 values, limits the immediate utility of these relationships for estimating 2002-2004 loadings. Future work might also examine the potential for nonlinear relationships between nutrient parameters.

Table 1. R^2 matrix for Mission Creek 2002-2004 nutrient concentrations.

	N+N diss	**N tot**	**O-P Diss**	**P-T**	**Phos tot**
N+N diss	1	0.05	0.34	0.03	0.01
N tot	-	1	0.40	0.21	0.23
O-P Diss	-	-	1	0.02	0.40
P-T	-	-	-	1	0.27
Phos tot	-	-	-	-	1

Data availability limitations in combination with distributional complexities provide an additional confounding factor in evaluating recent nutrient loadings from Mission Creek. A simple approach to calculating loading over some period is to simply multiply the mean discharge and mean concentration over that period. However, empirical cumulative distribution functions of Mission Creek daily mean discharge and nutrient concentrations are non-Gaussian. An example is provided below in **Figure 5** for N+N (diss) over 2002-2003. Also shown is the CDF of daily mean discharges for days on which 2002-2003 N+N (diss) samples were taken.

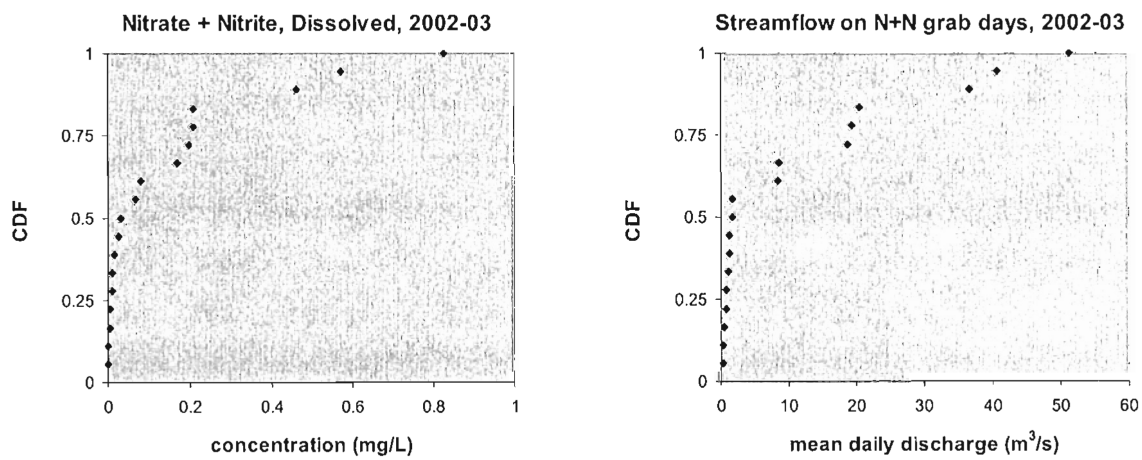

Figure 5. CDFs of 2002-03 a) N+N (diss) data, and b) corresponding daily mean streamflow.

One way to circumvent the question of whether or not the arithmetic mean is, in practise, an appropriate descriptor of central tendency for a skewed distribution in any particular application is to use the median instead. One could also formally identify the distributions followed by the data and use the corresponding location measure (e.g., the geometric mean for a lognormal distribution). Another approach is to calculate an estimated loading for each day on which a concentration measurement was taken, using that measurement and the daily mean discharge on that day, and to then take the arithmetic mean of the daily loading values and scale up the result to a yearly basis. For the N+N (diss) data shown above, the daily loadings are far less skewed than the daily concentrations and discharges used to compute them (see **Figure 6** below), mitigating distributional complications. This also seems theoretically the best approach to estimating loadings insofar as the individual loading calculations directly reflect the concentration and discharge on the day the sample was taken. Unfortunately, this approach may also be more sensitive to limited data collection, or at least make less efficient use of available data, in that the vast majority of the day-to-day discharge data available is discarded because no corresponding daily concentration is available. Similarly, in application to Mission Creek, the 2004 concentration data are effectively discarded in this approach because daily discharge data are not currently publicly available for the days on which 2004 concentration measurements were taken.

