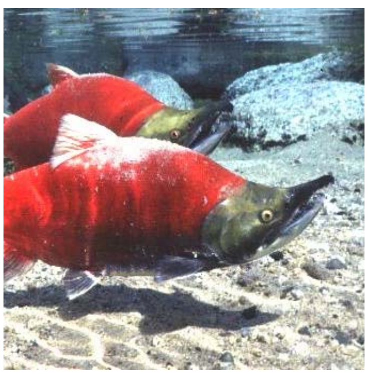

A Novel Approach: Reconnaissance Analysis of the Little Campbell River Watershed.

Final Project Report

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Prepared for:

Environmental Quality Section
Environmental Protection Division
Lower Mainland Region
Ministry of Environment

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Contract Products, Report Distribution, and Statement of Limitations:

The results of the current Little Campbell River work performed by Aquatic Informatics Inc. (AI) on contract to the British Columbia Ministry of Environment (MOE) are presented in three associated sets of deliverables: this report, a Microsoft Excel™ spreadsheet containing collated Little Campbell River water quality data as described in this report, and a series of comma-separated values (CSV) files containing checked and, if felt necessary and appropriate, corrected data files from the new automated water quality monitoring program as described in the addendum to this report.

AI permits use of visual products of analysis from this project to be used in informational materials within reports, brochures, posters, and MOE affiliated websites in order to help the public, local stewardship groups and decision-makers better understand conditions in the Little Campbell Watershed. AI permits MOE to distribute the report produced, to the public and stakeholders, as necessary to work towards improved water quality in this watershed.

It is to be emphasized that this report, which presents analyses and recommendations regarding certain key aspects of environmental conditions in the Little Campbell River watershed, as well as the data compilation and analyses upon which they are based, are highly preliminary in nature. Every reasonable effort has been made to provide the best, most accurate analyses and recommendations possible. However, given the complexity of environmental systems, the limited nature of the available data, the particular scope of the contract, as well as the ambitiousness of some of the analyses, particularly with respect to climatic change impacts, all materials presented here must be duly regarded as preliminary and subject to potentially significant or fundamental change as more information becomes available.

Caveat:

This report presents the results of analysis using forward-looking research and development work performed by AI on contract to MOE. As such, some of the methodologies used in this report remain experimental.

EXECUTIVE SUMMARY

The Little Campbell River watershed is an important ecosystem, being home to a number of significant and/or at-risk species. However, intermittent monitoring has revealed degraded water quality, with negative effects on the ecology of the system. In addition, the Little Campbell River has been shown to be a significant contributor of fecal coliforms to Boundary Bay, which has marine fisheries and trans-national environmental management implications.

Water quality will likely be further degraded with current and planned increases in conversion of watershed area to more intensive land uses. To date, watershed planning has not been coordinated amongst groups or across jurisdictions. A watershed approach is necessary to better understand cumulative effects and to work towards sustainability. Little Campbell River stakeholders have an interest in developing a coordinated and comprehensive monitoring program to better understand water quality and hydrological processes in the watershed, and to promote the use of this information proactively in a planning process with a whole-watershed approach.

The purpose of this project was to complete a reconnaissance analysis study for the Little Campbell River watershed. Specifically, the main objectives of the current study were to obtain a general picture of water quality in the watershed, explore some important climatic influences upon Little Campbell environmental conditions, and make recommendations for a medium-term water quality monitoring program for consideration by stakeholders. This report is provided to stakeholders for their consideration in managing the resources of this watershed. The climate and temperature analysis and modelling done for this report is a product of an emerging science that can benefit from discussions about utility at a local watershed management level. The findings from each of the project sub-components are as follows.

Compilation and assessment of available water quality data

Historical and recent water quality data collected by a range of agencies and groups were identified, quality-assessed, culled as necessary, geolocated, and assembled into a single self-consistent spreadsheet. Recent (2000-2003) data were statistically summarized, preliminarily compared against federal and provincial water quality guidelines, and tentatively mapped. Bacteriological loadings were also estimated and mapped. Due to the nature of the available data, an emphasis was placed upon developing conceptualizations of the overall environmental quality of the watershed, and spatial variability in water quality within the watershed.

Overall, water quality in the Little Campbell River might best be described as mediocre, locally ranging from good to abysmal. pH and, to the extent that minimal available grab sample data captures it, turbidity generally appear to be within acceptable ranges. Nutrient and metals concentrations were variable, ranging from good to poor. Exceedance of guidelines was locally observed for several metals, and while nitrate levels were generally not in violation, they may be sufficiently high to lead to eutrophication problems. At many sampling locations, measures of bacteriological contamination were extremely high. In general, and with some partial exceptions, water quality was consistently better in the upstream half of the watershed. Pollution sources seem to be widespread, but of the sub-catchments considered, the Twin Creeks watershed appears to be particularly problematic, especially with respect to microbial indicators. Ditches and culverts generally had poor water quality, which may be of particular concern for certain at-risk (*e.g.*, amphibian) species. Additionally, the culverts which enter the Little Campbell River near its mouth showed extremely poor water quality for several parameters. In terms of geospatial variability within the watershed, no clear connections between water quality and land use were identified on the basis of the available information.

The majority of water quality data obtained to date in the Little Campbell River watershed have been collected at a large number of locations, with a small number of samples infrequently collected at any given location. This shotgun approach has assisted in identifying site-level pollution and tracing out some general water quality patterns. However, the small number of samples (often as little as one) at any given site largely precludes analysis of temporal patterns, analysis of relationships between water quality and external environmental variables, and formal statistical analysis of geospatial patterns in water quality, and their relationships to such potential controlling factors as land use. The conclusions listed above are therefore strictly preliminary; a more detailed accounting of water quality in the Little Campbell River is currently impossible, and will require collection of additional data.

Evaluation of the local hydroecological impacts of El-Niño Southern Oscillation

Large-scale ocean-atmosphere circulation patterns have become an important organizing theme for understanding the effects of climate variability upon both ecosystems and water resource systems. Chief among these climate modes is El-Niño Southern Oscillation (ENSO). We explored the impacts of ENSO upon the surface meteorology, fluvial hydrology, and water-table aquifers within and near the Little Campbell River using climatological composite analysis with Monte Carlo bootstrapping. The potential modulating effects of the Pacific Decadal Oscillation (PDO) were also evaluated.

El Niño events lead, on average, to higher winter-spring temperatures, lower winter-spring precipitation, lower winter-spring streamflows, and lower groundwater levels starting in winter and lasting throughout much of the year. Hydrologic variability over the winter may be of particular importance to spawning salmonids, a key watershed management target in the region. The longer-lasting hydroclimatic anomalies in groundwater resources presumably reflect the fact that aquifers are large storage systems with long memory. The local effects of ENSO are slightly nonlinear, insofar as La Niña events lead to surface meteorological and hydrological conditions which are only approximately opposite to El Niño; in general, the data considered here seem to suggest that La Niña effects may be somewhat larger.

From an ecological perspective, ENSO is a natural phenomenon, and British Columbian species have evolved in its presence. As a result, it may be inappropriate to view El Niño or La Niña events as ecologically positive or negative per se. Nevertheless, such large-scale ocean-atmosphere circulation patterns have significant explanatory power for assessing climatic impacts upon habitat conditions. Moreover, in heavily degraded watersheds, large ENSO events might have a tipping-point effect, pushing already-degraded ecosystems over the precipice. There is also some general evidence that the Southern Oscillation may be exacerbated by global climatic changes. Consequently, the hydroecological effects of ENSO events could add to the habitat-related impacts from human land use in local watersheds, and together these could conceivably exceed the limits within which native species evolved, and which they can readily accommodate.

Assessment of temperature risks to salmonids and the effects of projected climatic change

We performed a preliminary assessment of acute and chronic temperature risks to steelhead, which is taken as an indicator salmonid species for the watershed, on the basis of currently available (limited) water temperature data. A novel approach previously proposed by AI, which directly assesses the chronic impacts of total high-temperature exposure by incorporating both magnitude and duration considerations, was used. Tentative quantitative estimates of the potential effects of climatic changes upon chronic thermal risk to steelhead were also made using output from the CCCma global climate model under the IS92a greenhouse gas scenario for 2020, 2050, and 2080, in conjunction with empirical downscaling, which was implemented using a linear statistical model of air-water temperature relationships.

Acute risks to salmonids are defined in terms of immediate fish mortality, whereas chronic risks consist of sublethal impacts which can compromise the overall viability of salmonid populations. Using 1999 water temperature data, no acute risks to salmonids were identified. However, cumulative yearly growth risk due to higher-than-optimal stream temperatures was found to be about 10%. This is a relatively high value for British Columbia coastal streams, and may reflect the low-elevation, low-gradient nature of this particular watershed, and/or the effects of conversion of the watershed to human uses, including partial urbanization. Although the details remain tentative, our analysis strongly suggests that climatic change may have large negative impacts upon fisheries resources in the Little Campbell River via substantial increases in growth loss from higher water temperatures. Such growth impacts upon native cold-water stenotherms would likely also increase their susceptibility to other factors, such as watershed degradation, year-to-year hydroclimatic variability, and invasive species. Supplementary quantitative analyses suggested that current and future watershed management practices may greatly affect ultimate thermal risk impacts potentially associated with long-term climatic change.

Identify important questions and provide a suite of recommended future analysis work

For each of the above tasks, outstanding issues, including but not limited to important data gaps, were identified and specific recommendations for additional future work were made. This includes analysis of land use-water quality relationships, hydrological modelling, and process-based coupled hydrological, chemical, and ecological modelling. Details are provided in appropriate sections of the report. Completing this new set of tasks will enable development of a more detailed, integrated, and holistic long-term plan for this watershed.

Design a 5-year environmental monitoring program for the Little Campbell River

Future water quality data collection needs to focus on far more frequent and regular sampling at key locations. This includes both the installation of one or more automated water quality monitoring stations, collecting a suite of data parameters on a semi-continuous basis, as well as more frequent and consistent grab sampling for a broad range of water quality parameters at several locations within the watershed. Far more discharge data must also be obtained to enable hydrologic modelling, assessment of relationships between water quality and quantity, and loading calculations.

On the basis of these considerations, recommendations have been provided for a detailed 5-year water quality and quantity monitoring program for the Little Campbell River watershed. This includes recommendations regarding strategic locations of real-time monitoring stations (thermistors and multi-parameter stations), hydrologic stations (stage recorders and staff gauges), and water quality grab-sampling sites (surface and groundwater). It is recommended that the monitoring program be implemented immediately and, subject to technical adjustments as necessary, be consistently followed over the long term to establish a baseline dataset, and to monitor changing conditions in the watershed. A number of major developments are planned within the drainage area to the Little Campbell River. Assessment of the environmental impacts of such development requires, at a minimum, an adequate pre-development baseline dataset, against which water quality measurements during and after development can be properly compared. Moreover, any attempt to quantitatively or semi-quantitatively predict the environmental effects of specific development proposals requires some level of mathematical predictive capability, which can only be obtained by constructing models on the basis of historical data.

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INTRODUCTION

I. Background

Keeping a watershed healthy while accommodating economic growth can be difficult. Land development activities such as urban growth, agriculture, and logging make management for maintaining water quality, conservation, and biodiversity a challenge. Often, management decisions are based on generic policies or Best Management Practices (BMPs) applied at the site level or to pieces of the watershed. Decisions are often made without consideration of the overall development density, the rate of land use intensification, and the resulting cumulative effects on the watershed.

Occasionally, sparse datasets or short-term studies meant to characterize watershed conditions are utilized. These studies, however, rarely capture transient events even though the systems studied may be strongly event-driven. In addition, they seldom consider the combined effects of local land use layered together with 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, local summertime maximum stream temperatures can be more than 7^{o}C warmer during an El Niño year (Quilty *et al.*, 2004a), and climate change is estimated to have increased mean stream temperatures by 1-2^{o}C over the last 100 years in some creeks (Quilty *et al.*, 2004a). Forecasts suggest that summertime mean stream temperatures could locally increase by as much as 3^{o}C by the 2080s (Quilty *et al.*, 2004b). Significant climate variability and change impacts upon the flow and temperature of larger river systems, such as the Fraser, have also been identified (*e.g.*, Foreman *et al.*, 2001). Making permanent development decisions without climate information is akin to signing a lifelong employment contract without any consideration for inflation. Making development decisions without a good understanding of watershed processes and cumulative impacts is akin to signing without reading.

Even when good information is available, and climate change is considered, a coordinated watershed-focused plan is often not established. This is particularly challenging when a watershed crosses multiple jurisdictions and/or borders. Without a "whole-watershed" approach, planning may be driven by development requests, in a piecemeal approach, rather than development by planning. In the absence of a comprehensive watershed management plan, the upstream activities are not held accountable for downstream consequences, and water quality, conservation, and biodiversity are rarely maintained.

The Little Campbell River watershed is an important ecosystem. It is home to a number of species of concern including steelhead, Pacific water shrew, great blue heron, green heron, and coho salmon. It was also historically inhabited by the Oregon spotted frog and Salish sucker, and could be considered for re-introduction in the future as part of recovery planning. The River drains into Boundary Bay, which is a designated Internationally Important Bird Area on the

Pacific Flyway. Little Campbell is in relatively good condition from a habitat perspective, and its hydrology relatively natural. However, from a water quality perspective, there are several concerns. Intermittent monitoring over the last 30 years have shown the river to have high bacterial concentrations, low dissolved oxygen, warm water temperatures, and elevated metals. In addition, water licences oversubscribe the system. These conditions can have negative effects on the ecology of the system, including on salmonids and rare species. In addition, modelling work suggests the Little Campbell River is a leading contributor of fecal coliforms to Boundary Bay (Hay and Company, 2003). Elevated fecal bacterial levels can be problematic to the sea-side resort town of Whiterock, where tourists and local residents use the water for swimming and boating, and to a re-opened shellfish harvest across the U.S. border in Drayton Harbour.

Water quality is likely to continue to degrade with increased development in the watershed. Numerous large-scale developments have been proposed, or are already under construction, including a very large shopping mall and an industrial area development. The watershed passes through three municipal jurisdictions (Surrey, Langley, and Whiterock), and has cross-border implications through its influence on Boundary Bay. There are a number of community groups working on water quality issues within the watershed, and there is an international water quality working group called the "Shared Waters Roundtable." To date, the level of coordination in terms of water quality monitoring and watershed planning amongst groups or across jurisdictions has been limited. To this point, much of the planning process within this basin has tended to focus on pieces of the watershed through individual development applications or Neighbourhood Concept Plans. In the past, in terms of water, planning has tended to focus on trying to control flow from developing areas. In the future, Integrated Stormwater Management Plans initiated by local governments, if coordinated across jurisdictions, may provide a good opportunity for watershed-level planning to help protect water quantity and quality in the Little Campbell Watershed. A watershed approach is necessary to better understand cumulative effects and to work towards sustainability.

The working groups have an interest in developing a coordinated and comprehensive monitoring program to better understand water quality and hydrological processes in the watershed, and to promote the use of this information proactively in a planning process with a whole-watershed approach. **Table 1** provides a proposed list of questions to work towards answering through monitoring, data analysis, and/or modelling. In order to work toward answering these questions, it is expected that it may be necessary to develop:

- a coordinated longer-term water quality monitoring program;
- a hydrological model of the Little Campbell River watershed;
- a pollutant loading model for *E. coli* or fecal coliforms, and potentially nutrients and metals, with projections for how water quality may change as pollution source contributions are changed in the watershed;
- a model of temperature characteristics in the watershed and projections given anticipated climate change, land use, *etc.*;
- a more detailed assessment of dissolved oxygen conditions in the watershed;
- a watershed characterization which would collect and summarize detailed information on key indices that correlate with water quality. This may include collating information on agricultural, rural and urban land use, pollution sources, water extraction, impervious surfaces, riparian corridors, etc;

- an analysis of the potential costs/benefits (economic, environmental, social) that could result from changes in water quality as a result of future land use scenarios and BMP programs,
- a set of visuals and maps that could be used for presentations to agencies, groups, and the public.

Table 1 *Proposed questions to work toward answering for the Little Campbell watershed using monitoring, modelling and assessment*

	Questions		
Objectives	**A** **(high priority &/or info available)**	**B** **(medium priority, or high priority but information needed from A or further monitoring)**	**C** **(medium priority, or high priority but with information needed from A+B)**
Describe the present water quality conditions in the Little Campbell River watershed (main stem and tributaries)	What is the status of the river in terms of fecal coliform or *E. coli*. loading? Which sub-basins produce the highest fecal coliform, *E. coli* loadings to the system? Is water quality in the sub-basins and mainstem becoming increasingly event-driven? What is the relationship between discharge and water quality parameters during storm events ?	What are the current temperature conditions in this watershed given existing land use and climate? What is the status of the river in terms of nutrient loadings? Which sub-basins produce the highest nutrient loadings? What is the status of this river in terms of metals levels, and where are metals concentrations highest? What are the watershed's dissolved oxygen characteristics?	
Identify and characterize pollutant sources in priority basins and throughout watershed	What urban/rural land use and agricultural intensification indices could be correlated with water quality (based on existing literature)? What information is available for this watershed for these indices?	Which pollutant sources are likely having the largest influence with respect to fecal bacterial levels, temperature, nutrients and DO by sub-basin?	
Predict water quality response to scenarios of future land use and best management practices		What are the expected water quality conditions if land use proceeds as currently planned? What water quality conditions may result from alternate land use patterns? What effect do climate change predictions have on these scenarios?	How would water quality be expected to respond to changes in land characteristics such as: • effective impervious area, • area & connectivity of vegetated land cover • natural riparian area, • connectivity of pollution sources to watercourses, • function of septic systems, • manure levels in the landscape, and • water extraction levels?
Identify the potential negative or positive results of predicted outcomes on future community use of water and associated resources			What are the costs/benefits (economic, environmental, social) that could result from changes in water quality as a result of future land use scenarios, BMP programs, and climate variability and change? – relates to use of water for irrigation, livestock watering, recreation, aquatic life, shellfish
Identify resources required to strengthen accuracy of assessment and predictive capacity of modelling work	What gaps exist in the available information, that if filled would improve the usefulness of the modeling and assessment work? What additional monitoring would be required? What would this cost?		

II. Project Objectives

The purpose of this project is to complete a reconnaissance analysis study for the Little Campbell River watershed, in order to work towards answering the questions in **Table 1**. Specifically, the main objectives of the current study are to obtain a general picture of water quality in the watershed, develop an understanding of important climatic driving forces upon Little Campbell environmental conditions, and design a medium-term monitoring program. As part of this, we perform the tasks listed below.

Assess and collate all available relevant hydrological and water quality data

Historical and recent surface water quality data collected by the Ministry of Environment (MOE), Environment Canada (EC), Water Survey of Canada (WSC), community groups, consultants, and schools (*e.g.*, Kwantlen College) are identified, quality-assessed, geolocated, and assembled into a single self-consistent spreadsheet. Such data consolidation is a prerequisite to any further analysis of lotic environmental quality.

Conduct preliminary statistical summarization, mapping, and interpretation of water quality data

Data are statistically summarized, preliminarily compared against federal and provincial water quality guidelines, and tentatively mapped. Due to the nature of the available data, an emphasis is placed upon developing conceptualizations of the overall environmental quality of the watershed, and spatial variability in water quality within the watershed.

Quanitfy the effects of coherent modes of low-frequency climatic variability upon water resources in and near the Little Campbell River watershed

Large-scale ocean-atmosphere circulation patterns have become an important organizing theme for understanding the effects of climate variability upon both ecosystems and water resource systems. Chief among these climate modes is El-Niño Southern Oscillation (ENSO). We determine the impacts of ENSO upon the surface meteorology, fluvial hydrology, and groundwater regimes within and near the Little Campbell River using climatological composite analysis with Monte Carlo bootstrapping. The potential modulating effects of the Pacific Decadal Oscillation (PDO) are also evaluated.

Assess temperature risks to salmonids, and the effects of projected climatic change upon thermal risk

We perform a preliminary assessment of acute and chronic temperature risks to steelhead, which is taken as an indicator salmonid species for the watershed, on the basis of currently available water temperature data. A novel approach previously developed by AI, which directly assesses the chronic impacts of total high-temperature exposure by incorporating both magnitude and duration considerations, is used. Preliminary quantitative estimates of the potential effects of climatic changes upon chronic thermal risk to steelhead are also made using output from the CCCma coupled general circulation model under the IS92a global warming scenario for circa 2020, 2050, and 2080, in conjunction with empirical downscaling implemented via a linear statistical model of air-water temperature relationships.

Identify important questions and provide a suite of recommended future analysis work
For each of the above tasks, outstanding issues, including but not limited to important data gaps, are identified and some specific recommendations for additional future work are made.

Design a 5-year monitoring program that addresses any data gaps and fits with monitoring goals
On the basis of findings from the foregoing tasks, a detailed 5-year water quality and quantity monitoring program is designed for the Little Campbell River. This includes recommendations regarding strategic locations of real-time monitoring stations (thermistors and multi-parameter stations), hydrologic stations (stage recorders and staff gauges), and water quality grab-sampling sites (surface and groundwater).

Completing this set of tasks sets the stage for more fully addressing the issues outlined in **Table 1**, which in turn will provide a stronger basis for the development of a detailed, integrated, and holistic long-term plan for this watershed.

ANALYSIS

The data compilation, analysis, and modelling we performed for the Little Campbell River watershed falls into two broad categories.

The first, discussed in Part I immediately below, consists of compiling, summarizing, and assessing historical grab sample water quality data. This includes comparison to regulatory guidelines and evaluation of overall geospatial patterns in water quality within the Little Campbell River watershed. The second, discussed in Part II of this section of the report, consists of climate variability impact assessment. This includes ENSO effects, and thermal risks to salmonids under both contemporary environmental conditions and projected future climate.

I. Little Campbell River Water Quality

I.1 Introduction

A total of several thousand spatiotemporal point (grab sample) values of a suite of water quality parameters within the Little Campbell River (LCR) watershed have been measured by MOE, Environment Canada (Cheung, 2003), community groups (most notably the Little Campbell Watershed Society, LCWS), and academic institutions (in particular, Kwantlen College). Assessing the reliability of these measurements, determining the exact locations at which the samples were taken, and collating the data into a self-consistent electronic format constituted the necessary first step toward characterization of water quality conditions in the LCR watershed.

Analyses were then performed of the collated water quality data. It was found that the bulk of the available data were collected using a shotgun-type approach, which focussed on sampling throughout the watershed to locate "hotspots" and sources of pollution. Specifically, grab samples were taken at a large number of locations at a relatively small number of times, with a general emphasis upon monitoring fecal coliform counts and, to a slightly lesser degree, nutrient concentrations and general water quality parameters such as pH and specific conductivity. The vast majority of the water quality sampling locations, hereafter referred to as stations, were operational only over the period 2000-2003 at most. In addition, metals concentrations were rarely measured.

Unfortunately, the generally small number of samples at any given location, even for fecal coliforms, severely hampered efforts to perform rigorous statistical comparisons and modelling of water quality within the LCR, and in particular, largely ruled out the possibility of time series analysis of water quality parameters. In addition, the spatiotemporally variable nature of sampling to date in the LCR watershed limits the ability to assess water quality against guidelines, as both low and high values of any given parameter can easily be missed by such a monitoring regime.

On the other hand, the available data are reasonably well-suited to a qualitative, preliminary geospatial analysis of contaminant concentrations, tracing out spatial patterns of water quality within the watershed. This is a useful goal, given current land uses in the LCR watershed, and previously-expressed concerns about fecal coliform loadings from the LCR to marine waters and their potential effects on the shellfish harvest. To the extent possible, metals concentrations were also geospatially assessed in a preliminary effort to outlined potential sources of industrial or urban pollution within the watershed. Values were also compared, again to the extent currently possible, to federal and provincial guidelines.

I.2 Data Compilation

The task of determining what data were available, precisely where they were collected from, how reliable they were, which data to incorporate into the collated database, and the actual construction of that spreadsheet proved to be more daunting than originally anticipated, and involved direct support and input from MOE and the LCWS. In particular, the process required an iterative approach involving AI, Krista Payette of MOE, and volunteers from the LCWS, who had also collected much of the data originally. We ultimately constructed, in effect, a database which can be directly used for LCR water quality characterization and analysis. The water quality stations selected for inclusion in the database are listed below in **Table 2**, along with location coordinates and a brief station description. Note that many stations possessed data only for a limited set of water quality parameters. It is strongly recommended that any additional water quality data collected in the LCR be promptly placed in this spreadsheet to avoid an unnecessary future time reinvestment in data compilation.

Table 2 *Water quality stations incorporated into spreadsheet*

Sub-catchment	Station ID	Station description	UTM zone 10	
			Easting	Northing
McNalley Creek	145-1 (30.7) (31.1)	McNalley Cr – fresh water site upstream of confluence with LCR	516632.1	5429177.5
	145-3 (145-2) (31.2)	McNalley Cr at N side of 8th Ave	516572.4	5429330.9
	145-4 (31.4)	McNalley Cr, W fork, access by walking S off 11A Ave; sample just upstream of where E & W forks meet	516652	5429934
	145-5 (31.31) (31.5)	McNalley Cr, E fork, access by walking S off 11A Ave; sample just upstream of where E & W forks meet	516651	5429931
	145-6 (31.3)	McNalley Cr, N side of 10th Ave	516685	5429747
	31.6	McNalley Cr, S of school site – access by walking N up path from cul-de-sac at end of 11A Ave	516545	5430128
Fergus Creek	146-2 (146-2-B)	Fergus Cr in Peace Portal Golf Course, upstream from LCR mainstem, near green bridge downstream from pond	517955	5429039

	146-2-A	Fergus Cr at upper end of pond above fish ladder in Peace Portal Golf Course; downstream from big foot bridge	517917	5429139
	146-2-C	Fergus Cr on W side of 168th around 11th Ave alignment, from the N side of private driveway; N of golf course	517732	5430027
	146-3-A	Fergus Cr at 8th Ave	518076	5429335
Kuhn & Theodore Creeks	147-1 (147-1-A)	Kuhn Cr in Hazelmere golf course upstream of confluence with LCR mainstem	520161	5428913
	147-1-B	Kuhn Cr at E side of 184th St	520966	5428826
	147-2-A	Theodore Cr before it joins ditch at 184th St	520963	5428549
	147-2-B	Theodore Cr as ditch sample between Theodore Cr and Kuhn Cr	520966	5428677
	147-2-C	S of Theodore Cr in ditch along 184th St; across from gate at 287-184th St	520954	5428349
	147-2-D	Going E on 2nd Ave from 184th St, sample 2nd culvert off 2nd Ave, N side of road	521061	5428153
	147-2-E	Going E on 2nd Ave from 184th St, sample 1st culvert off 2nd Ave, N side of road	520988	5428155
	147-2-F	Near the end of 2nd Ave, sample ditch running along the S side of 2nd Ave; site was W of end property that had been cleared	521276	5428139
	147-2-G	Tributary entering 184th St ditch just N of 2nd Ave on the E side of 184th St; flowing down from 2nd Ave	520947	5428266
Sam Hill & Thomson Creeks	137-2-A	Thomson Cr at 12th Ave	519860	5430156
	137-2-B	Sam Hill Cr at E side of 176th St	519367	5430089
	137-2-C	Ditch between Thomson Cr & 176th St, N side of 12th Ave (tributary to Thomson Cr)	519536	5430152
Twin Creeks	136-1-A	West Twin Cr – US of 184th St	520966	5430830
	136-1-AA	West Twin Cr @ 16th Ave	520987	5430982
	136-1-B	West Twin Cr – DS of 184th St	520954	5430819
	136-1-BB	Culvert entering West Twin Cr on N side, downstream of 184th St	520956	5430822
	136-1-C	West Twin Cr on N side of 18th Ave	521145	5431383
	136-1-D	West Twin Cr on S side of 20th Ave	521336	5431773
	136-1-E	Ditch W side of 184th St – downstream of driveway at 1646 184th (metal gate) (tributary to W. Twin Cr)	520945	5431091
	136-1-F	Ditch E side of 184th St, across from 136-1-E (tributary to West Twin Cr.)	520959	5431096
	136-1-G	Ditch N Side of 16th Ave & W of 16th/184th intersection (flowing toward 16th/184th intersection) (tributary to West Twin Cr)	520873	5430976
	136-2-A	East Twin Cr at E side of 184th St	520963	5430533
	136-2-B	East Twin Cr u/s of 16th Ave	521376	5430966
	136-2-C	East Twin Cr at 20th Ave	521964	5431784
Jacobsen, Jenkins & Highland Creeks	138-1	Jenkins N of 8th Ave	522473	5429367
	138-1-B	Highland Cr, S of 8th Ave	522162	5429347
	138-2	Jenkins Cr, E side of 192nd St	522586	5429345
	138-3	Jenkins Cr, at 3A Ave	522710	5428442
	139-1	Tributary ditch running along N side of 8th in front of property 19313-8th Ave (failing tile field site at property to E); samples have been taken slightly E & W of seepage that was visible at front ditch	522846	5429364
	139-1-F (139-1-C)	Jacobson Cr at 8th Ave	523294	5429324
	139-1-D	Jacobsen Cr from road to Puesta del Sol development off 8th Ave; entrance to access road is W of where Jacobsen Cr crosses 8th Ave	523152	5429643

	139-1-E	Tributary to Jacobsen Cr upstream of 8th Ave and just E of Jacobsen Cr	523358	5429329
	139-2-A	Jacobsen Cr at E side of 200th St	524213	5428652
	139-2-B	Jacobsen Cr at W side of 200th St	524196	5428676
	139-2-C	Tributary ditch S of Jacobsen Cr on W side of 200th St	524198	5428605
Kerfoot Creek	1005-1	Kerfoot Cr at 525-232nd (Holls property) upstream of confluence with LCR; if access is not available on private property sample at 232nd St	530586	5428744
small tributaries to LCR mainstem	701-3	Tributary to main stem - from 212th & 4th, N to confluence with mainstem (sample 150m u/s of confluence & main stem)	526381	5428815
	146-2	Tributary entering N side of LCR just E of 172nd St from feedlot property	518642.9	5428962.3
	701-2	Tributary to LCR in Campbell Valley Park, from S of Davies or Baldwins rear yard – 21328 8th Ave; taken from foot bridge; can also be accessed from path starting just N of where LCR crosses 216th St	526823.4	5429151.6
	714-1	Tributary to main stem - at 20th Ave & 204A St (spawning channel)	525027	5431773
Little Campbell River mainstem	137-1-A (723-2)	Mainstem on W side of Semiahmoo Fish & Game Club Hatchery property on E side of 184th St; some samples may have been on W side of 184th St as 723-2	520970	5430341
	137-1-B	Mainstem at 12th Ave	520512	5430142
	137-2	Mainstem at 8th Ave & 180th St downstream of confluence with Sam Hill Cr (formerly erroneously identified as Sam Hill Cr)	520163	5429349
	146-1 (146-1-A)	Mainstem at 172nd St downstream of feedlot, E side of 172nd St (some previous sampling may have been on W side of 172nd St as 146-1-A)	518581	5428953
	146-1-B	Mainstem at truck crossing bridge at 176th near border – W side samples	519330	5428838
	147-1-D	Mainstem sampled from Hazelmere golf course across channel from polo field property; a few samples have been taken from the polo field side before it was determined access was a safety issue	520214	5429060
	701-1	Mainstem crossing 216th at 600 block	527409	5428878
	711-1	Mainstem crossing 16th Ave at 20400 block	525022.3	5430994.3
	722-1	Mainstem crossing at 24th & 19600 block, downstream of confluence with Horne Pit drainage	523575	5432563
	722-2	Mainstem upstream of hatchery at 16th Ave	522846	5430949
	722-4	Mainstem at 200th St South of 27th Ave, at bridge	524151	5433028
	722-5	Mainstem at 24th Ave & 204th St downstream of bridge	524953	5432581
	723-1	Mainstem, E side of Semiahmoo Fish and Game Club Hatchery site; from metal bridge along foot path	521652.4	5430196
	1005-1-A	Mainstem at 232nd St	530553.9	5429051.2
	1006-1	Mainstem crossing at 224th & 600 block	529007	5429065
	1009-1	Mainstem out of 1st order tributaries at 1300 block, W of 240th St	532179.7	5430459.4
LCR, near the mouth	144-2-A (29.10)	Mainstem at mouth	516250.5	5428918.9
	144-2-B (29.12)	Mainstem just E of mouth	516265.3	5428927.1
	29.20 (29.0)	Mainstem at bend downstream of Habgood culverts (144-1-C & 144-1-D) & culverts 144-1-A & 144-1-B	515888.8	5429182.3
	29.21 (144-1)	LCR between Habgood culverts (144-1-C/144-1-D) & culverts 144-1-A/144-1-B	515927.8	5429206
	29.3	LCR at footbridge	516119	5429301
	29.31	LCR in mainstem near culvert 144-1-F (30.6)	516182.6	5429295.8
	29.40 (144-1-G)	LCR at mouth of McNalley Cr	516639.1	5429144.4
	29.41 (144-1-H)	LCR ½ way between footbridge and Hwy 91	516857	5429117

	29.50 (144-1-I)	LCR just W of Hwy 91	517532	5429115
Culverts at LCR mouth	144-1-A (30.2)	Furthest W of culverts at this location (just NW of #30.1)	515890.7	515890.7
	144-1-C (30.3)	Culvert to LCR – Upper Habgood (originally #30 in 1999-2000 study)	515945	5429200
	144-1-D (30.4)	Culvert to LCR - Lower Habgood (originally #31 in 1999-2000 study)	515945	5429200
	144-1-E (30.5)	Culvert to LCR – W of footbridge	516075	5429284
	144-1-F (30.6)	Culvert to LCR – E of footbridge; across from pump house N of 8th Ave	516189	5429317
	30.8 (144-1-J)	Culvert to LCR – at open ditch just W of Hwy 91 and LCR site #29.5 (144-1-I)	517590	5429138

The contents of the compiled data spreadsheet are essentially impossible to include in a usable print form in this report. The spreadsheet is therefore provided to MOE by AI as a second, associated deliverable. In the following section of the report, selected statistical summarizations, geospatial maps, and preliminary analyses of the data within this spreadsheet are presented.

I.3 Data Summarization and Mapping

I.3.1 All Recent Data: Watershed-Wide Summary

Summary statistics (number of samples; minimum, mean, and maximum values) were determined for each water quality parameter and sampling location. When a concentration was less than the detection limit for the laboratory analytical method used, the value was set to one-half the reported detection limit for the purpose of calculating summary statistics. A watershed-wide summary of results is given in **Tables 3 to 5** below for selected water quality parameters, using data over the recent (2000-2003) period to emphasize current environmental conditions. This timeframe includes the vast majority the available LCR water quality data. Key metadata, such as the number of samples contributing to each displayed mean, are also provided.

Also shown, solely for purposes of preliminary and qualitative comparison, are corresponding general water quality guidelines suggested by British Columbia MOE (available online at wlapwww.gov.bc.ca/ wat/ wq/ wq_guidelines.html#approved) and the Canadian Council of Ministers of the Environment (CCME) (available online at www.ec.gc.ca/ ceqg-rcqe/ English/ Ceqg/ Water/ default.cfm). These guidelines are generic, non-site-specific, and (in general) non-enforceable. Guidelines for protection of freshwater aquatic life were used, with the exception of bacteriological indicators, for which we use the recreational–primary contact guideline. We also show site-specific water quality objectives suggested for the LCR and its tributaries by MOE, to the extent that they have been developed (available online at http://www.env.gov.bc.ca/wat/wq/ objectives/boundarybay/boundarybay.html#table1). Multiple quantitative guidelines or objectives may exist for a given parameter, depending upon conditions such as salmon life cycle stage or prior water quality conditions; only one for a given parameter was selected for inclusion here. Where possible, instantaneous minima (for oxygen) or maxima (other parameters) were applied here due to the temporal point nature of grab sampling. Note that the maximum or minimum (as appropriate) observed values, rather than the mean observed values, are the formal point for comparison against such guidelines.

In the following tables, a dash indicates that no guideline or objective from the corresponding level of government exists for that water quality parameter. An asterisk indicates a variable MOE instantaneous guideline or objective; of these, the most protective one (for instantaneous measurements) is given here. The MOE general guideline for fecal coliforms is defined in terms of a geometric mean to be evaluated from at least 5 samples over a 30-day period; the MOE LCR objective is more complicated, but also requires at least 5 samples over 30 days. The nitrate guidelines correspond to direct effects, and do not include potentially very important indirect impacts through eutrophication. No federal or provincial guideline exists for specific conductivity, but Welch *et al.* (1998) indicate that specific conductivities in the thousands of μmho/cm (equal to thousands of μS/cm) indicate near-brackish water conditions detrimental to freshwater aquatic animals. B.C. guidelines for total lead, manganese, and zinc are currently defined as functions of hardness, but hardness values were not reported in the data sources available. In general, Pacific coastal streams are relatively soft, with hardnesses of less than 50 mg/L $CaCO_3$ equivalent (Welch *et al.*, 1998). As the Mg and Ca data (see below) suggest that the LCR may have relatively hard water by regional standards, British Columbia Pb, Mn, and Zn guidelines were calculated assuming a hardness of 50 mg/L $CaCO_3$ equivalent. The MOE guidelines for temperature are too complex to be listed in the table, and do not directly incorporate both magnitude and duration of fish exposure to high temperatures. Our analyses of acute and chronic temperature risks to salmonids, performed using limited available semi-continuous water temperature data, are discussed in detail in Part II of the analysis section of this report.

Table 3 *Synopsis of general chemistry from grab/point sampling throughout the Little Campbell River watershed, 2000-2003, for all available stations. DO: dissolved oxygen; SC: specific conductivity; TSS: total suspended solids; T: temperature; ND: non-detect. See text for details regarding CCME and MOE guidelines and MOE LCR objectives. Asterisk denotes variable guideline.*

	pH	**DO (mg/L)**	**SC (μs/cm)**	**TSS (mg/L)**	**T (°C)**
Mean	7.5	6.7	725	6.4	8.0
Minimum	5.4	0.1	7	ND	3.6
Maximum	8.1	13.1	26,300	21.0	13.8
CCME guideline	6.5-9.0	> 5.5-9.5	-	-	-
MOE guideline	-	> 9*	-	< 25*	See text
MOE LCR objective	6.5-8.5	> 11*	-	< 10*	-
# stations reporting	60	3	60	2	3
Total # observations	566	18	552	14	18
Mean # obs/station	9.4	6.0	9.2	7.0	6.0
Min # obs/station	1	3	1	7	3
Max # obs/station	26	8	26	7	8

Table 4 *Synopsis of key bacteriological and nutrient parameters from Little Campbell River watershed grab sampling, 2000-2003, for all available mainstem, tributary, and outfall stations. These parameters are particularly, but not uniquely, sensitive to potential agricultural pollution sources. ND indicates non-detect. See text for details regarding guidelines and objectives.*

	Fecal coliforms (cfu/100mL)	Nitrate N (mg/L)	Dis. ortho-phosphate (mg/L)
Mean	9,820	1.2	0.068
Minimum	ND	ND	ND
Maximum	5,700,000	12.5	1.47
CCME guideline	-	< 13 mg/L	-
MOE guideline	geometric mean < 200	< 200 mg/L	-
MOE LCR objective	< 200 MPN/100 mL*		
# stations reporting	80	60	60
Total # observations	885	570	541
Mean # obs/station	11.1	9.5	9.0
Min # obs/station	1	1	1
Max # obs/station	34	26	26

Table 5 *Synopsis of key metals concentrations from Little Campbell River watershed grab sampling, 2000-2003, for all available stations. Most of these parameters are particularly, but not uniquely, sensitive to potential industrial and urban pollution sources. Fe: iron, Cd: cadmium, Pb: lead, Mg: magnesium, Mn: manganese, Zn: zinc. ND indicates non-detect. See text for details regarding CCME and MOE guidelines and objectives. All values are for total concentration and are reported in $\mu g/L$. Note the small number of observations per station.*

	Fe	Cd	Pb	Mg	Mn	Zn
Mean	1,111	0.012	0.37	32,675	201	7.5
Minimum	119	ND	0.04	82	5.9	1.6
Maximum	3,040	0.030	2.20	192,600	704	17.2
CCME guideline	< 300	< 0.017	< 1-7	-	-	< 30
MOE guideline	-	-	< 34	-	< 1,091	< 33
# stations reporting	12	12	14	12	12	11
Total # observations	15	15	25	15	15	14
Mean # obs/station	1.3	1.3	1.8	1.3	1.3	1.3
Min # obs/station	1	1	1	1	1	1
Max # obs/station	3	3	5	3	3	3

I.3.2 Geospatial Patterns

For a subset of 29 sampling locations, preliminary maps were created of station mean values for each of pH, specific conductivity, fecal coliforms, nitrate, ortho-phosphate, and the six metals listed above in **Table 5**. As the majority of data were collected over 2000-

2003 and these measurements are more representative of current watershed conditions, we again limit the analysis to the recent period.

The purpose of these maps is to provide a broad view of potential water quality variations within the LCR watershed. The 29 specific stations were selected for mapping on the basis of inferred representativeness of overall conditions in each sub-catchment, number of data available at the station, and/or potential ability to trace out water quality variations along the LCR mainstem. For sub-catchments, an emphasis was placed upon stations sampling the creek rather than (for example) drainage ditches, and upon stations located near the downstream edge of the sub-catchment.

It is crucial to point out that these maps provide only temporal and spatial average conditions, and local water quality at various points along the LCR or within certain sub-catchments may be considerably better or worse than indicated in the maps. For example, very high fecal coliform counts were identified in several small ditches; we focus here instead upon overall conditions within a sub-catchment or at a given location on the LCR mainstem, integrating the effects of both better and worse water quality conditions within each sub-catchment or everywhere upstream of the LCR mainstem station. It should also be noted that the mean values for different stations may be based upon measurements at a different suite of sample times, and that in general, relatively few measurements are available at any given location for any given parameter.

Moreover, many of the mapped metals values reflect only a single available station measurement, and thus provide only a snapshot in time of water quality conditions. Additionally, metal concentrations were available at far fewer stations than other water quality parameters, such as fecal coliforms.

These substantial limitations notwithstanding, the resulting maps (shown below in **Figures 1 through 11**) do provide a useful first look at possible geospatial patterns of water quality within the Little Campbell River watershed. The values illustrated on the maps are also provided in **Tables 6 and 7**. Note that time and resource constraints placed limits upon the detail with which a basemap could be constructed for the purposes of this report. For small locational inconsistencies between the maps and the tables, the tables should be taken to be correct. Similarly, the maps are intended only to portray some overall watershed-scale geospatial patterns, and for more detailed information on water quality conditions in specific creeks, the tables (or spreadsheets accompanying this report) should be referred to instead.