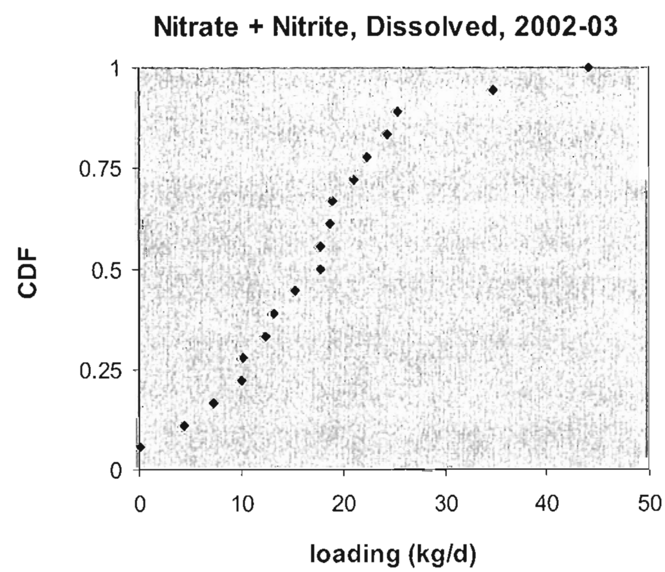

Figure 6. Empirical CDF of estimated daily mean N+N (diss) loadings, 2002-2003

Such questions are not of purely academic interest. **Table 2** below shows estimated mean annual N+N (diss) loadings for Mission Creek using the methods described above. Due to discharge data limitations, the mean or median 2002-2004 concentration data and mean or median 2002-2003 discharge data were used for the first two methods; only 2002-2003 concentration and discharge data were used for the daily loading approach. There is an order of magnitude difference between the estimates.

Table 2. Estimated Mission Creek recent N+N (diss) loadings using different methods

Basis for Method	Estimated Loading (kg/yr)
Mean(discharge) x Mean(concentration)	20932
Median(discharge) x Median (concentration)	2165
Mean(day-by-day loadings)	6452

We proceed by assuming that protection of aquatic habitat is the highest priority, and that the risk associated with an estimate potentially larger than the true value is, therefore, preferable to the risk associated with a nutrient loading estimate potentially smaller than the true value. Considering the results of Table 2, then, estimates of mean 2002-2004 loadings for each parameter were therefore calculated using the mean concentration over this period and the mean discharge over 2002-2003 (5.025 m^3/s; recall again that 2004 flow data are not yet publicly available for WSC 08MN116). Loading factors were also calculated using a basin area of 811 km^2 above the streamgauge. Results are shown **Table 3**.

Table 3. Preliminary estimates of 2002-04 mean annual nutrient loadings from Mission Creek.

Parameter	Mean (mg/L)	Loading		
		kg/yr	$kg/km^2/yr$	kg/ha/yr
Nitrate dissolved	0.065	10336	12.7	0.13
Nitrate + Nitrite, dissolved	0.132	20932	25.8	0.26
Nitrogen, total	0.338	53576	66.1	0.66
Ortho-Phosphate, dissolved	0.004	697	0.9	0.01
Phosphorus, total	0.036	5697	7.0	0.07
Phosphorus, total dissolved	0.007	1184	1.5	0.01

It must be emphasized that the values in the foregoing table should be regarded as highly approximate estimates. More frequent and regular sampling of nutrient concentrations and discharge would permit better estimates of mean annual loading, as concentrations could effectively be pro-rated for discharge variability in the total loading calculations. Given a sufficient duration of relatively high-frequency and regular data acquisition, year-to-year variability in loading could therefore also be estimated. ***We suggest at least one grab sample for nutrients per month; one per week would be preferable.*** As more data is obtained, further analyses could also be performed to better evaluate relationships between various water quality parameters; if strong relationships are identified, the range of constituents which need to be sampled could conceivably be reduced.

References

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