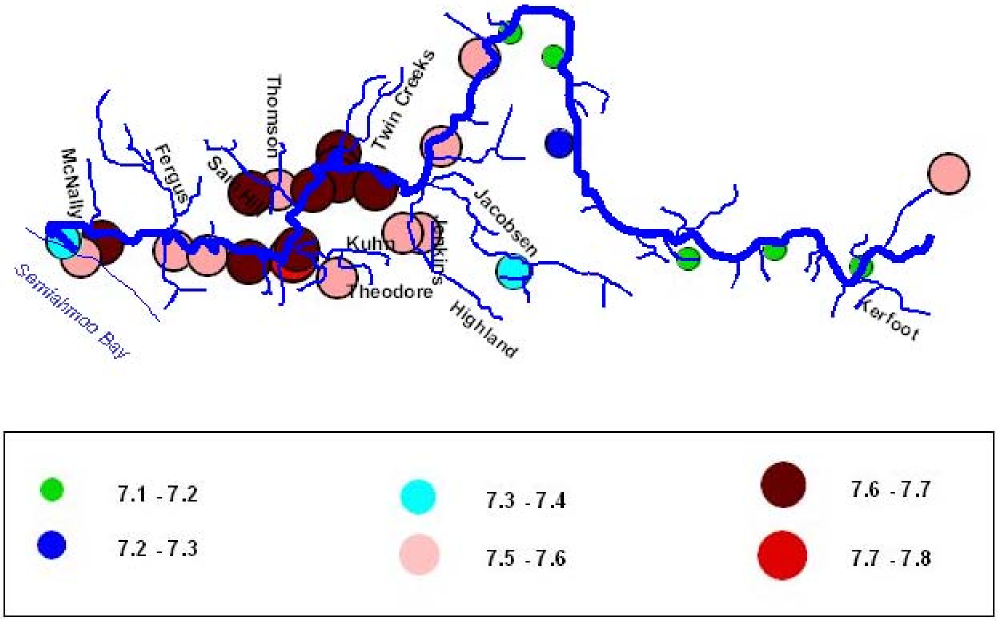

Figure 1 *pH spatial patterns, selected stations*

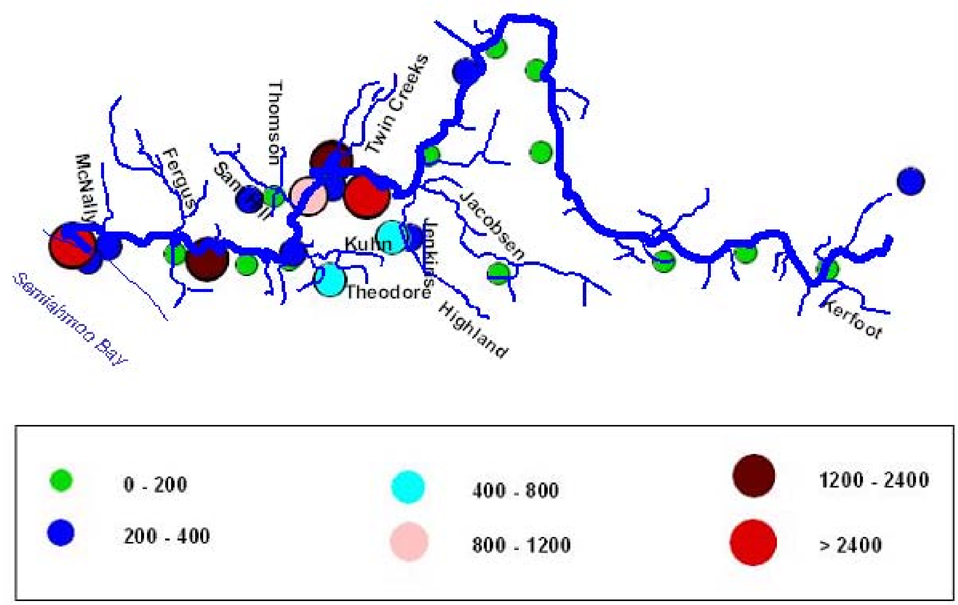

Figure 2 *Specific conductivity spatial patterns, selected stations (μs/cm)*

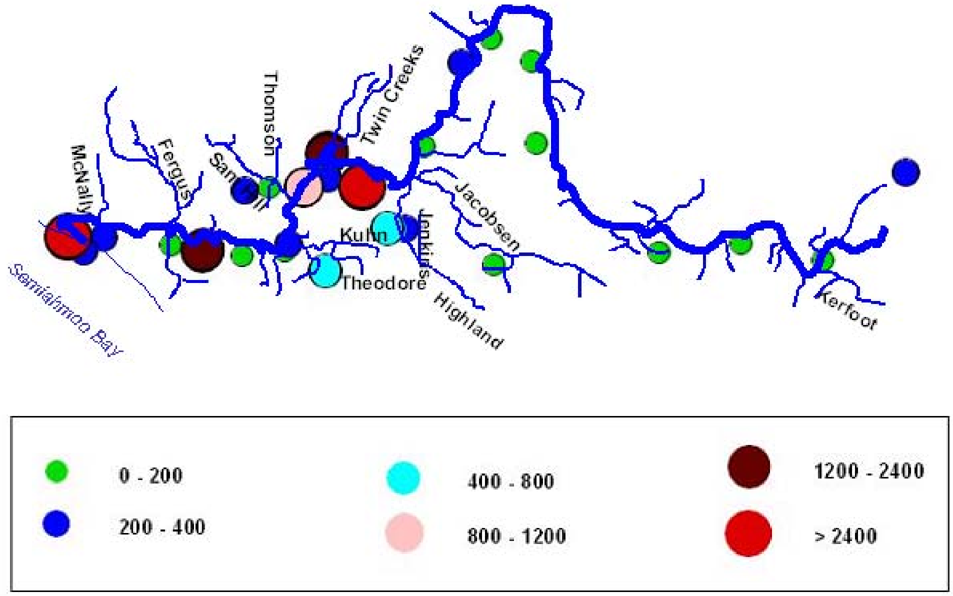

Figure 3 *Fecal coliform spatial patterns, selected stations (cfu/100mL)*

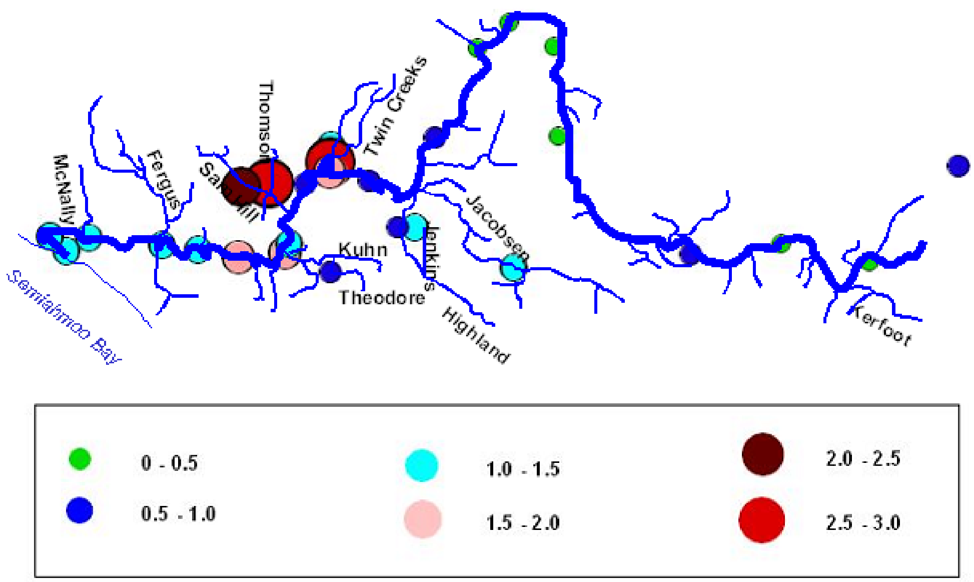

Figure 4 *Nitrate spatial patterns, selected stations (mg/L)*

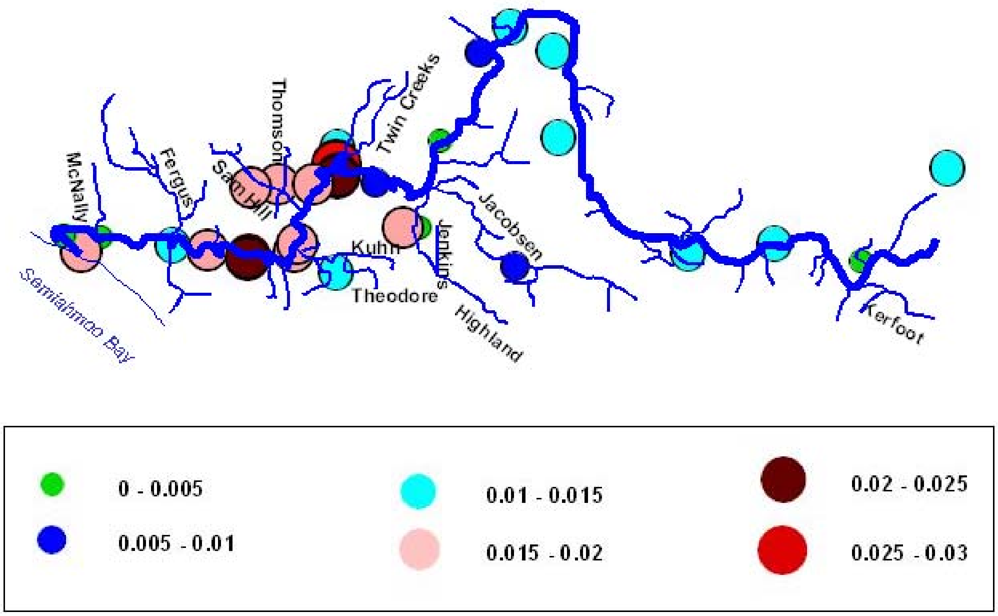

Figure 5 *Ortho-phosphate spatial patterns, selected stations (mg/L)*

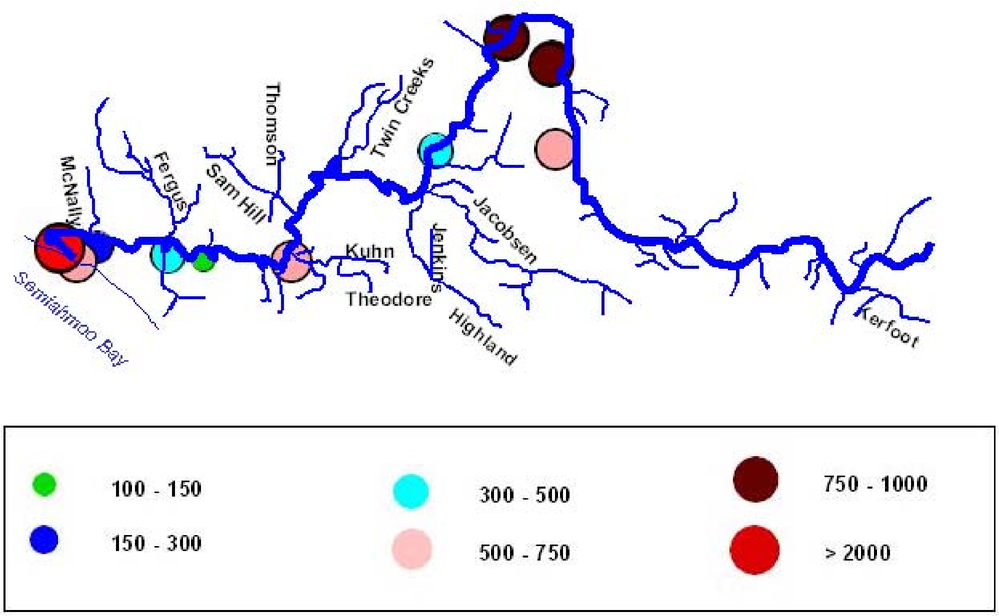

Figure 6 *Iron spatial patterns, selected stations ($\mu g/L$)*

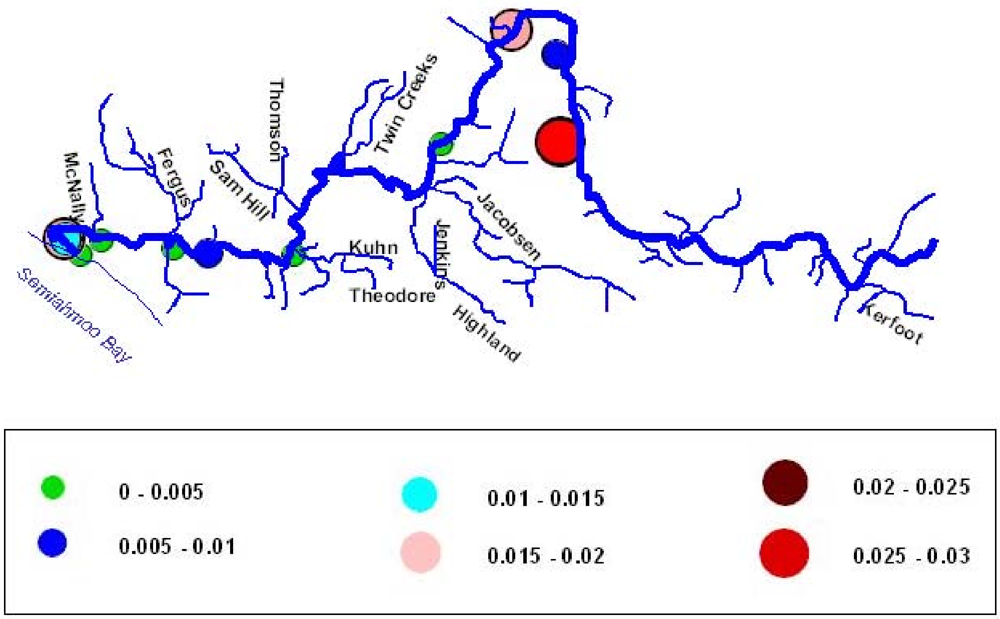

Figure 7 *Cadmium spatial patterns, selected stations (μg/L)*

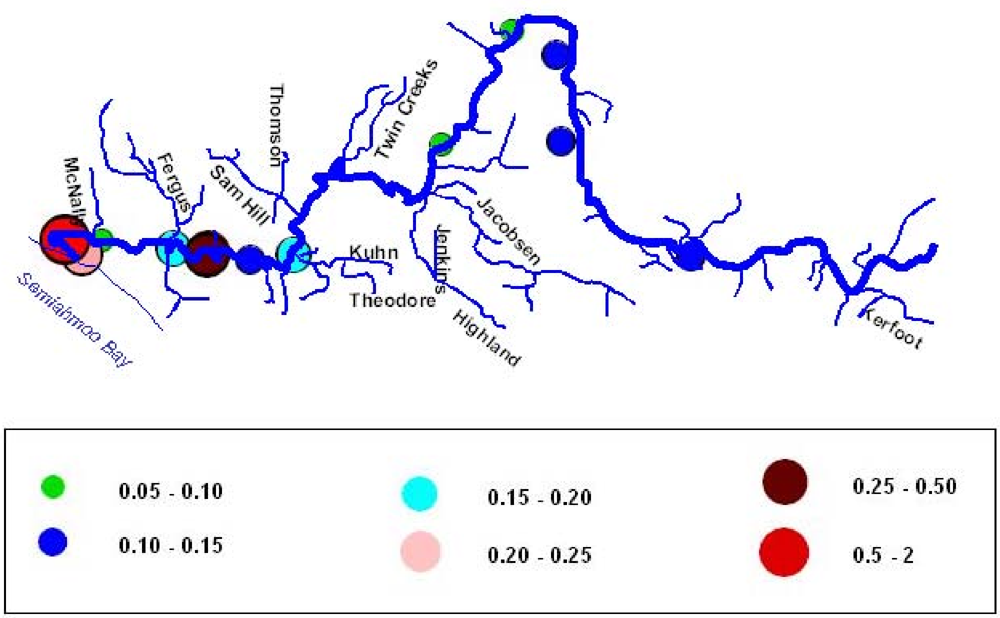

Figure 8 *Lead spatial patterns, selected stations (μg/L)*

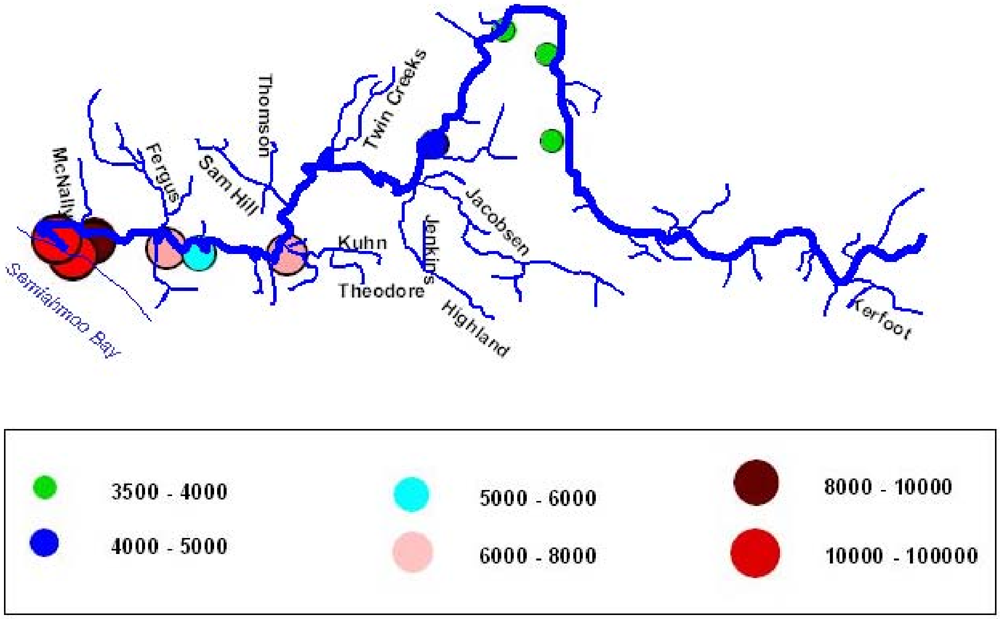

Figure 9 *Magnesium spatial patterns, selected stations (µg/L)*

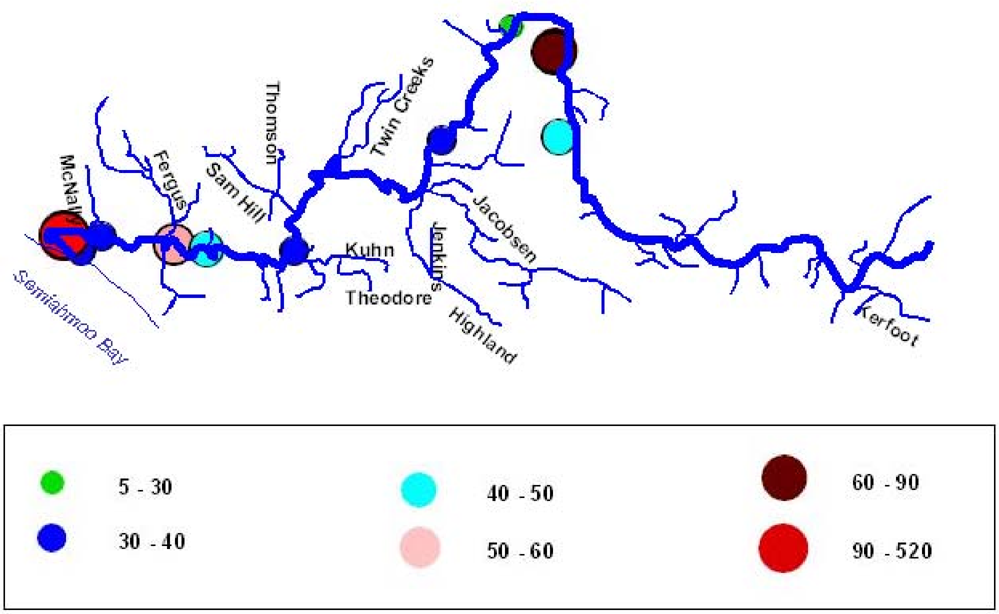

Figure 10 *Manganese spatial patterns, selected stations (µg/L)*

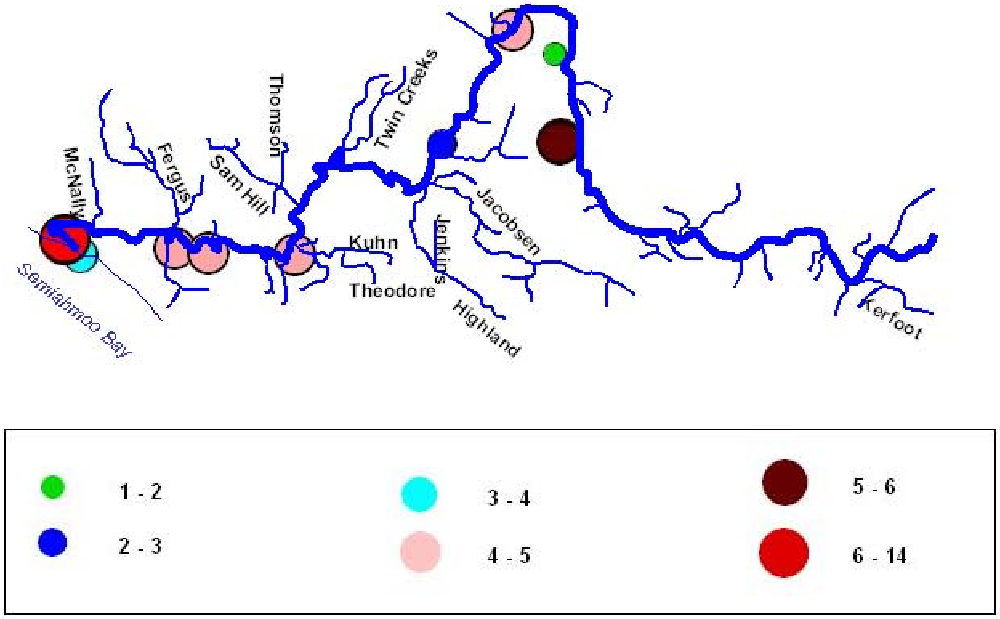

Figure 11 *Zinc spatial patterns, selected stations (μg/L)*

Table 6 *Mean values mapped in Figures 1 through 5 (general water quality, bacteriological conditions, and nutrient concentrations). Full station descriptions and geographic coordinates are provided in Table 2.*

ID	River	pH	SC (µs/cm)	Fecal coliforms (cfu/100mL)	Nitrate N (mg/L)	Dis. ortho-phosphate (mg/L)
145-1	McNalley	7.7	363	327	1.3	0.011
146-2	Fergus	7.6	192	194	1.1	0.033
147-1	Kuhn	7.8	220	126	1.7	0.060
137-2-A	Thomson	7.6	259	122	2.6	0.180
137-2-B	Sam Hill	7.7	239	323	2.3	0.165
136-1-A	West Twin	7.7	179	1718	1.4	0.023
136-2-A	East Twin	7.7	252	124	2.8	0.414
138-1	Jenkins	7.5	117	275	1.3	0.008
138-1-B	Highland	7.6	168	428	1	0.072
139-2-A	Jacobsen	7.4	98	104	1.2	0.020
1005-1	Kerfoot	7.2	94	12	0.1	0.007
147-2-A	Theodore	7.6	164	531	1	0.023
137-1-A	LCR	7.7	187	307	1.9	0.240
137-1-B	LCR	7.7	164	1068	1	0.068
146-1	LCR	7.5	211	1452	1.5	0.138
146-1-B	LCR	7.7	250	189	1.8	0.215
147-1-D	LCR	7.7	160	310	1.1	0.057
701-1	LCR	7.1	138	86	0.7	0.027
711-1	LCR	7.3	123	23	0.3	0.023
722-1	LCR	7.5	129	209	0.3	0.017

722-2	LCR	7.6	121	150	0.6	0.009
722-4	LCR	7.1	140	73	0	0.036
722-5	LCR	7.1	142	78	0	0.034
723-1	LCR	7.7	134	3463	0.7	0.018
1006-1	LCR	7.2	104	72	0.5	0.038
1009-1	LCR	7.6	168	248	1	0.030
144-2-A	LCR mouth	7.6	1437	256	1.4	0.072
144-1-D	Culvert	7.4	5180	1991	1.2	0.007
144-1-C	Culvert	7.4	5464	7475	1.2	0.008

Table 7 *Mean or (when only one observation available) single point values mapped in Figures 6 through 11 (metals). Station details are provided in Table 2. Fe = iron, Cd = cadmium, Pb = lead, Mg = magnesium, Mn = manganese, Zn = zinc. – indicates no value available for that parameter at that station. All values are for total concentration and are reported in μg/L.*

ID	River	Fe	Cd	Pb	Mg	Mn	Zn
145-1	McNalley	157	0.005	0.07	9110	33	-
146-2	Fergus	477	0.005	0.16	6330	59	4.2
147-1	Kuhn	721	0.005	0.18	7980	38	4.7
146-1	LCR	119	0.01	0.3	5030	50	4.9
146-1-B	LCR	-	-	0.14	-	-	
701-1	LCR	-	-	0.11	-	-	-
711-1	LCR	637	0.03	0.12	3890	43	5.1
722-2	LCR	391	0.005	0.07	4930	40	3
722-4	LCR	761	0.02	0.1	3810	6	4.1
722-5	LCR	941	0.01	0.11	3770	82	1.6
144-2-A	LCR mouth	624	0.005	0.22	30250	35	3.2
144-1-D	Culvert	2490	0.018	1.59	97086	516	14
144-1-C	Culvert	2240	0.013	0.91	73589	512	12.7

I.3.3 Bacteriological Loading Estimates: Preliminary Scoping Maps

A key management point for the Little Campbell River is its bacteriological loading of the marine waters of Semiahmoo Bay. Concerns have been repeatedly expressed regarding the potential effects of fecal coliform inputs from the LCR and other nearby locations upon the safety of the marine shellfish harvest (*e.g.*, Cheung, 2003). The issue also has trans-boundary environmental and fisheries management implications, insofar as the ecological health of adjacent American waters may also be affected by bacteriological loading from the Little Campbell River and other, nearby Canadian sources of microbial pollution.

Back-of-the-envelope loading estimates were made for strictly preliminary reconnaissance purposes by simply multiplying, for each station, the mean fecal coliform counts illustrated above in **Figure 3** and **Table 6** by that station's observed flow. Discharge observations, largely collected by the LCWS, were available only for 18 of the stations listed in **Table 6**. Thus, only 18 loading calculations were performed. Additionally, for several of these stations, discharge observations were made only once. In other cases, averages of the few available observations at the station were used. Recall, in addition, the caveats regarding the available water quality data listed in prior sections of this report. Moreover, the foregoing simple procedures, which are driven in large part by a lack of the resources necessary for detailed loading estimates, assume that concentration is independent of discharge, which may not be valid. Thus, the resulting loading estimates, illustrated in **Figure 12** and **Table 8**, are highly tentative in nature, their detailed accuracy is questionable, and they must be used with caution; they are presented here solely as an initial picture of what the bacteriological loadings in the LCR system may look like.

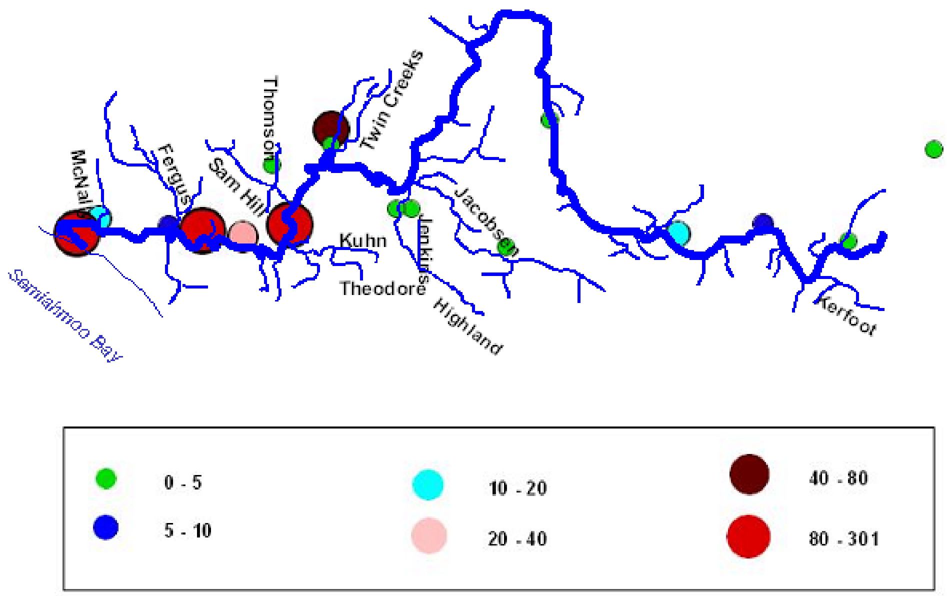

Figure 12 *Spatial patterns in fecal coliform loadings, selected stations (10^{12} cfu/yr)*

Table 8 *The rough estimates of fecal coliform loading values mapped in Figure 12. Full station descriptions and geographic coordinates are provided in Table 2.*

ID	River	Fecal coliforms (cfu/100mL)	Estimated flow (m^3/s)	Estimated loading (cfu x 10^{12} / yr)
145-1	McNalley	327	0.114	11.7
146-2	Fergus	194	0.144	8.8
147-1	Kuhn	126	0.090	3.6
137-2-A	Thomson	122	0.005	0.2
136-1-A	West Twin	1718	0.087	47.4
136-2-A	East Twin	124	0.039	1.5
138-1	Jenkins	275	0.053	4.6

138-1-B	Highland	428	0.007	1.0
139-2-A	Jacobsen	104	0.044	1.4
1005-1	Kerfoot	12	0.029	0.1
146-1	LCR	1452	0.260	119.2
146-1-B	LCR	189	0.585	34.9
147-1-D	LCR	310	0.859	84.0
701-1	LCR	86	0.387	10.5
711-1	LCR	23	0.280	2.1
1006-1	LCR	72	0.294	6.7
1009-1	LCR	248	0.006	0.5
144-2-A	LCR mouth	256	3.716	300.3

I.4 Discussion and Recommendations

I.4.1 Interpretation of Water Quality Data

Given the limitations to the available data discussed in the foregoing sections, and the restrictions these impose upon interpretation of the results, we limit our discussion here to a brief description of overall water quality in the Little Campbell River watershed, and identification of some potential problem parameters and locations with respect to water quality. Recommendations for future monitoring programs which will help address such important data gaps are also made.

Overall, water quality in the Little Campbell River might best be described as mediocre, locally ranging from good to abysmal. pH and, to the extent that available grab sample data captures it, turbidity are generally within acceptable ranges. However, dissolved oxygen concentrations have been observed to decrease to highly unacceptable levels, and observed specific conductivities, although highly variable, can be very high. As noted previously in this report, no federal or provincial guideline exists for specific conductivity, but Welch *et al.* (1998) indicate that specific conductivities in the thousands of μS/cm indicate near-brackish water conditions detrimental to freshwater aquatic animals. Such levels are observed well upstream from the tidally influenced mouth of the Little Campbell River. Fecal coliform counts can be extremely high within the LCR watershed. Nutrient concentrations are far more moderate; nitrate concentrations are within guidelines, and no guidelines are available for ortho-phosphate. Recall, however, that the nitrate guidelines do not include the ecological effects of eutrophication. Considered in that light, nutrient levels appear locally higher than desirable. LCR metal concentration conditions are particularly difficult to interpret given the very limited data available and uncertainty in the appropriate calculated guideline for certain elements (see Section I.3.1 of text). It appears, however, that iron and, locally, cadmium and perhaps lead (depending on the guideline used) are in violation of guidelines. The other three metals considered in **Table 5** approach but do not appear to exceed their respective guidelines, or do not have a guideline. Observed LCR Mg and Ca (not shown) concentrations are typically in the tens of mg/L. Ca and Mg concentrations are reflected in hardness, but hardness values were not reported in the data sources available. As noted above, Pacific coastal streams are generally fairly soft, with hardnesses typically less than about 50 mg/L $CaCO_3$ equivalent (Welch *et al.*, 1998). Thus, high Mg concentrations may simply indicate relatively hard water by Pacific coastal stream standards, although no hardness data are available to confirm this. In addition, the spatial patterns of Mg concentrations seem to generally mirror those of other metals. This may rule out a regional geologic source unless hydrogeochemical conditions are such that Mg concentrations would be expected to vary in accordance with other metals, and thus could conceivably point instead to anthropogenic sources.

As a general rule, water quality is far better in the upstream half of the watershed than in the lower portion. However, four of the six metals considered in this report also show a second region of peak concentrations, at various points within the northward LCR mainsteam meander, located at about the halfway point of the watershed. Brief visual inspections of aerial photographs did not immediately suggest a potential source, but further examination of such data might reveal the origin of this geospatial water quality anomaly. Sub-catchment-level patterns of water quality variability seem to depend in good part upon the water quality parameter considered, but overall, Twin Creeks appear to be hot spots for pollution of a likely agricultural nature (fecal coliforms, nitrate, ortho-phosphate). A curious feature of the available information is that there is currently little evidence for a systematic difference between the water quality of McNalley Creek and the other LCR sub-catchments. This is somewhat surprising given that land uses appear to be substantially different between McNalley Creek and the other catchments, the former being largely dominated by urban development. One might thus expect lower concentrations for generally agriculture-related parameters, and higher metals concentrations; the limited available data do not clearly suggest such a pattern. For most of the parameters considered, the worst water quality was observed at the mouth of the Little Campbell River and, in particular, at two culverts which enter the Little Campbell River at its mouth.

Our estimated concentration maps were specifically developed for the purpose of giving a preliminary view of overall water quality conditions for the main sub-catchments within the LCR watershed, and for the LCR mainstem itself. This is an appropriate approach for this reconnaissance analysis, but care must be exercised to avoid neglecting water quality issues in the many and varied small ditches and culverts within the watershed. Although such locations may not be considered optimal fish habitat, irrespective of water quality, the combined contributions of such small water courses to the accumulated contaminant load of the LCR could conceivably be appreciable. Moreover, such locations indeed constitute important potential habitat for other organisms at high risk; amphibians in particular are a chief concern. Although minimal ditch sampling for metals concentrations was performed, results for the other parameters considered generally indicate relatively poor water quality in various tributary ditches. As a particularly stark example, the mean fecal coliform count at station 136-1-BB, a culvert entering West Twin Creek, exceeded 600,000 cfu/100mL (on the basis of nine measurements taken during spring 2001 and fall 2003; note that no sample at this site gave lower than 1,000 cfu/100mL, but levels for water quality parameters other than fecal coliforms were much lower).

Considering bacteriological loading rather than concentration alone leads to a partial de-emphasis of contaminant contributions from Twin Creeks, but in other respects, the two pictures of microbial pollution patterns within the watershed are generally similar (compare **Figures 3** and **12**). Nevertheless, of the sub-catchments for which data permitted calculation of a preliminary loading estimate, West Twin Creek yields by far the highest fecal coliform load to the LCR mainstem – at least four times higher than that of any other sub-catchment – accounting for about 16% of the total fecal coliform loading at the mouth of the LCR. In general, however, the highest observed bacteriological loadings within the watershed occurred in the mainstem itself. While this may be in part an artefact of the available data, it also undoubtedly reflects the integrating effects of moving downstream and to higher river orders. Nevertheless, the result could additionally suggest that a considerable portion of the bacteriological loading to the LCR, and therefore much of the loading that the LCR contributes to Semiahmoo Bay, originates from localized bank-side sources within the lower portion of the LCR mainstem. Unfortunately, discharge data were not available for the culverts entering the Little Campbell River at its mouth, so that the contribution made by the corresponding very high fecal coliform levels to net LCR loadings cannot presently be evaluated on the basis of MOE data.

I.4.2 Recommendations

I.4.2.1 Immediate analysis and management tasks

The results to date, while preliminary, suggest some immediate points of management concern. In particular, further analysis and management work is required to:

(i) address the very high levels of fecal matter and, to a lesser degree, excess nutrients in small ditches and culverts. These may serve as crucial habitat for certain species, and as important semi-point sources of pollution to the Little Campbell River and its tributaries. One relatively long-term, but potentially highly effective, approach may be to develop community-based, cooperative efforts to extend riparian zones somewhat and to plant native, and perhaps nitrogen-fixing, streamside vegetation. Given the concentration and loading patterns observed to date, it may be appropriate to focus efforts upon the lower half of the Little Campbell River watershed, although the upstream portion should not be neglected. Such hands-on watershed management and remediation work may be embarked upon immediately to good effect and, if implemented with due regard to the needs and values of all stakeholders, involves very little risk.

(ii) rigorously identify, and remediate, the main source(s) of bacteriological contamination in the Twin Creeks sub-catchment. The available data suggest that this is the single most important sub-catchment within the LCR watershed in terms of microbial loading to the LCR and, therefore, to the LCR's bacteriological loading of Semiahmoo Bay.

(iii) identify metals sources within the watershed. Efforts should be focused on what appear to be contaminant hot spots in the lower half of the watershed, and within the large northward meander of the LCR. This work may be intimately tied to assessing the effects of land use upon LCR water quality (see below).

(iv) identify the source areas or points for the very poor-quality water discharged into the LCR from the culverts near its mouth, and obtain discharge estimates for these culverts so that loadings may be calculated. Given the high concentrations of a wide range of contaminants in the effluent from these culverts, they may play key roles in the environmental integrity of the Little Campbell River estuary and in total LCR loadings to Semiahmoo Bay.

(v) assess the hardness of LCR waters and its source(s). This may be closely tied to (iii) and to obtaining full explanations for the very high specific conductivities observed in portions of the watershed.

(vi) construct detailed and quantitative descriptions of temporal and geospatial patterns of land use within the LCR watershed. By detailed, we mean not only general land use classifications, but also specific site-scale activities and the contaminants they could plausibly contribute to the watershed. This is necessary for both tracing out the origins of contaminants within the watershed, and for developing more general models of the relationships between overall land uses and water quality. An initial contract task was to identify urban/rural land use and agricultural intensification indices that correlate well with water quality based on a literature search and consideration of regional characteristics. Potential metrics include % impervious surface area (a simple, common, and often highly effective measure), % each land use over watershed, % each land use along riparian corridor, population density, degree of fragmentation of vegetated area, and road density. However, highly preliminary comparisons of the limited, currently available water quality data to aerial photographs of the LCR watershed do not seem to suggest that such conventional indices provide a convincing description of geospatial water quality variation here. The situation appears particularly challenging for metals (see iii above), although this may represent in large part the inadequacy of current metals data. Both more water quality data (see below), and more detailed and quantitative land use data, are necessary to determine the origins of contaminants within the watershed and identify broader relationships between water quality and land use.

I.4.2.2 Medium-term analysis recommendations

A number of next steps, consistent with the general considerations outlined in **Table 1** but generally requiring additional data collection prior to implementation, can be identified as follows:

(i) assess the feasibility and effectiveness of developing an empirical (statistically based) land use-water quality model, following directly from the recommendations listed in the foregoing section of this report, and construct such a model if appropriate.

(ii) develop statistical streamflow models. These relate meteorological forcing to streamflow responses, and can be used to identify changes in such relationships due to watershed modifications. Rainfall-runoff relationships are particularly sensitive to the increase in percent impervious area associated with urbanization, and have strong consequences for water quality, habitat quantity, and erosion. Given proposed developments within the Little Campbell River watershed, this is a particularly important, forward-looking analysis goal.

(iii) assess and model biological oxygen demand (BOD) and eutrophication in the Little Campbell River. The often low dissolved oxygen levels observed in the LCR may be particularly harmful to salmonids, a primary environmental management target. These suboptimal oxygen levels likely have some relationship to the generally very high levels of fecal coliforms and possibly to eutrophication arising from moderately elevated nutrient concentrations.

(iv) develop a process- (physically) based, linked hydrological, ecological, and chemical model of the Little Campbell River. This could permit the effects of proprosed developments or remediation projects to be quantitatively explored, and could ultimately be a key management tool for the Little Campbell River. Construction of a robust process-based model, however, will likely require that the other analysis and modelling tasks outlined above, and the data collection outlined below, be performed first.

I.4.2.3 Water quality monitoring

Further water quality work in the Little Campbell River, focusing on changes to sampling regime, is immediately required. A detailed five-year monitoring program is outlined in a subsequent section of this report; some important points are outlined here.

The strong majority of water quality data obtained to date in the LCR watershed has been collected at a large number of locations, with a small number of samples infrequently collected at any given location. This shotgun approach is useful for tracing out some general water quality patterns. However, the small number of samples at any given location precludes analysis of temporal patterns, analysis of relationships between water quality and external environmental variables, and formal statistical analysis of geospatial patterns in water quality and their relationships to such potential controlling factors as land use.

Future water quality data collection needs to focus on far more frequent and regular sampling at particular key locations. This includes both the installation of one or more automated water quality monitoring stations, collecting a suite of data parameters on a semi-continuous basis, as well as more frequent and consistent grab sampling for a broad range of water quality parameters at several locations within the watershed. Far more discharge data must also be obtained to enable hydrologic modelling, assessment of relationships between water quality and quantity, and loading calculations.

The necessity for timeliness cannot be overemphasized. A number of major developments are planned for the Little Campbell River watershed. Assessment of the environmental impacts of such development requires, at a minimum, an adequate baseline dataset against which water quality measurements during and after development can be compared. Moreover, any attempt to quantitatively or semi-quantitatively pre-assess the environmental effects of specific development proposals requires some level of mathematical predictive capability, which can only be obtained by constructing models on the basis of historical data.

II. *Climate Variability and Change Impacts*

II.1. Introduction

II.1.1 El Niño Impacts

El Niño – Southern Oscillation (ENSO) is a dominant mode of planetary-scale atmospheric circulation variability having globally significant hydrometeorological and ecological implications (*e.g.*, Philander, 1990; Wallace and Thompson, 2002). These include streamflow impacts across western North America (*e.g.*, Cayan and Peterson, 1989; Redmond and Koch, 1991; Woo and Thorne, 2003). The coupled ocean-atmosphere oscillation exhibits timescales of about two to seven years, and the typical individual ENSO event lasts about a year. Less widely considered to date are the modulating effects of the Pacific Decadal Oscillation (PDO), a mode of North Pacific circulation variability which is analogous to ENSO but operates at much longer timescales, of the order of several decades. In general, ENSO events are stronger when they occur with the same phase as the PDO, and weaker when they are of opposite phase. 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).

We used climatological composite analysis to assess ENSO impacts upon Little Campbell River surface and subsurface hydrology and regional surface meteorology. Due to limited data availability within the watershed, we expanded the analysis to consider local-scale lower Fraser Valley floodplain effects in general. The mean annual regimes of streamflow, groundwater level, air temperature, and precipitation are compared between El Niño, La Niña, and neutral years. 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 bootstrap method. In conjunction with this resampling approach, the composite analyses are robust to both potential nonlinearity and non-Gaussian distributions. The results of the statistical analyses are physically interpreted, and some potential implications are identified, particularly with respect to Little Campbell River fisheries health. Note that some of these results have, with the client's (MOE's) permission and input, been published in the peer-reviewed open scientific literature (Fleming and Quilty, in press).

II.1.2 Climatic Change, Water Temperature, and Ecological Risk

Long-term global climatic changes, arising both from natural effects and from human augmentation of atmospheric greenhouse gasses, are of central scientific and, increasingly, political importance. It is well-recognized that such potential climatic changes might lead to degradation of fish habitat by warming lotic and lentic waters beyond historical levels (*e.g.*, Eaton and Scheller, 1996). In this section, we perform a preliminary assessment of current chronic (cumulative) temperature risks to Little Campbell River steelhead, which are a key watershed management concern and relatively susceptible to chronic thermal impacts, and then evaluate potential increases in chronic risk associated with climatic change.

Acute risks are defined in terms of immediate fish mortality, whereas 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 growth rates begin to be experienced at about 14°C. As in assessment of acute risks, however, the emphasis lies upon the summer period (about May to September), when British Columbia stream temperatures are highest and potentially in the range at which acute risks or chronic growth risks occur.

Due in part to severe data limitations, the following assessment must be considered a tentative – albeit instructive – exploration of potential climatic change impacts upon Little Campbell River fisheries resources.

II.2 Data

II.2.1 El Niño Impacts

We employed the list of ENSO event years developed by Kiffney *et al.* (2002), which is summarized below in **Table 9**. While the canonical ENSO event is roughly a year in duration, it typically spans two calendar years, often reaching its peak during the intervening winter. ENSO events are thus often identified as, for example, the 1982-1983 El Niño.

Table 9 *ENSO event years, adapted from Kiffney* et al. *(2002). For each ENSO event, concurrent PDO phase is also shown. For both ENSO and PDO, W = warm phase and C = cold phase. ENSO events for which both ENSO and PDO are listed as W are in-phase warm events (*e.g.*, 1982-83 El Niño); those for which ENSO and PDO are both listed as C are in-phase cold events (*e.g.*, 1998-99 La Niña). Out-of-phase ENSO events have opposite phase to the concurrent PDO regime (*e.g.*, 1957-1958 El Niño).*

year	ENSO	PDO	year	ENSO	PDO
1949-1950	C	C	1973-1974	C	C
1950-1951	C	C	1975-1976	C	C
1951-1952	W	C	1976-1977	W	W
1953-1954	W	C	1982-1983	W	W
1954-1955	C	C	1986-1987	W	W
1955-1956	C	C	1987-1988	W	W

1957-1958	W	C	1988-1989	C	W
1963-1964	W	C	1991-1992	W	W
1964-1965	C	C	1994-1995	W	W
1965-1966	W	C	1995-1996	C	W
1968-1969	W	C	1997-1998	W	W
1969-1970	W	C	1998-1999	C	C
1970-1971	C	C	1999-2000	C	C
1972-1973	W	C			

Hydrometeorological data were sourced from the online Water Survey of Canada HYDAT database; the online Meteorological Service of Canada Historical Canadian Climate Database (HCCD; see Mekis and Hogg, 1999 and Vincent and Gullett, 1999); and the online MOE Observation Well Network database. Four hydrometeorological parameters, each measured at two or more stations, were considered: mean monthly air temperature, total monthly precipitation, mean monthly river discharge, and monthly groundwater level. Because the reliable list of ENSO event years used here only covers the period 1949-2000 (**Table 9**), we truncated hydrometeorological time series having longer records at these start and end dates, where applicable. When selecting stations, we only used surface and subsurface hydrologic stations with record lengths, after accounting for gaps and the other foregoing issues, of about 20 years or more. All data were parsed into hydrological years, which consist of data from October of the previous calendar year to September of the current calendar year; this step is important when there is negligible snowpack storage in the watershed, which is the case for the LCR. For example, the 1982-1983 hydrologic year consists of the 12 months of data from October 1982 through September 1983. This format corresponds closely to the manner in which ENSO years are defined (see above). We retained the seasonal cycle in the data because the resulting composites (see below) are more readily interpretable in that form.

Operation of the WSC gauge on the Little Campbell River was seasonal and relatively short-lived. Monthly mean data were only consistently available for the months of May through September. Thus, the winter peak flow period was not sampled. Moreover, data gaps were such that only 10 years of discharge data were available: 1984 through 1994, without 1989. In addition, the Kerr-Wood-Leidal (City of Surrey) LCR gauge data are of insufficient duration (from 2000) to perform hydroclimatic analyses of this type. For the purposes of hydroclimatic analysis, we therefore used data from other lower Fraser Valley rivers with generally similar characteristics as a surrogate for LCR data. In particular, we selected only rivers with drainage areas strictly within the lower Fraser Valley lowland, omitting those with headwaters in adjacent mountainous regions. The foregoing criteria ultimately led to selection of three hydrometric stations for analysis. Note that no Reference Hydrometric Basin Network (RHBN; Harvey *et al.*, 1999) stations meet the requirement for drainage area containment strictly within the lower Fraser Valley lowland, so the rivers considered here may have substantial anthropogenic influences. Using such data would be problematic for climate change signal detection, whereby a long-term hydrologic trend could arise from trends in either climate or watershed modification and water abstraction. For detecting discrete ENSO events, however, anthropogenic effects seem likely to obscure potential climatic effects, rather than lead to false positive identifications. Evaluation of ENSO impacts using such data thus probably leads to a conservative result.

Of the available locations in the Observation Well Network, only well 012 lies within the Little Campbell River watershed. The well is described as being completed in the unconfined Abbotsford-Sumas aquifer, although the listed lithology indicates a low-permeability (10^{-6} m/d) clay layer to a depth of 7 m, and water levels can be as little as 1.1 m below ground surface, which may suggest that the aquifer might be locally confined and almost artesian. Unlike some other wells in the network, no long-term drift obviously due to groundwater depletion was evident. To confirm the well 012 results, all other Observation Well Network sites within the lower Fraser Valley were also screened for inclusion in the analysis. A total of three additional wells, not showing long-term drift, satisfied the foregoing record length criterion. In general, it appears that effort was made to take about one water level reading per month for the selected wells. Because groundwater levels generally fluctuate much more slowly than river levels (at least for relatively small streams, like the Little Campbell River), it is reasonable to take a once-monthly reading as being generally representative of aquifer conditions over that month. When more than one reading was taken during a month, the reading closest to the middle of the month was generally used and the other discarded. If there was no sample for a given month, but multiple readings were taken the next or previous month and one was close to the beginning or end of the month (respectively), we generally used that value to fill in the missing sample. For example, if readings were taken May 10, July 1, and July 18, then we would use the May 10 and July 18 values as being representative of May and July, respectively, and the July 1 measurement would be assigned to June. Finally, if after these steps there was a gap of no more than one month's duration, linear interpolation was used to fill the gap. A year which did not have data for all 12 months following these procedures was omitted from the analysis. As with the river discharge data employed, there are no guarantees that the groundwater level data are free of anthropogenic influences, such as pumping interference. Again, this likely leads to a conservative result.

The surface meteorological and surface and subsurface hydrometric stations ultimately selected for analysis are listed and described in the following tables. In these tables, N_T is the total number of data; N_W is the total number of El Niño events sampled over the record; N_C is the total number of La Niña events sampled; $N_{W,\,IP}$ is the number of El Niño events in phase with the PDO occurring during the record; and $N_{C,\,IP}$ is the number of observed La Niña events in phase with the PDO. The start and end years listed refer to the period of record used in the analysis, which is not necessarily the full suite of data available at that station. Similarly, the mean value was calculated from all months of data over the period of record actually used in the analysis.

Table 10 *Background, meteorological data. These homogenized HCCD data are gap-free.*

	precipitation		temperature	
	Agassiz CDA	**Vancouver Intl A**	**Agassiz CDA**	**Abbotsford A**
Station ID	1100120	1108447	1100120	1100030
Mean	134 mm	102 mm	10.3 °C	9.8 °C
Interval	1949-2000	1949-2000	1949-2000	1949-2000
N_T	52	52	52	52
N_W	15	15	15	15
N_C	12	12	12	12
$N_{W, IP}$	7	7	7	7
$N_{C, IP}$	10	10	10	10

Table 11 *Background, groundwater level data. All the time series contain gaps.*

	Huntingdon Rd, Abbotsford	**Mt. Lehman, Abbotsford**	**McCallum Rd, Abbotsford**	**2145 200th St, Langley**
Station ID	002	003	008	012
Mean	-12.2 m BGS	-9.9 m BGS	-17.8 m BGS	-5.3 m BGS
Interval	1967-2000	1963-2000	1963-2000	1968-2000
N_T	31	32	31	29
N_W	9	10	10	8
N_C	6	7	7	6
$N_{W, IP}$	7	5	5	5
$N_{C, IP}$	4	6	5	5

Table 12 *Background, river flow data. One time series (Salmon River) contains gaps.*

	Anderson Creek at the mouth	**Nicomekl River below Murray Ck**	**Salmon River 72nd Ave, Langley**
Station ID	08MH104	08MH105	08MH090
Area, km^2	27.2	64.5	49.0
Mean	0.69 m^3/s	1.8 m^3/s	1.5 m^3/s
Interval	1966-1986	1966-1984	1961-1999
N_T	21	19	33
N_W	6	6	9
N_C	3	3	6
$N_{W, IP}$	2	2	7
$N_{C, IP}$	3	3	4

II.2.2 Climatic Change, Water Temperature, and Ecological Risk

Hourly temperature data were collected by M. Pearson over April 22 to October 6, 1999 in the Little Campbell River at Highway 15. Dr. Pearson kindly provided these data to us. The data adequately bracket the summer warm period. The maximum observed hourly temperature was 19.9°C, so no acute risks to salmonids appear to have been present in the LCR at this location in 1999, and we focus our efforts upon assessment of cumulative risk. We converted the data to daily means for use in the chronic risk analysis (see below).

II.3 Methods

II.3.1 El Niño Impacts

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 Campbell River discharge record, for instance, we separate the 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, for example, June discharge is constructed by drawing observations from the historical June record at random; the three composites are constructed from this synthetic time series; 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-year June discharge versus mean neutral-year 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 95th 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 again, considering only those ENSO events which occurred in phase with the PDO, out-of-phase ENSO events being placed in the neutral subset.

II.3.2 Climatic Change, Water Temperature, and Ecological Risk

II.3.2.1 Chronic Risk Assessment

Elevated stream water temperatures present two general kinds of risks to salmonids: acute (also known as lethal), and chronic (also known as sub-lethal or cumulative). Acute impacts occur when fish are subject to sufficiently high water temperatures for a sufficient amount of time to experience mortality. Chronic effects occur when fish are exposed to sufficiently high temperatures to compromise feeding, growth, disease resistance, competitive ability, predator avoidance, and migration and spawning success, primarily via bioenergetic (metabolic) pathways (see Kitchell *et al.*, 1977; Elliott, 1981; Poole *et al.*, 2001). The temperatures at which chronic effects occur are lower than those associated with acute risks. While chronic exposures by definition do not directly cause fish mortality over the short term, they can contribute to eventual mortality of individual fish and can lead to severe degradation of overall population viability (Poole *et al.*, 2001).

Formal protocols for assessing human and ecological risks arising from toxins in the environment are well established. While much thought has been given to the fundamental science of environmental temperature effects upon salmonids, no parallel risk assessment framework has been formally developed and broadly accepted as a practical management tool for temperature risk assessment. A powerful complication with temperature risk is that meaningful and reliable, single-valued, risk-based threshold temperatures are difficult to develop, and may in fact be inappropriate altogether.

Unlike most toxicological risks, water temperatures vary greatly in both space and time under fully natural conditions, even within a generally uniform hydroecological area, and consequently are quite likely to be biologically sub-optimal at any given place and date in the absence of thermal pollution. The net result is that no single threshold temperature can appropriately be set as a general watershed management standard, even for a single life stage. For example, a threshold high enough to account for naturally warm streams may leave thermal pollution in a colder river undetected, and a threshold low enough to detect thermal pollution in a cool river may inaccurately identify naturally warmer rivers as being in violation (for detailed discussions, see Poole *et al.*, 2001; Ice *et al.*, 2004). In addition, such an approach fails to recognize the biological importance of both magnitude and duration of exposure (for example, see Sullivan *et al*., 2000; Ice *et al.*, 2004).

AI has developed a proposed method for quantitatively assessing chronic risks to salmonids from high stream water temperature, which adequately addresses the foregoing issues while remaining straightforward to implement as a practical watershed management tool. The resulting protocol is divided into two steps. Phase I yields a primarily visual assessment, and phase II provides a single but relatively comprehensive risk index, the risk quotient (*RQ*), which gives a clear flag for the presence of ecologically negative changes in river thermal regime. The approach was applied to the Little Campbell River using summer 1999 water temperature data and assuming steelhead to be the target species for watershed management.

This proposed magnitude-duration approach to chronic temperature risk assessment was introduced and explained in detail by Fleming *et al.* (2005) and Fleming and Quilty (in review). Readers should refer to those publications for a full technical explanation of the method. In summary, the proposed approach has the following general properties. (i) It uses temperature impacts upon 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 relative to the use of a fixed upper threshold temperature, 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 proposed 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 the Little Campbell River. In the current application, then, we present our results primarily in terms of *TGR* (see above for definition), 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 1999. This factor is closely analogous to *RQ*. A similar approach was used by Hudson *et al.* (2005).

The results are species-dependent (although the impacts of species dependence may be mitigated in part through the normalization by a historical risk value; see Fleming *et al.*, 2005 and Fleming and Quilty, in review). The Fisheries Information Summary System (FISS) online database lists the following species as having been identified in the Little Campbell River at some point in the last 25 years: chinook, chum, sockeye, pink, and coho salmon; cutthroat, steelhead, and non-anadramous rainbow trout; Dolly Varden; brown catfish; coast range, prickly, and slimy sculpin; flathead chub; fathead minnow; pumpkinseed; threespine stickleback; and Salish sucker, although this native species has since been extirpated from the LCR (M. Pearson, pers. comm., 2005). Sturgeon, bass, sunfish, and lamprey are also listed as present, but particular species are not indicated. Sampling performed by M. Pearson at several LCR locations in May 1999 and August 2000 identified coho, rainbow/steelhead, prickly sculpin, threespine stickleback, fathead minnow, pumpkinseed, and brown bullhead, as well as salamanders, bullfrogs, and crayfish. A number of the foregoing are introduced warm-water species. The primary management focus in the LCR lies on salmonids, and steelhead are a particular point of concern due to dramatic stock declines in this watershed (B.C. Conservation Foundation, 2005). Moreover, the optimal growth temperature for steelhead/rainbow is a relatively low 10-14^{o}C (see Ford *et al.*, 1995). Steelhead are therefore an appropriate watershed-specific target for chronic temperature risk assessment, and the evaluations should also be generally protective of other salmonid species. A relationship between daily mean water temperature and rainbow/steelhead specific growth rate, defined specifically for temperatures exceeding the optimum, was developed by Fleming *et al.* (2005) and Fleming and Quilty (in review) on the basis of information provided in Sullivan *et al.* (2000), and is applied here for assessing potential growth losses.

II.3.2.2 Controls on LCR Water Temperature

To obtain projections of chronic temperature risks under climatic warming, water temperature predictions must be developed, which in turn first requires determining controls upon water temperature in the Little Campbell River. A brief summary of general controls upon stream water temperature is given below, drawn from Brown (1969), Cluis (1979), Stefan and Preud'homme (1993), Webb and Nobilis (1997), Mohseni and Stefan (1999), and Webb *et al.* (2003). Stream water temperature is a function of a broad variety of factors, including air temperature, intensity and duration of solar radiation, wind speed, water vapour pressure in the air, river depth, river discharge, degree of mixing, riverbed thermal conductivity, and the temperatures of surficial and groundwater flows. A number of these in turn depend on other parameters, such as degree of riparian shading and catchment geology, aspect, elevation, and size. For a given river with constant watershed properties, however, air temperature is usually the statistically dominant control upon time variation in water temperature, in part because it integrates the effects of other meteorological parameters.

The relationship between air and water temperature varies depending upon the time discretization of the data and the temperature range considered. In general, the closest relationship exists between monthly mean air and water temperatures, and the quality of the relation degrades when smaller (*e.g.*, daily mean) or larger (*e.g.*, yearly mean) data discretizations are considered. The relationship is generally considered to be linear. When the full annual temperature range of a river is considered, however, the air-water temperature relationship is theoretically nonlinear, particularly at very low (~freezing) and very high (> ~25^{o}C) water temperatures. It has been indicated that the latter might have strong implications for evaluation of climatic change impacts upon stream water temperature, as the linear air-water temperature relationship developed for a study site on the basis of a historical record might not well-predict water temperatures in a much warmer future. However, further research has suggested that, at least in temperate climates, nonlinearity at high values of the air-water temperature relationship are subtle when hourly data is considered; moreover, there is little empirical evidence for high-temperature nonlinearity when larger (*e.g.*, daily or weekly) sampling intervals are used, which is the case in many climatic change studies.

Analyses of the available LCR temperature data were broadly consistent with the foregoing general summary. April 22 – October 6, 1999 daily mean LCR temperatures correlated with Abbotsford Airport daily mean air temperatures at R = 0.84, and May – June 1999 monthly mean LCR temperatures correlated with Abbotsford Airport monthly mean air temperatures at R = 0.94. Linear slope estimates were similar to those found in the literature. Air temperature may thus serve as a reliable linear predictor of LCR water temperature.

II.3.2.3 Risk Projections to 2020, 2050, and 2080

We considered climate predictions for 2020, 2050, and 2080 from the CGCM2 model under the widely employed, midrange IS92a 1 scenario (transient model, green house gases plus sulphate aerosols, 1% per year CO_2 increase) (Leggett *et al.*, 1992; Flato and Boer, 2001; CCCma, 2004). A simple transfer function approach to empirical downscaling was employed. Specifically, a linear regression relationship was developed between Little Campbell River water temperature and CGCM2 modelled air temperature, using May-September monthly mean values from 1999, and climate model output from a grid cell centred at approximately 123.75°W and 50.10°N. Cell dimensions are about 3.75° by 3.75°. Note the climate model output is available only at monthly, not finer, intervals. In spite of few degrees of freedom (N = 5), the relationship was strong and significant using a parametric approach (R = 0.90, P < 0.05); note that empirical CDFs of summer monthly water and CCCma air temperatures do not suggest departures from normality. The regression relationship was then used to estimate monthly mean water temperatures for May-September of 2019-2021, 2049-2051, and 2079-2081 from climate model predictions over those intervals. For each of these three future timeframes, we then calculated average increases in overall summer mean water temperature, ΔT, relative to present conditions. LCR water ΔT estimates were 1.1°C (ca. 2020 versus 1999), 1.7°C (ca. 2050 versus 1999), and 2.2°C (ca. 2080 versus 1999). Three May-September daily mean water temperature time series, T_t, ca. 2020, 2050, and 2080 were then calculated as $T_t = {}^{1999}T_t + \Delta T$. Finally, we performed risk analyses for each of these predicted daily time series. A generally similar approach was used by Fleming and Quilty (in review).

It is important to explicitly state some of the limitations to this approach. Like all empirical downscaling techniques, ours assumes that relationships between variables remain stationary. We also assume that statistical properties of daily mean water temperature other than the summer mean remain stationary; only a single forcing scenario is considered; and we have only one summer of historically observed LCR water temperature data which can be used in developing downscaling relationships, and which can be projected forward under climatic change. In addition, the analysis focuses upon a single aspect of thermal impacts upon fisheries health. Other potentially important questions, such as further displacement of native species by warm-water introduced species under climatic warming, or how chronic risk changes quantitatively translate into changes in population health and size, are not directly addressed.

Nevertheless, the results provide rough but useful estimates of what the LCR summer thermal regime, and associated chronic temperature risk to salmonids, could look like under anthropogenic climatic forcing. Moreover, this process of developing models for climate change assessment helps delineate the types of data acquisition that will be needed to better evaluate such impacts, and thus help define LCR monitoring requirements.

II.3.2.4 Sensitivity of Risk Projections to Current Management Actions

It is worthwhile to briefly explore how changes in current watershed management strategy might affect the ultimate impacts of potential climatic changes. For example, riparian planting along the Little Campbell River, which has lost much of its shading, might quickly reduce summer LCR water temperatures. The LCR stream temperatures that might ultimately occur under climatic shifts would be lower in that case, and the chronic thermal risk under a warmer climate would therefore also be less. Conversely, current watershed management decisions which lead to an elevation of LCR stream temperature would thus heighten the increases in thermal risk that might eventually be associated with climatic change.

To obtain some quantitative estimates of how the management-controlled current starting point might ultimately effect the thermal risks potentially arising from long-term climatic change, the suite of analyses discussed in Section II.3.2.3 were re-performed on two datasets: (i) observed 1999 LCR summer water temperatures increased by 10%, loosely representing some of the possible effects of poor watershed management; and (ii) observed 1999 LCR summer water temperatures decreased by 10%, loosely representing some of the possible effects of watershed remediation.

II.4 Results and Interpretation

II.4.1 El Niño Impacts

II.4.1.1 *All ENSO Events*

Magnitude of response

Results of composite analyses considering the effects of all ENSO events, without regard to PDO phase, are shown in **Figures 13 to 23**.

The key of these figures is as follows. 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. The groundwater levels are presented as depth below ground surface, with greater depths represented by larger negative values. As noted above, we consider here hydrologic years, where -2, -1, and 0 indicate October, November, and December of the prior year (that is, the year of ENSO event onset), and 1 through 9 denote January through September of the current year.

ENSO anomalies are seen to be generally strongest in winter and spring, with La Niña events yielding cooler temperatures and higher rainfall. This is consistent with prior results for the British Columbia lower mainland (see Shabbar *et al.*, 1997; Kiffney *et al.*, 2002). Such precipitation variability is clearly reflected in the available hydrologic data. El Niño and La Niña years are generally associated with lower and higher winter and spring river discharges. Similarly, groundwater levels tend to be considerably higher during La Niña years and lower during El Niño years due to variations in winter and spring aquifer recharge arising from ENSO-related precipitation variability.

Local hydrometeorological responses to ENSO show some nonlinearity insofar as their warm- and cold-phase events are not exact opposites, a common characteristic of extratropical ENSO teleconnections (see Hoerling *et al.*, 1997). The effect appears least noticeable for temperature, and most consistent for groundwater level. In general, the hydrological impacts of La Niña appear to be locally somewhat greater than those of El Niño.

ENSO-related temperature anomalies appear to have few local hydrologic effects, likely because these only occur during winter and early spring. Such temperature variability may thus be unlikely to have substantial evapotranspiration impacts. Moreover, the climatic regime within the watershed is sufficiently mild that virtually all winter precipitation falls as rain, regardless of variability in winter temperature. Consequently, the snowpack and subsequent streamflow and groundwater level impacts of wintertime temperature variability, which can be strong in other hydroclimatic regions, do not play a substantial role here.

The observed monthly significance levels are variable between parameters, and between individual stations for a given parameter. Significance was most consistent for the four HCCD meteorological time series, which are much longer than the hydrologic records and have also been rigorously quality-controlled and corrected (Mekis and Hogg, 1999; Vincent and Gullett, 1999). Thus, the relatively weak consistency of significance in the surface and subsurface hydrologic composites may simply reflect fewer degrees of freedom and, notably, climate signal detection problems potentially associated with changes in watershed land use and water abstraction. Moreover, most of the surface and subsurface hydrometric stations indeed show significant differences during one or more months of the year and, in particular, the mean El Niño and La Niña responses for a given parameter are very similar across stations.

Timing of response

Table 13 gives the month during which the annual cycles in precipitation, river discharge, and groundwater level occur at each station, under historical average neutral and warm- and cold-phase conditions. These are simply the months at the which the composites illustrated in the preceding figures have their maxima. Although timing is dependent upon the individual station, overall, the annual streamflow cycle lags precipitation by roughly one or two months, and the annual groundwater level cycle lags precipitation by roughly three or four months. However, there is little evidence that ENSO events lead to earlier or later peak values. That is, La Niñas and El Niños change the amplitude of the annual hydrometeorlogical cycle, but do not appear to systematically vary its overall timing.

Table 13: *Month during which annual peak value occurs, in the mean.*

	Month of annual cycle maximum		
Parameter and station	**El Niño**	**Neutral**	**La Niña**
Precipitation:			
Agassiz CDA	1	-1	-1
Vancouver Intl A	0	-1	-1
Streamflow:			
Anderson Creek	1	1	1
Nicomekl River	0	0	1
Salmon River	1	0	0
Groundwater level:			
Well 002	4	4	4
Well 003	3	3	3
Well 008	4	5	4
Well 012	3	3	2

However, visual inspection of the composites suggests that ENSO-related groundwater level anomalies are far more persistent throughout the year relative to those in precipitation. This presumably reflects the fact that much of the annual recharge to long-term aquifer storage occurs during the winter wet period, and precipitation variations in that period thus strongly control water levels the remainder of the year. Moreover, it is well-recognized that, relative to most other terrestrial hydrologic systems, aquifers are generally slow-responding, long-memory systems (*e.g.*, Gottschalk, 1977). The seasonal persistence of the ENSO-related change in streamflow appears to be roughly intermediate between that in precipitation and groundwater level, likely due to the competing effects of fast surface runoff and shallow interflow, versus longer-memory watershed storage. The latter may predominantly consist of aquifer storage in the study watersheds.

This issue was further explored using the serial correlation coefficient as a measure of anomaly persistence. All the precipitation, streamflow, and groundwater flow stations were considered. For each parameter, station, and ENSO phase, a 12-month composite anomaly was generated as the difference between the neutral and ENSO event composites shown above. The lag-1 serial correlation coefficient was then calculated for each of the 18 resulting composite anomalies. Finally, the mean serial correlation coefficient was calculated for each of the three parameters. The values were 0.20 for precipitation, 0.22 for streamflow, and 0.51 for groundwater level. There was considerable within-group variability, no doubt in part due to the small number of samples (11) used to calculate each serial correlation coefficient, and a preliminary ANOVA under the standard assumptions did not suggest significant ($P < 0.05$) differences between the three means. However, this reflects in part the similarity between the mean serial correlation coefficients for monthly precipitation and streamflow anomalies. Thus, the streamflow and precipitation serial correlation coefficients were lumped into a single group with a mean of 0.21, and the null hypothesis of equality was tested against the one-sided alternative hypothesis that this lumped mean is smaller than the mean serial correlation coefficient of the groundwater composite anomalies. A *t*-test assuming equal variances was used; note that an *F*-test did not indicate significant differences between the variances of the two populations. The test suggested at $P < 0.05$ that groundwater anomaly persistence is greater than that in precipitation and streamflow. While these results are strictly preliminary, they do lend quantitative support to the hypothesis that the degree to which wintertime ENSO effects are distributed over the year is in rough proportion to the degree of physical system memory.

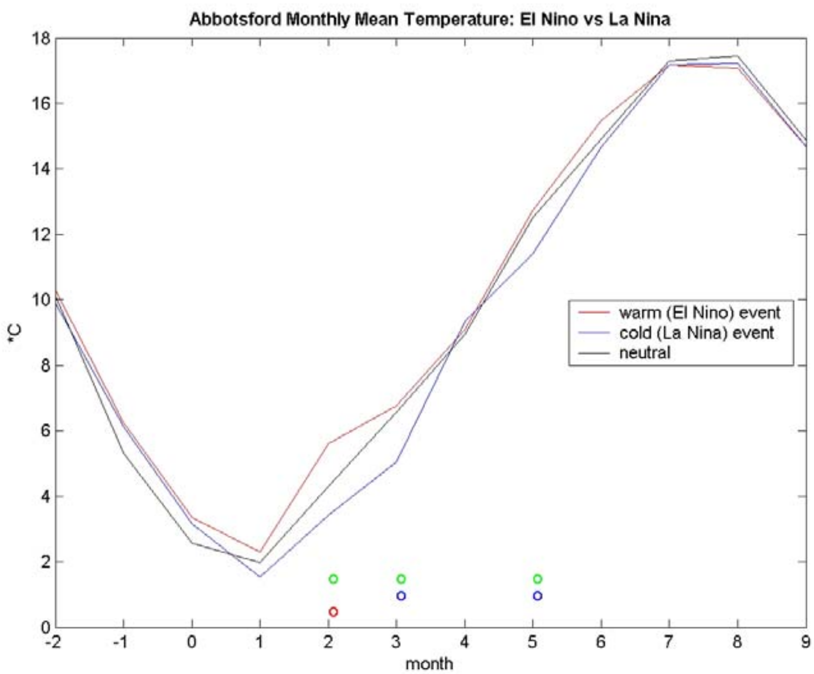

Figure 13 *Average response of Abbotsford air temperature to ENSO states over the hydrologic (water) year. –2 through 0 are October to December of the year of event onset, 1 through 9 are January to September of next calendar year.* **o** *denotes a statistically significant difference between mean warm- and neutral-phase conditions for that month;* **o** *denotes a statistically significant difference between mean cold- and neutral-phase conditions for that month; and* **o** *indicates a statistically significant difference between mean warm- and cold-phase conditions for that month.* ***Figures 14*** *to* ***34*** *use this same notation.*

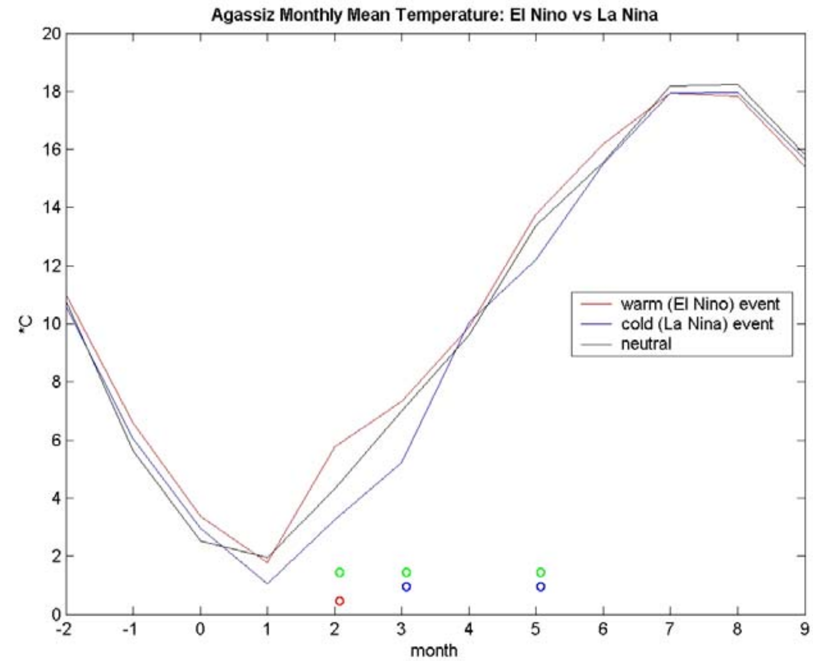

Figure 14 *Response of Agassiz air temperature to ENSO*

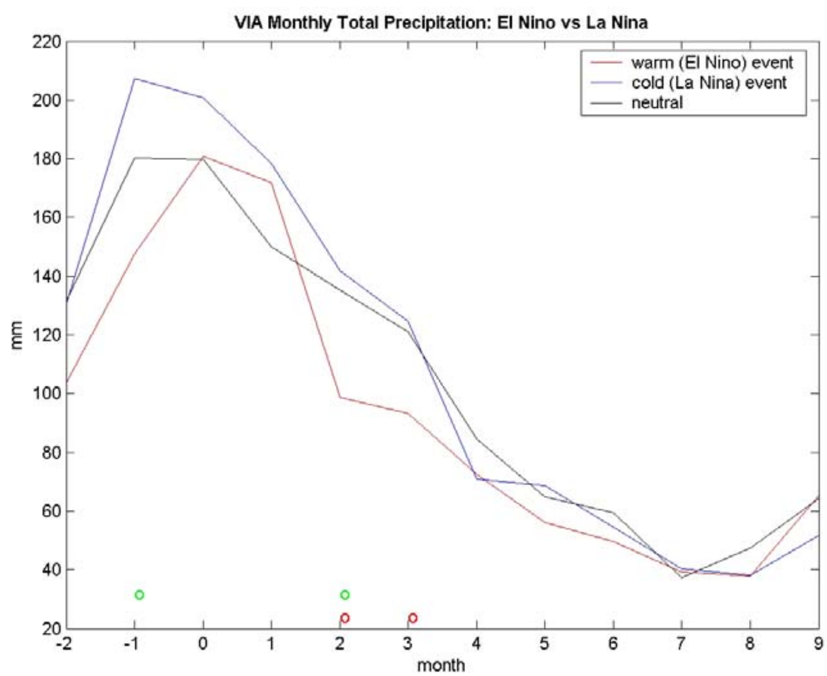

Figure 15 *Response of Vancouver International Airport precipitation to ENSO*

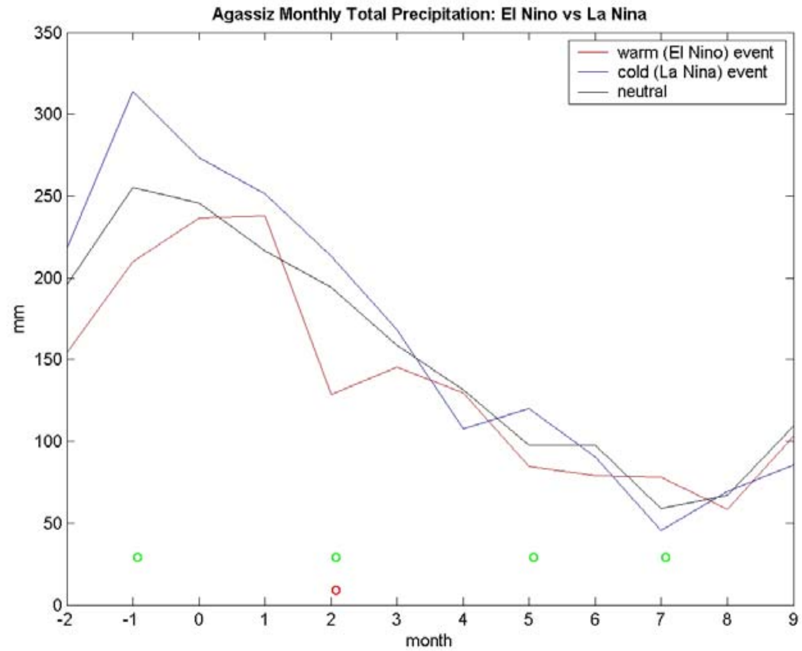

Figure 16 *Response of Agassiz precipitation to ENSO*

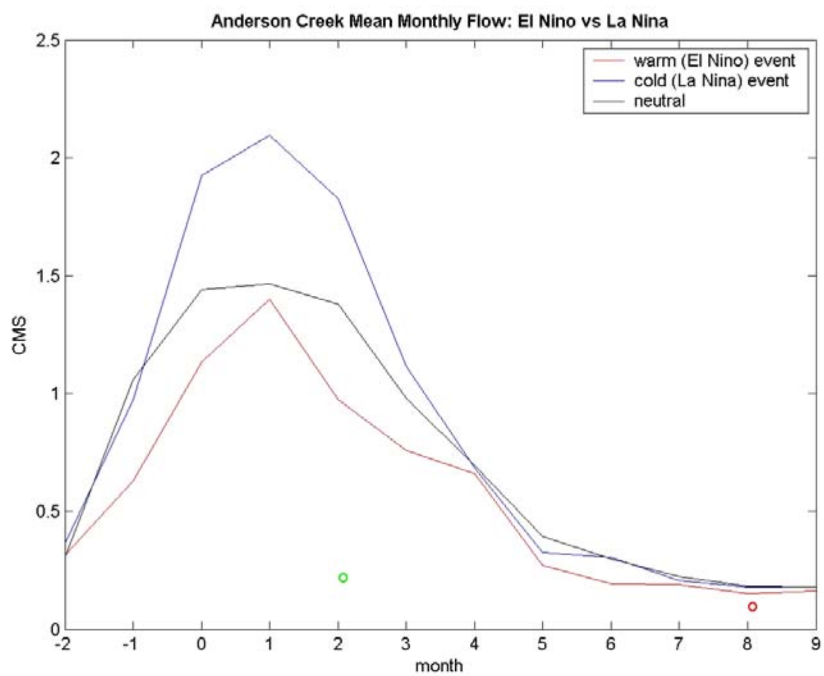

Figure 17 *Response of Anderson Creek streamflow to ENSO*

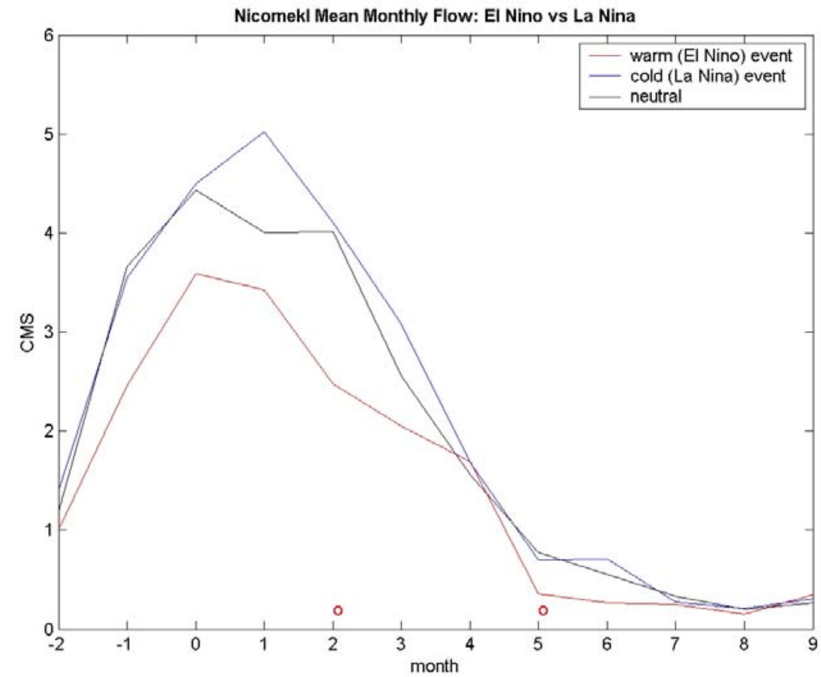

Figure 18 *Response of Nicomekl River discharge to ENSO*

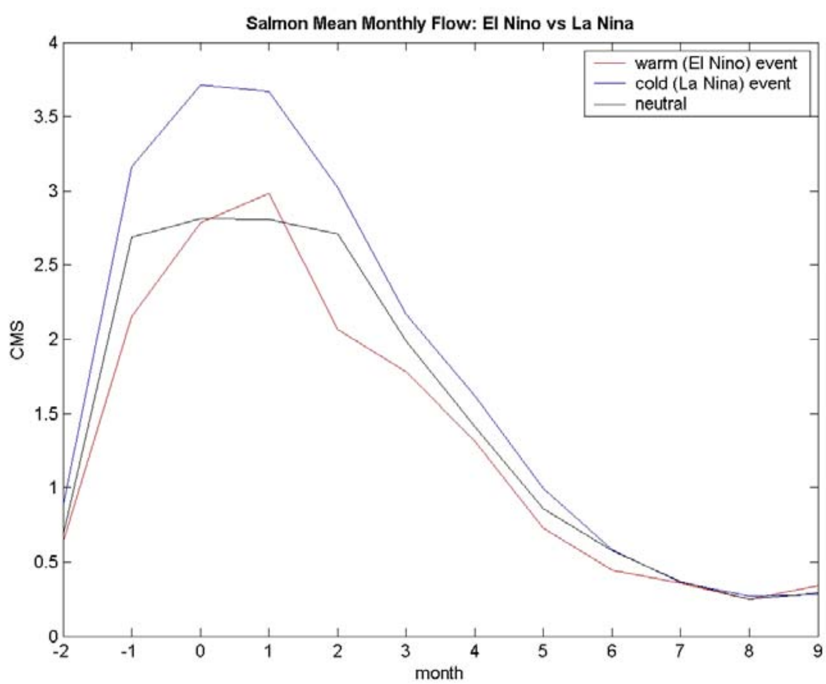

Figure 19 *Response of Salmon River discharge to ENSO*

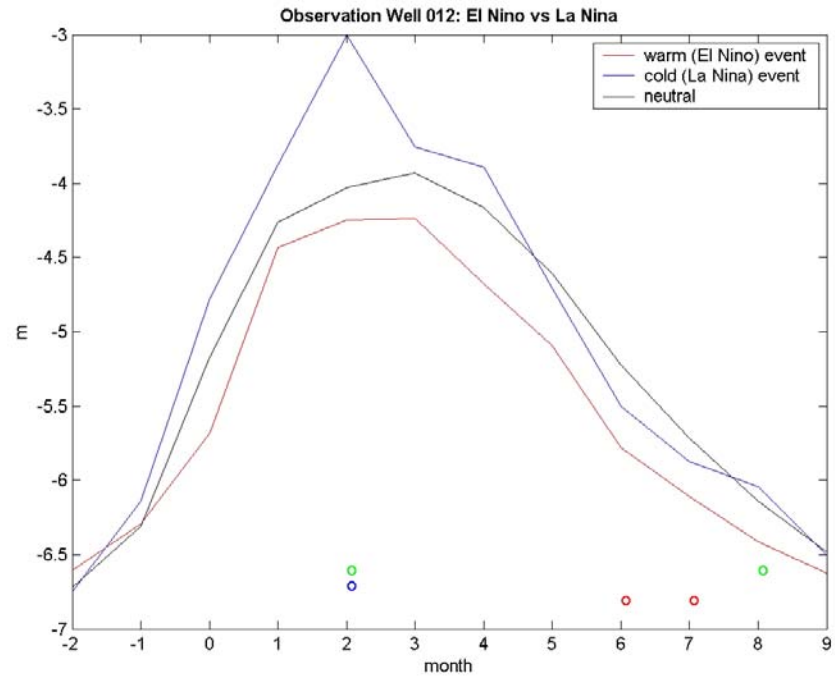

Figure 20 *Response of Well 012 groundwater levels to ENSO*

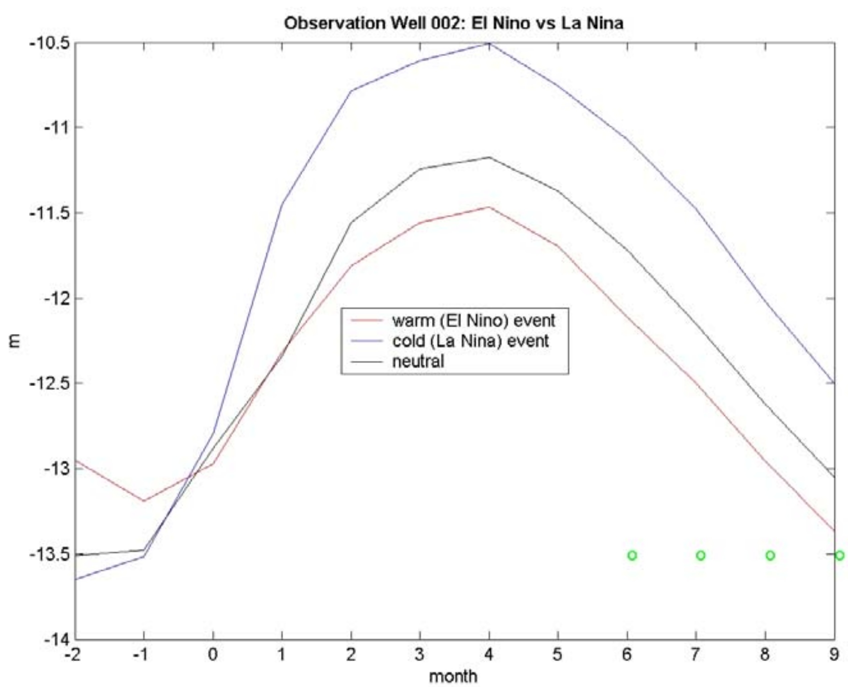

Figure 21 *Response of Well 002 groundwater levels to ENSO*

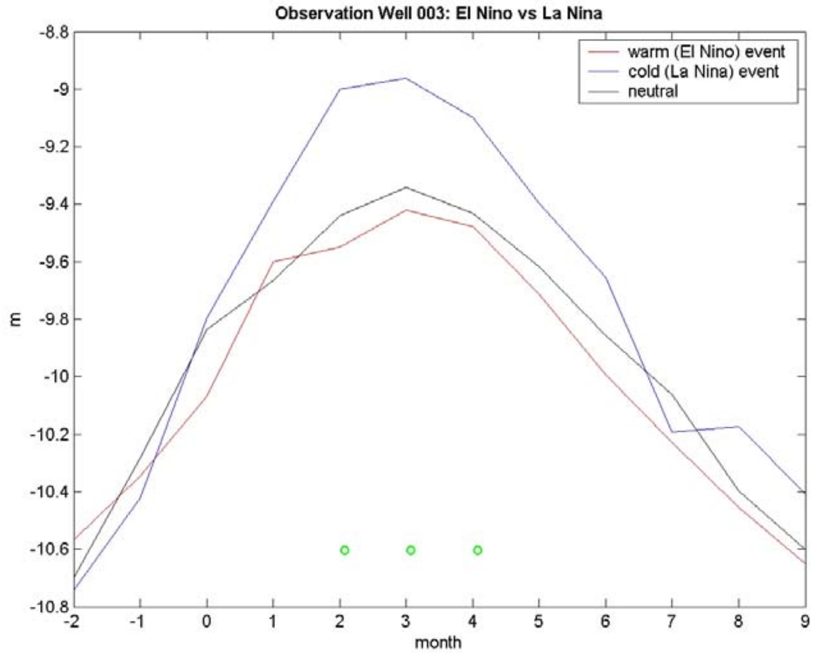

Figure 22 *Response of Well 003 groundwater levels to ENSO*

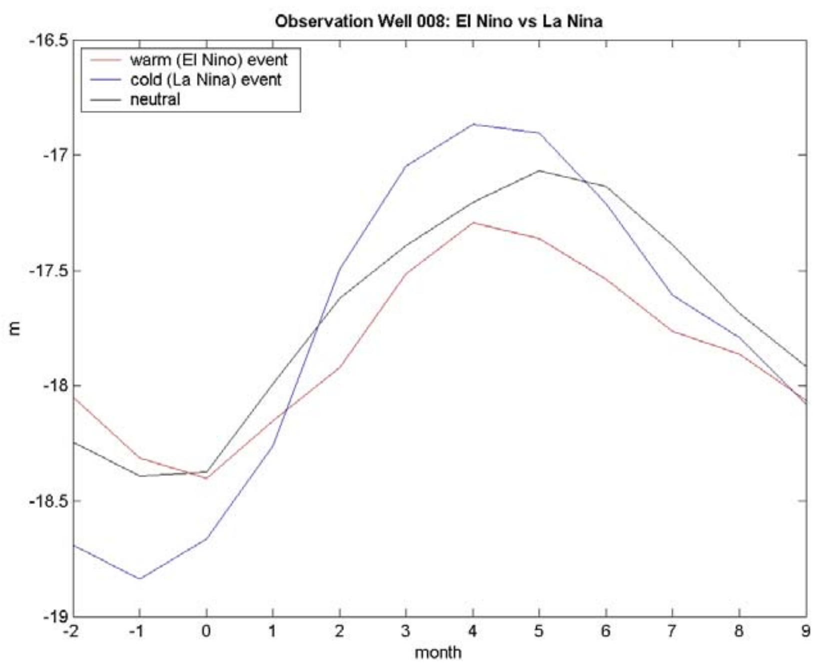

Figure 23 *Response of Well 008 groundwater levels to ENSO*

II.4.1.2 PDO-Modulated ENSO Events

Results of composite analyses considering only those ENSO events with the same phase as the PDO are shown in the following figures. The colour scheme is the same as that in the previous section. The results are very similar to those found when all ENSO events are considered, regardless of PDO phase (see previous section). For some parameters, such as both air temperature records and Observation Well 003 groundwater levels, month-by-month estimated significance is stronger for PDO-modulated ENSO effects, whereas for others, such as both precipitation records, it is weaker. The composite averages are, in general, very similar. Overall, the data considered here suggest that the local effects of PDO modulation of ENSO impacts do not appear to be large or consistent.

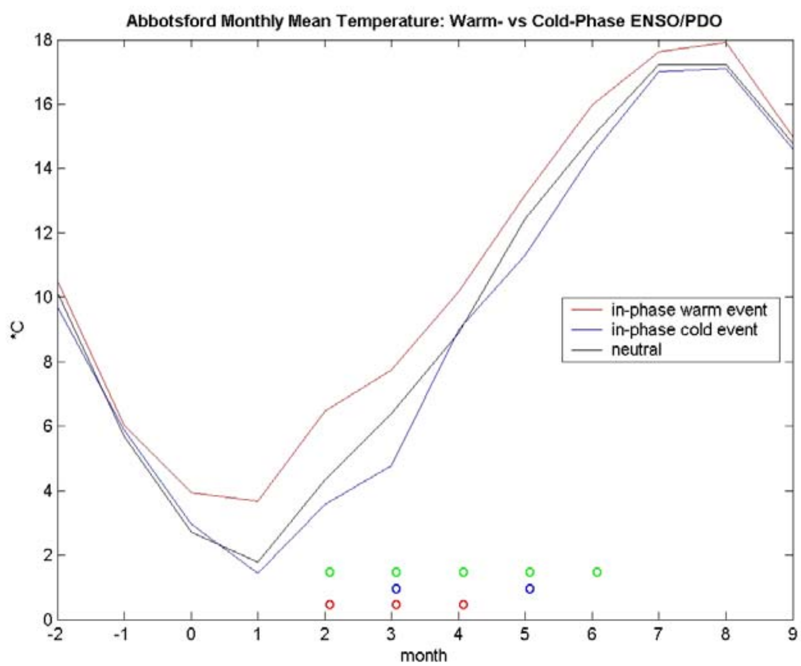

Figure 24 *Response of Abbotsford air temperature to ENSO events in phase with the PDO*

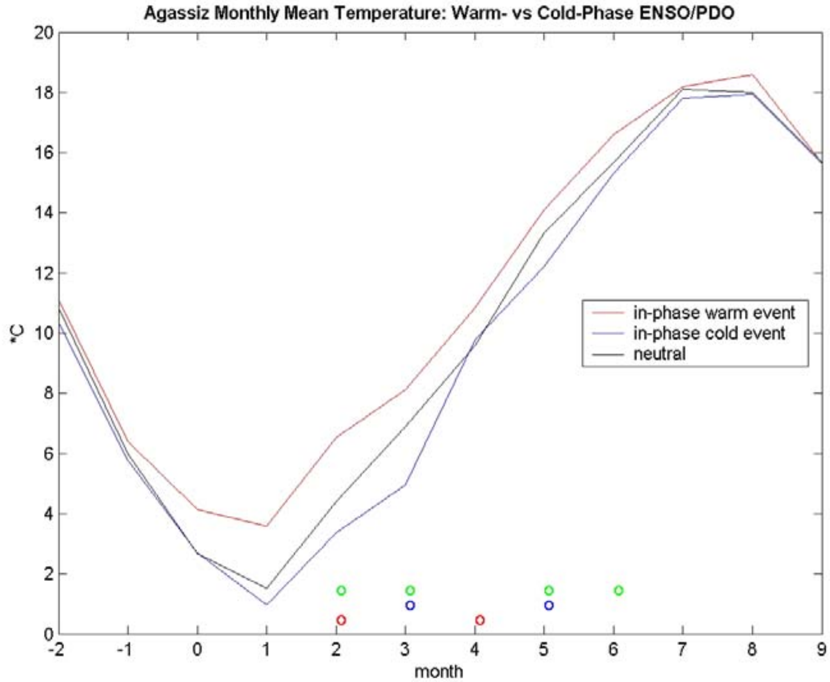

Figure 25 *Response of Agassiz air temperature to ENSO events in phase with the PDO*

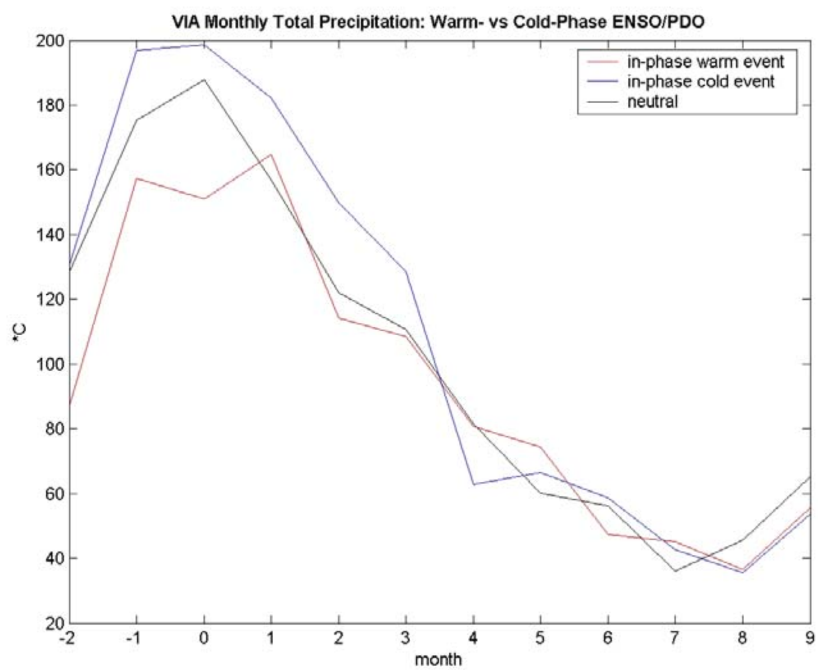

Figure 26 *Response of Vancouver International Airport precipitation to in-phase ENSO events*

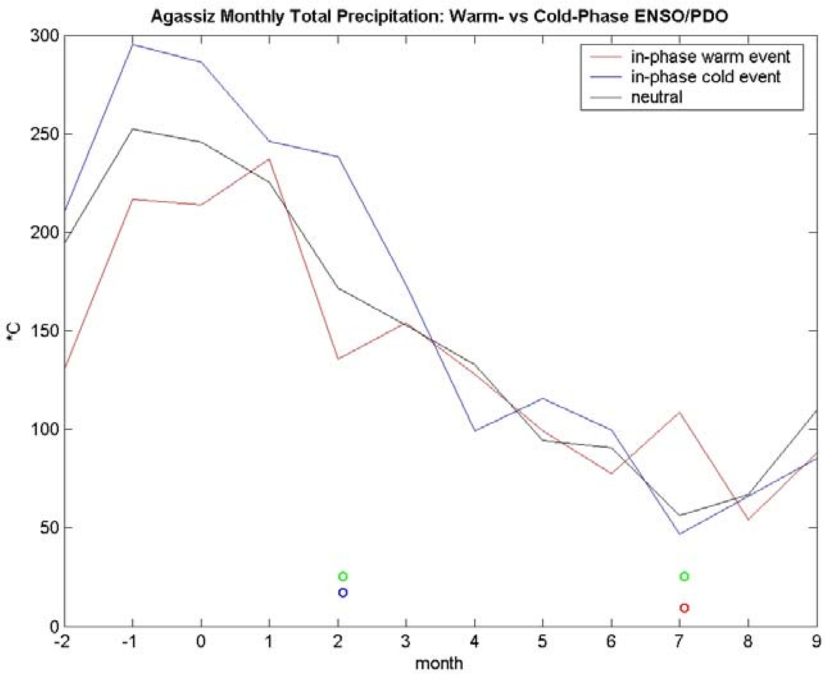

Figure 27 *Response of Agassiz precipitation to in-phase ENSO events*

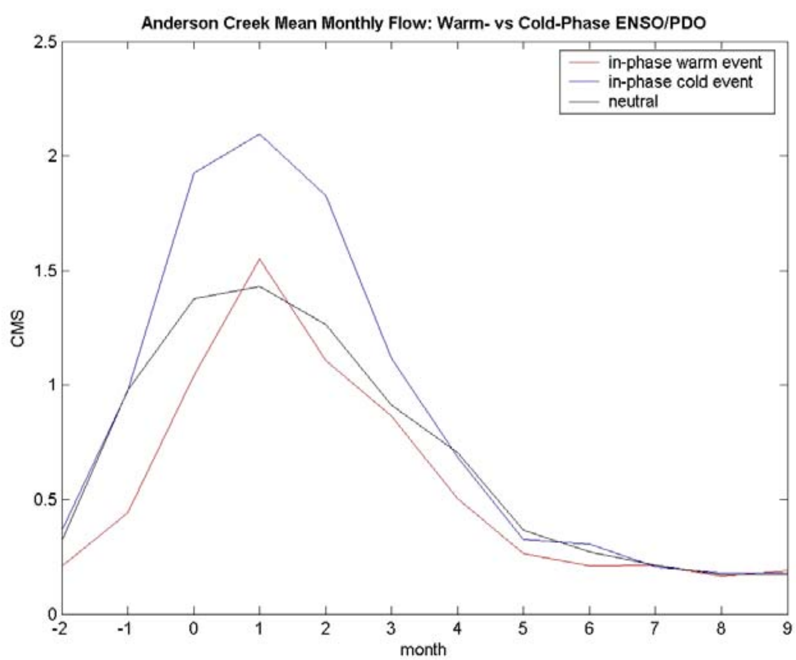

Figure 28 *Response of Anderson Creek discharge to in-phase ENSO events*

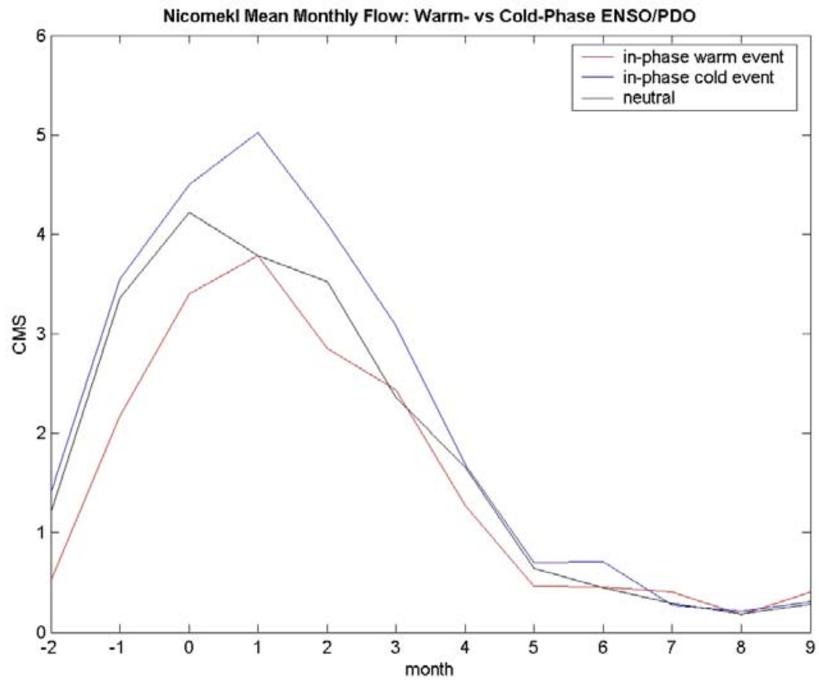

Figure 29 *Response of Nicomekl River discharge to in-phase ENSO events*

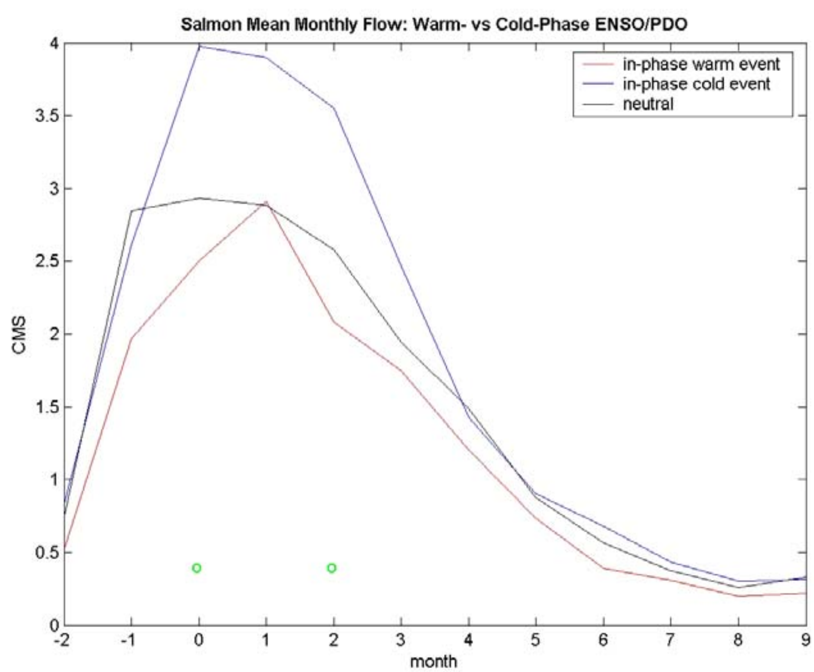

Figure 30 *Response of Salmon River discharge to in-phase ENSO events*

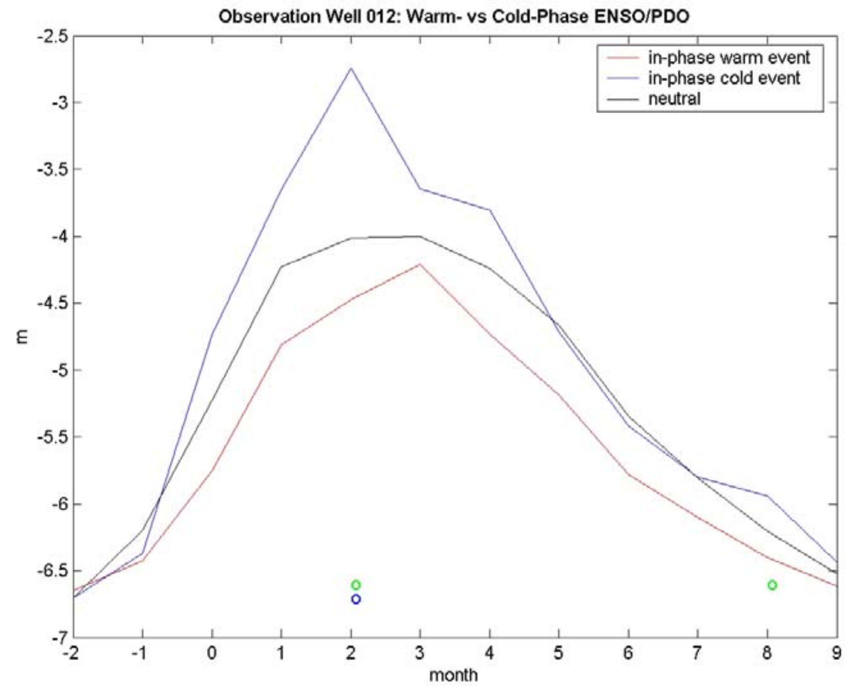

Figure 31 *Response of Well 012 groundwater level to in-phase ENSO events*

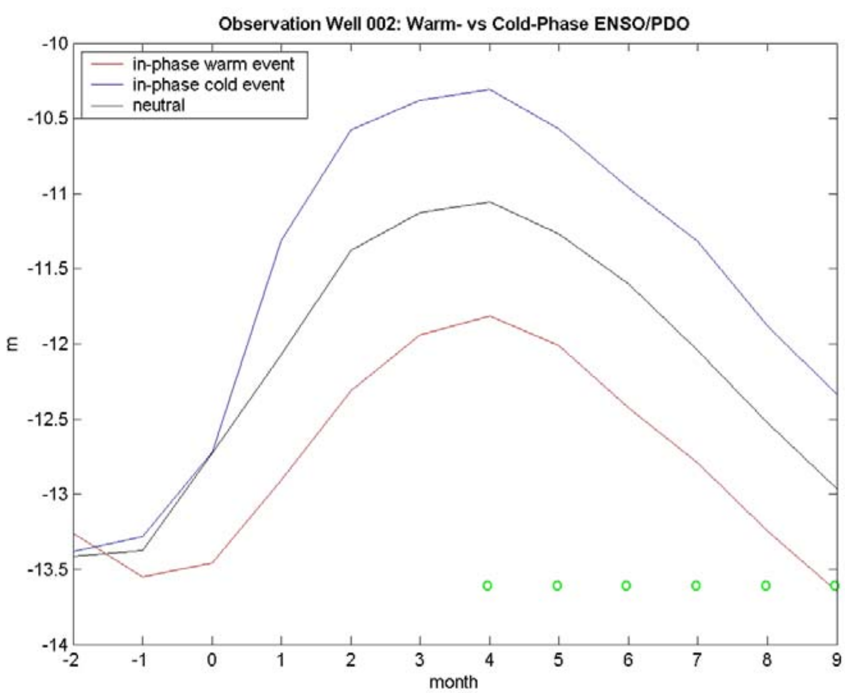

Figure 32 *Response of Well 002 groundwater level to in-phase ENSO events*

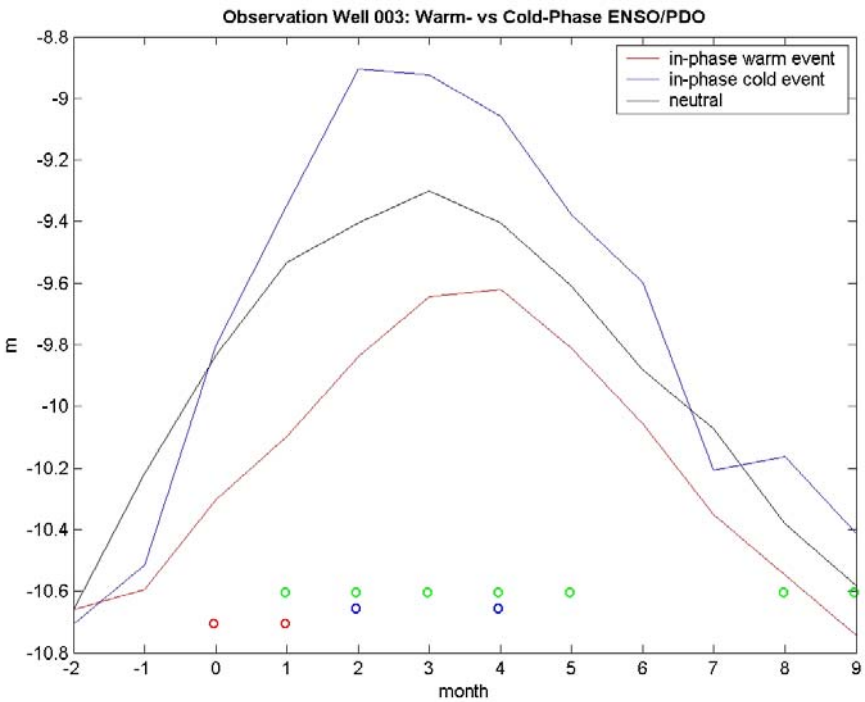

Figure 33 *Response of Well 003 groundwater level to in-phase ENSO events*

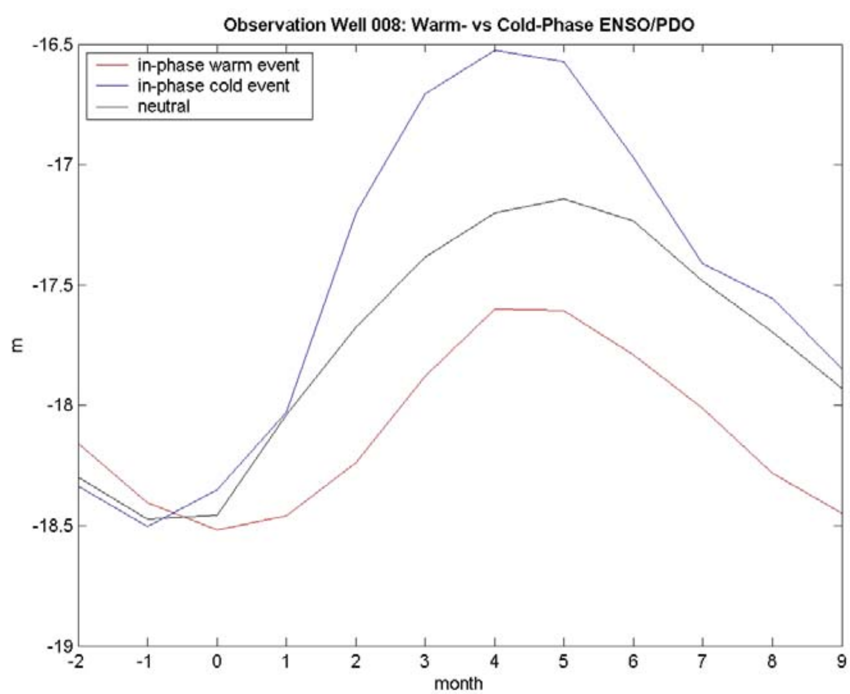

Figure 34 *Response of Well 003 groundwater level to in-phase ENSO events*

II.4.1 Climatic Change, Water Temperature, and Ecological Risk

Results are summarized in the **Table 14** below. These findings were obtained using observed 1999 temperatures as the starting point for climatic change impact assessment (top section of table), as well as observed 1999 temperatures ± 10% (two bottom sections) as heuristic estimates of how current watershed remediation or degradation might mitigate or exacerbate long-run climatic change effects. The number of days over the April – October period having sub-optimally high temperatures is N_{exc}; the average temperature over all such days of temperature exceedance is T_{exc} (^oC); *TGR* is annual total growth risk (%); and *f* is the ratio of predicted *TGR* to historical (*i.e.*, 1999) *TGR*.

The corresponding magnitude – cumulative duration curves are also provided below, for the case of estimated risks associated with observed 1999 temperatures and projections of those temperatures to 2020, 2050, and 2080. 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 which therefore contribute to the cumulative yearly total high-temperature growth risk (*TGR*). Note that growth is a nonlinear function of temperature.

Table 14 *Projected potential chronic temperature risks under climatic change, LCR*

year	N_{exc} (d)	T_{exc} (^oC)	*TGR* (%)	*f*
Using observed 1999 temperatures as a basis (extrapolate from present conditions):				
current	83	16.3	10.2	1.0
~ 2020	123	16.4	21.0	2.1
~ 2050	129	16.9	30.6	3.0
~ 2080	136	17.3	41.5	4.1
Using observed 1999 temperatures – 10% as a basis (extrapolate from improved conditions):				
"current"	58	15.3	2.8	1.0
~ 2020	77	15.8	6.4	2.3
~ 2050	99	16.0	10.4	3.8
~ 2080	118	16.2	15.4	5.6
Using observed 1999 temperatures + 10% as a basis (extrapolate from worsened conditions):				
"current"	126	16.8	30.2	1.0
~ 2020	136	17.6	52.8	1.7
~ 2050	144	18.1	71.8	2.4
~ 2080	151	18.4	92.4	3.1

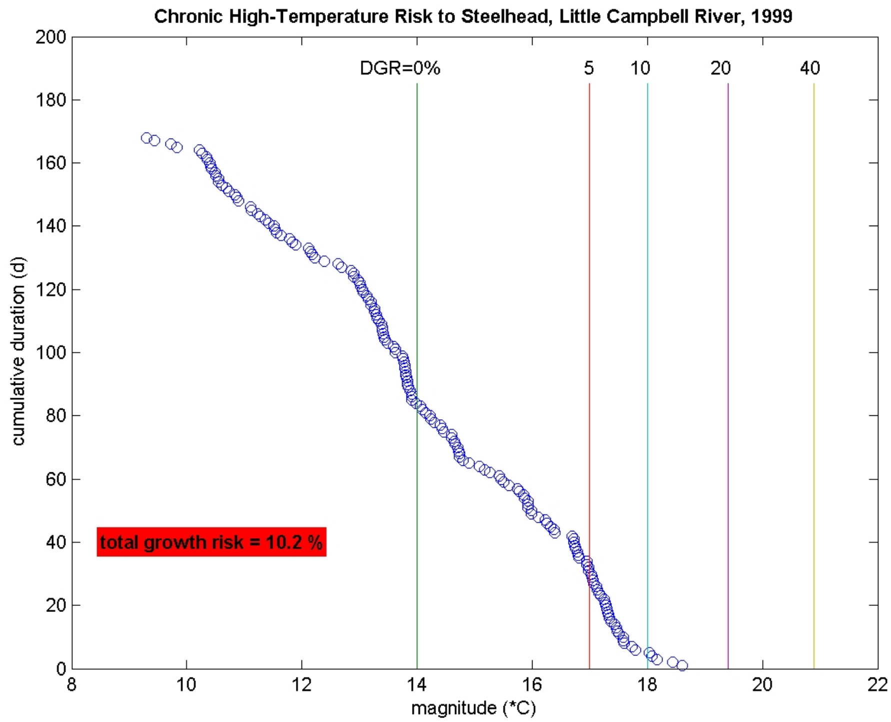

Figure 35 *Daily and cumulative yearly total temperature growth risk, steelhead, LCR, 1999*

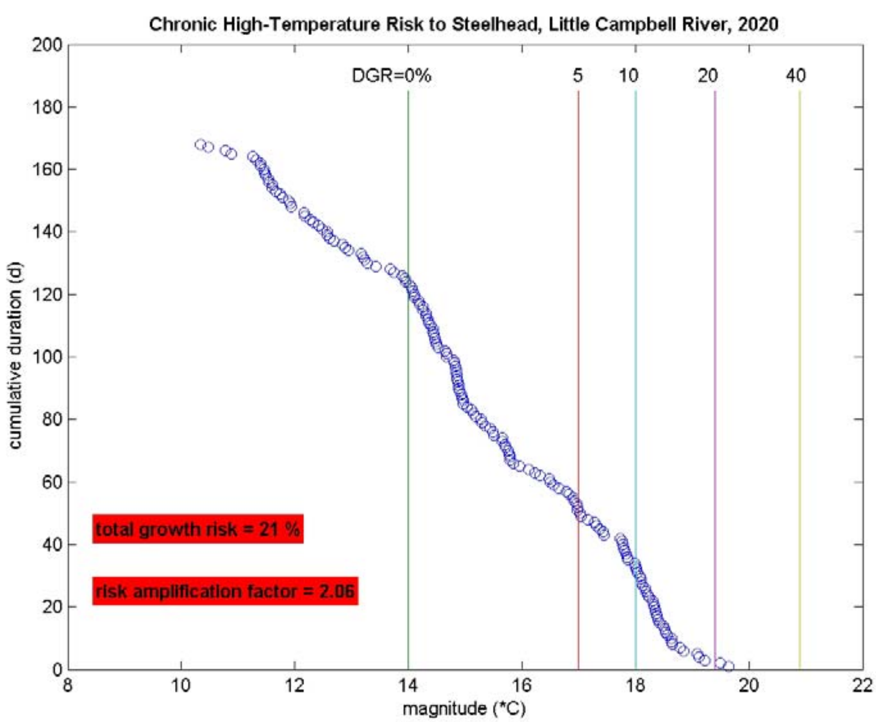

Figure 36 *Temperature growth risk to LCR steelhead ca. 2020 under IS92a projection*

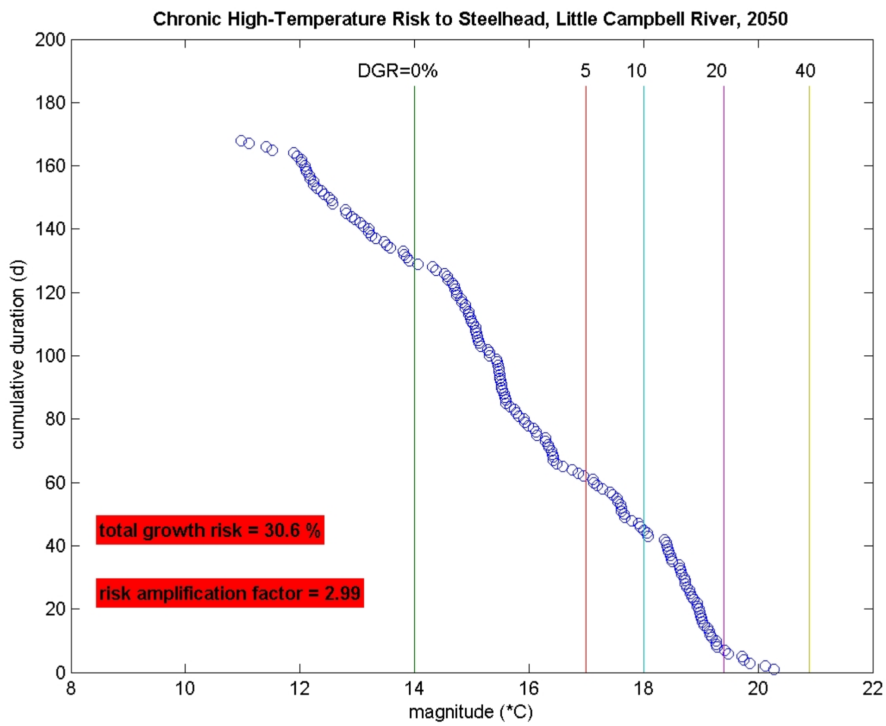

Figure 37 *Temperature growth risk to LCR steelhead ca. 2050 under IS92a projection*

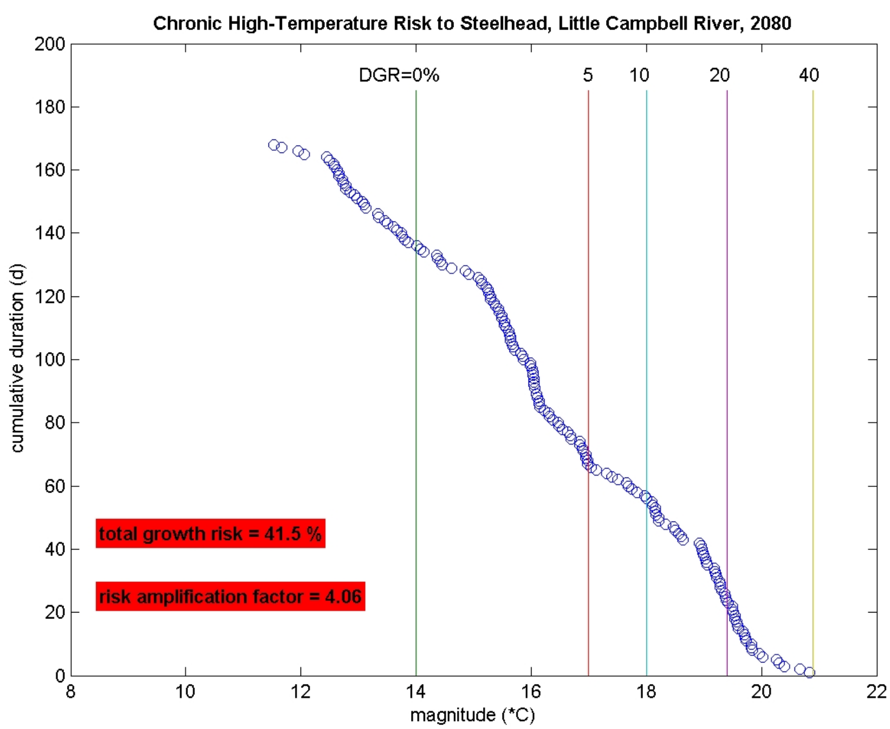

Figure 38 *Temperature growth risk to LCR steelhead ca. 2080 under IS92a projection*

Progressive increases in risk over time are projected here (top section of **Table 14**, and **Figures 35** to **38**) to 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}). 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. Maximum daily mean water temperatures are not estimated, however, to reach acute levels by 2080, although spot temperatures might temporarily and/or locally exceed 24^{o}C during the warmer periods of the day.

Watershed remediation or degradation can greatly affect the ultimate impacts of climatic change upon chronic thermal risks to steelhead (bottom two sections of **Table 14**), with important environmental and fisheries management implications. Using a 10% decrease from 1999 summer daily mean temperatures as a baseline for assessing long-term climate change implications, the estimated thermal risk by 2050, for example, is only 10.4%, about the same as the observed historical value. On the other hand, using a 10% increase from 1999 as the baseline for projections under climate change, total growth risk reaches almost 100% by 2080, which might essentially exclude steelhead from the LCR. Note also that under that scenario, daily mean temperatures may reach about 23^{o}C (not shown), raising a much stronger possibility of protracted periods of acute thermal risk.

II.5 Conclusions and Recommendations

II.5.1 El Niño Impacts

ENSO-related precipitation anomalies in the lower Fraser Valley were found to consist primarily of substantial wintertime increases and decreases during La Niña and El Niño events, respectively, consistent with prior analyses in the region. The average historical groundwater level response to such recharge variability was as much as 1 m, relative to an annual hydrologic cycle amplitude of about 1.5 to 3.5 m. River discharge records showed analogous responses. ENSO-related water resource anomalies were more broadly distributed throughout the year than seasonal precipitation anomalies, particularly for groundwater levels, presumably because aquifers are storage mechanisms with long system memory. Precipitation, river flow, and groundwater responses to ENSO were observed to be locally nonlinear, insofar as effects were generally stronger during cold phases than warm phases. However, the statistical significance of the fluvial and groundwater responses were somewhat erratic. This could imply that teleconnections to the tropical Pacific only weakly influence interannual lower Fraser Valley surface and subsurface water resource variability, although climatic signals in the available long-term hydrologic data may also be obscured by local human factors, such as watershed modifications and surface water and groundwater extraction. The effects of PDO modulation of ENSO variability appear to be locally minor. Significant wintertime temperature anomalies were also found to be associated with ENSO, but these are believed to have little hydrologic effect locally.

The results have clear implications for interannual variability in water resource availability, habitat availability, and potentially contaminant loadings and erosion in the Fraser Valley lowlands. However, with the partial exception of groundwater effects, such broader impacts appear to be limited largely to the winter-early spring period. On the other hand, hydrologic variability over this interval may be of particular importance to spawning salmonids, a key watershed management target in the region.

From an ecological perspective, ENSO is a natural phenomenon, and British Columbian species have evolved in its presence. As a result, it may be inappropriate to view El Niño or La Niña events as ecologically positive or negative per se. Nevertheless, such large-scale ocean-atmosphere circulation patterns have significant explanatory power for assessing climatic impacts upon habitat conditions. Moreover, in heavily degraded watersheds, large ENSO events might have a tipping-point effect, pushing already-threatened ecosystems over the precipice (see Scheffer *et al.*, 2001). Finally, there is some evidence that the Southern Oscillation may be exacerbated by global climatic changes (*e.g.*, Trenberth and Hoar, 1996; Tsonis *et al*., 2003). Consequently, the hydroecological effects of ENSO events could conceivably exceed the limits within which native species evolved, and which they can readily accommodate.

The composite results presented here are believed to well-represent hydroclimatic variability within the Little Campbell River watershed. However, only one of the four wells and none of the three streams considered actually lie within the LCR catchment: the hydrometric stations selected for analysis were used as surrogates for LCR data, which are currently inadequate for such hydroclimatic analyses. It is strongly recommended that continuous, long-term hydrometric data be obtained for the Little Campbell River and its tributaries in order to facilitate further hydromclimatic assessments. Such data would also be invaluable for evaluating pre- and post-development impacts, calculating contaminant loadings in the LCR and its tributaries, developing statistical and physical rainfall-runoff models necessary for quantitative examinations of potential land use impacts, and assessing climatic change impacts upon streamflow. Continuation of groundwater level monitoring in MOE observation well 012 and other lower Fraser Valley wells in the Observation Well Network is also strongly recommended, and should, if possible, be extended to include additional monitoring wells within the LCR watershed. The frequency and regularity of groundwater level sampling should also be improved.

II.5.2 Climatic Change, Water Temperature, and Ecological Risk

Although the details remain tentative, our baseline analysis strongly suggests that climatic change may have large negative impacts upon fisheries resources in the Little Campbell River via substantial increases in growth loss from higher water temperatures. Such growth impacts upon native cold-water stenotherms would likely also increase their susceptibility to other factors, such as watershed degradation, year-to-year hydroclimatic variability, and invasive species.

Heuristic re-analyses using linearly rescaled historical data suggest that how the Little Campbell watershed is managed could have a substantial impact upon salmonid susceptibility to climate change. Watershed remediation – for example, riparian planting to reintroduce shading – could greatly reduce climate change impacts, potentially to the point where there are virtually are none, relative to present, partially degraded conditions. Conversely, poor watershed management, leading to further anthropogenic increases in stream water temperature, would likely render LCR salmonids far more susceptible to the additional impacts of climatic change.

Further data collection would greatly facilitate more detailed and robust analyses of potential climatic change effects upon the Little Campbell River. At a minimum, automated semi-continuous water temperature monitoring at an hourly or shorter sampling interval is required. Obtaining several years of such data, particularly during the summer period, would lead to better regression relationships for use in empirical downscaling, and would allow a more comprehensive suite of future temperature and risk projections to be developed.

RECOMMENDED FIVE-YEAR MONITORING PROGRAM

As noted in previous sections of this report, the majority of water quality data obtained to date in the Little Campbell River watershed has been collected at a large number of locations, with a small number of samples infrequently collected at any given location. This shotgun-type approach is useful for tracing out some general water quality patterns. However, the small number of samples (often as little as one) at any given location precludes analysis of temporal patterns, analysis of relationships between water quality and external environmental variables, and formal statistical analysis of geospatial patterns in water quality and their relationships to such potential controlling factors as land use.

Future water quality data collection needs to focus on far more frequent and regular sampling at particular key locations. This includes both the installation of one or more automated water quality monitoring stations, collecting a suite of data parameters on a semi-continuous basis, as well as more frequent and consistent grab sampling for a broad range of water quality parameters at several locations within the watershed. Far more discharge data must also be obtained to further facilitate hydrologic modelling, assessment of relationships between water quality and quantity, and loading calculations.

The recommended elements of the Little Campbell River watershed monitoring program are outlined below in **Table 15**. The eight major elements are listed very roughly in what we believe to be descending order of importance, (1) being most important, but no element is expendable.

Table 15 *Recommended five-year Little Campbell River watershed monitoring program*

(1) Continuous mainstem water quality and water level monitoring	
Measurement type	Automated semi-continuous water quality monitoring station
Purpose	Provide temporally detailed and long-term baseline, monitoring, and analysis dataset of overall LCR watershed health
Location	On LCR mainstem. At least one station required, near LCR mouth to integrate all upstream effects, but upstream from tidal influence. A second station at about the half-way point of the LCR mainstem would be highly desirable, so that overall water quality in the upper and lower sections of the watershed can be quantitatively compared.
Sampling frequency	Between 1 sample/15 min and 1 sample/1 hr, constant
Parameters	Water level; pH; DO; turbidity; water temperature; specific conductivity

(2) Mainstem grab sampling	
Measurement type	Manual field measurements
Purpose	Provide temporally detailed and long-term baseline, monitoring, and analysis dataset of overall LCR watershed health, for parameters that cannot be remotely sampled using automated technologies; obtain occasional redundant measurements for parameters measured by automated station for calibration and data QA purposes
Location	On LCR mainstem. At least one station required, near LCR mouth to integrate all upstream effects, but perhaps upstream from tidal influence. A second station at about the half-way point of the LCR mainstem would be highly desirable, so that water quality in the upper and lower sections of the watershed can be quantitatively compared.
Sampling frequency	Monthly, constant
Parameters	Water temperature; hardness; specific conductivity; DO; BOD; TSS or turbidity; full nutrient suite; full metals suite; hydrocarbon suite; fecal coliforms; chloride
(3) Sub-catchment continuous flow monitoring	
Measurement type	Automated semi-continuous water level stations
Purpose	Monitor overall hydrology of major LCR sub-catchments; locate sources of LCR mainstem hydrological variations; permit sub-catchment-scale loading calculations to locate sources of LCR mainstem loading variations; trace effects of land use change upon sub-catchment dynamics, including stormflow and baseflow characteristics.
Location	Near the mouths of as many of the following creeks as practicable: McNalley, West Twin, East Twin, Fergus, Kuhn, Highland, Thomson, Sam Hill, Jenkins, Jacobsen, Theodore, Kerfoot
Sampling frequency	Between 1 sample/15 min and 1 sample/1 hr, constant
Parameters	Water level (pressure transducer)
(4) Sub-catchment grab sampling	
Measurement type	Manual field measurements
Purpose	Monitor overall water quality in major LCR sub-catchments; locate sources of LCR mainstem water quality variations
Location	Near the mouths of the following creeks: McNalley, West Twin, East Twin, Fergus, Kuhn, Highland, Thomson, Sam Hill, Jenkins, Jacobsen, Theodore, Kerfoot
Sampling frequency	Monthly, constant
Parameters	Water temperature; hardness; specific conductivity; DO; BOD; TSS or turbidity; full nutrient suite; full metals suite; hydrocarbon suite; fecal coliforms; *E. coli.*; chloride

(5) Additional continuous thermistor measurements	
Measurement type	Automated, low-cost, semi-continuous water temperature stations (*e.g.*, "Tidbit" technology)
Purpose	Monitor water temperature conditions at locations additional to those listed in (1), providing much clearer picture of thermal regime adequacy; and a basis for better analyses of the habitat impacts of climatic variability and change
Location	At various convenient points along LCR mainstem, and near the mouths of major tributary creeks, such as McNalley, West Twin, East Twin, Fergus, Kuhn, Highland, Thomson, Sam Hill, Jenkins, Jacobsen, Theodore, Kerfoot
Sampling frequency	Between 1 sample/15 min and 1 sample/1 hr, constant
Parameters	Water temperature
(6) Groundwater level and quality sampling	
Measurement type	Manual field measurements and automated data collection
Purpose	Extend limited current monitoring of the existing MOE Observation Well Network, and preferably additional wells, to obtain a measure of physical and chemical hydrogeologic conditions within the LCR watershed. This may be crucial to detailed understanding and control of contaminant sources and modes of contaminant travel from the land surface to surface water bodies within the LCR watershed.
Location	Current MOE well 012, which lies within the LCR watershed. Extension to additional MOE well sites, or other potential groundwater monitoring locations within the LCR watershed, would be extremely useful.
Sampling frequency	Manual: bi-weekly or monthly; automated: hourly; constant
Parameters	Manual: water temperature, hardness, specific conductivity, DO, full nutrient suite, full metals suite, hydrocarbon suite, fecal coliforms, *E. coli*., chloride; automated: water level, pH, specific conductivity, temperature.
(7) Storm event grab sampling	
Measurement type	Manual field measurements
Purpose	Develop a better understanding of how water quality parameters, including pollutant concentrations, vary with reference to the storm hydrograph in the LCR basin, helping to define hydrochemical relationships as relevant to watershed dynamics and pollutant loadings
Location	Several locations on the LCR mainstem and its tributaries
Sampling frequency	In general, very high frequency measurements over a single short timeframe (*e.g.*, 5 min measurements over a 6-hour period spanning before, during, and after a rainstorm); occasional repetition of experiment at one or more locations as deemed necessary and appropriate in light of

	local conditions
Parameters	Water temperature; hardness; specific conductivity; DO; BOD; TSS or turbidity; full nutrient suite; full metals suite; hydrocarbon suite; fecal coliforms; *E. coli.*; chloride. Also requires simultaneous discharge measurements.
(8) Watershed-wide shotgun sampling	
Measurement type	Manual field measurements
Purpose	Obtain continuing, spatially detailed snapshots of water quality throughout the watershed, consistent with water quality measurements taken to date, including but not limited to both minor ditches and culverts and alternative LCR mainstem locations
Location	As many of the water quality stations listed in **Table 2** of this report as practicable
Sampling frequency	Two sampling rounds per year. Each round should contain a sufficient number of individual sample dates to assess all results against CCME and MOE guidelines and objectives (*e.g.*, for fecal coliforms). Timing would preferably be consistent year-to-year.
Parameters	Water temperature; specific conductivity; DO; TSS; full nutrient suite; fecal coliforms. It would also be desirable to perform at least one full sampling round, at all stations, for metal and hydrocarbon suites.

It is recommended that the program be implemented immediately and (subject to technical adjustments as necessary) consistently followed over the long term, to establish a baseline dataset and to monitor changing conditions in the watershed. A number of major developments are planned for the Little Campbell River watershed. Assessment of the environmental impacts of such development requires, at a minimum, an adequate pre-development baseline dataset, against which water quality measurements during and after development can be properly compared. Moreover, any attempt to quantitatively or semi-quantitatively predict the environmental effects of specific development proposals requires some level of mathematical predictive capability, which can only be obtained by constructing models, either process-based or statistical, on the basis of historical data.

ADDENDUM:
2005-06 AUTOMATED MONITORING RESULTS

A.1 Introduction

In 2005, MOE took substantial initial steps toward implementation of the recommended monitoring program described in the foregoing section of this report. A multi-parameter water quality monitoring (Hydrolab) station was established on the Little Campbell River at the 12th Avenue bridge, downstream of East and West Twin Creeks and upstream of Sam Hill and Thompson Creeks. A pre-existing staff gauge was present at this location. The Hydrolab station collects DO, pH, water level, temperature, SC, and turbidity data. The sampling interval for both the thermistor network and the Hydrolab station was 15 minutes. Aquatic Informatics Inc. was contracted to aid in location selection and station installation for the thermistor network and multi-parameter station; subsequent data downloading and station maintenance has been performed by MOE. In addition, a network of thermistor stations was established to sample water temperature at five LCR mainstem locations and nine tributaries, listed in **Table A.1**.

Table A.1 *Themistor locations and periods of currently available records.*

Location	start	end
Fergus Cr at 168th St	Jun 30	Sep 28
East Twin Cr at 184th St	Jun 30	Sep 28
West Twin Cr at 184th St	Jun 30	Sep 28
Creek between Thompson Cr and 176th St	Jun 30	Sep 28
McNalley Cr north of 8th Ave	Jun 30	Sep 28
Jacobsen Cr at road to Puesta del Sol	Jul 6	Sep 28
Jenkins Cr north of 8th Ave	Jul 6	Sep 28
Sam Hill Cr at 176th St	Jul 6	Sep 28
Kuhn Cr in Hazelmere Golf Course	Jul 6	Sep 28
LCR at 216th St	Jul 28	Sep 28
LCR at 172nd St	Jun 30	Sep 28
LCR at Boy Scout camp	Jul 28	Sep 28
LCR at Semiahmoo Fish and Game Club hatchery	Jun 30	Sep 28
LCR at 16th Ave, west river loop	Jul 6	Sep 28

Such automated, semi-continuous water quality monitoring offers tremendous potential. Traditionally, water quality was (and to a large extent still is) measured using grab samples or manual field measurements taken weekly or less frequently. However, this approach tends not to capture extreme events, such as storms or pollution spills, as samplers are unlikely to be in the field precisely when such events occur. Moreover, occasional field sampling cannot characterize higher-frequency aquatic processes, such as the diurnal oscillations of pH and dissolved oxygen that can result from biological activity or temperature forcing. Advances in technology have led to a change in the way aquatic data are collected. Since the advent of low-power electronics, remote automated water quality monitoring has become widely feasible. Automated water quality stations have become a very important method for scientists and practitioners to best monitor and manage aquatic systems, because such semi-continuous, high-frequency measurements mitigate or eliminate many of the problems associated with more occasional manual field sampling.

However, automated water quality observation systems have their own set of issues. Aquatic monitoring sensors can often produce data that may not be representative of actual conditions. For example, optical (turbidity) sensors are prone to record unrealistically high values if bubbles pass by or biological fouling obscures the sensor window. pH and dissolved oxygen sensors can be miscalibrated or can drift if the control solution becomes contaminated with ambient water. Water level sensors can produce spurious data due to the effects of (for instance) frazil ice. Even solid-state sensors, such as thermistors, can record nonrepresentative values when exposed to air during low flow periods. Since data series are only useful if they actually reflect true aquatic conditions, data validation and, if necessary and appropriate, data correction are required.

Thus, automated water quality measurements typically have sections of data errors such as outliers, drift, noise, and gaps, and before data analysis is attempted, data must be validated and corruptions eliminated to the extent feasible. AI was contracted by MOE to perform validation and correction of automated station measurements from the above-described thermistor network and multi-parameter station. Methodological details are discussed in Quilty *et al.* (2004c,d), and their application here is briefly described below. The results are summarized in this addendum. The processed datasets are provided to MOE as comma-separated values (CSV) ASCII text files concurrently with this report. We also provide brief summary statistical results for the processed datasets.

A.2 Method

Automated station data were provided electronically by MOE to AI in the form of spreadsheet files. The period of record for the thermistor network varied between locations, depending on when the individual station was installed (June 30/05, July 6/05, or July 28/05; see **Table A.1**). The thermistor data were downloaded by MOE on September 26/05. This was the most recent download available at the time of writing. Note that the timing of thermistor installation was such that although peak 2005 summer temperatures generally appear to have been captured, a sufficient amount of the summer warm period was missed that AI did not feel recompletion of the chronic risk analyses presented in Section II of this report was appropriate. However, the thermistor network remains in operation and we recommend that, when it becomes available, closer and more thorough inspection and analysis of the full summer 2006 temperature dataset should be performed. For the Hydrolab station, these MOE spreadsheets also contained manual field sampling data collected by MOE personnel at times of data retrieval and station maintenance. The period of record covered by the Hydrolab dataset provided to AI for processing extended from October 5/05 through March 7/06, with substantial gaps.

All our data validation and correction was performed within the **AQUARIUS** software environment. The **AQUARIUS** platform provides an efficient and effective means of visualizing, validating, calibrating and correcting automated water quality time series. While advanced technologies like **AQUARIUS** greatly facilitate this process and improve its reliability, such data validation and correction procedures unavoidably still involve a substantial measure of subjective professional judgment, and the results are therefore subject to the strengths and weaknesses of such non-objective input. All the processed datasets presented here come with this strong caveat. We believe that the validated and corrected data form a superior basis for description and analysis of water quality conditions. Nevertheless, we strongly recommend that MOE also retain the original, unprocessed station data.

In general, data validation and correction procedures included, at one or more stations, removal of what were deemed to be spurious outliers; correction of data sections (using static shifts and drift adjustments, as appropriate) to approximately match field measurements taken manually by MOE personnel during site visits; linear interpolation of short data gaps; removal of data which were felt to be both corrupted and irrecoverable; and empirical model-based validation, correction, and gap-filling. For the Hydrolab data, which was provided to AI in three sections corresponding to three site visits and data download events, for each parameter the available data were concatenated into a single data stream in **AQUARIUS** prior to validation and (if performed) correction.

Preliminary statistical analyses were also completed for each corrected dataset. We calculated values for measures of central tendency (mean and median), dispersion (range, standard deviation, and interquartile range), and extrema (minimum and 5^{th} percentile values, maximum and 95^{th} percentile values). The mean, standard deviation, range, and minimum and maximum are common and familiar approaches to summarizing water quality data. The rank-based metrics, in contrast, may be substantially more robust to statistical outliers and non-Gaussian (*e.g.,* skewed) data distributions, and thus may provide a somewhat less intuitive but potentially more representative picture of overall water quality conditions. For the thermistor network, we also calculate: (i) the average, across all the LCR mainstem locations, of the minimum, mean, and maximum temperatures observed at the individual stations; (ii) the average, across all the tributary stations, of the minimum, mean, and maximum temperatures observed at the individual stations; (iii) the range in the minimum, mean, and maximum temperatures across all the LCR mainstem stations; and (iv) the range in the minimum, mean, and maximum temperatures across all the thermistor stations located on tributary streams.

A.3 Results

A.3.1 Thermistor Network

The checked raw data and, for cases where corrections were judged appropriate, the corrected data are illustrated in **Figures A.1** through **A.14** below. In these figures, the dark red line indicates the raw time series. If and when corrections were performed, the corrected time series is denoted by a bright red line; note that this overlies the raw data in certain portions of the graph.

Thermistors typically provide the least expensive and most reliable and accurate form of automated water quality monitoring. Overall, we judged data from the thermistor network to be of very good to excellent quality, and in general no corrections appeared necessary.

Two partial exceptions were the stations on Jacobsen Creek at the road to Puesta del Sol, and on the LCR mainstem at 216th Street. In both cases, the thermistor appears to have become elevated above the water surface during the late-summer low-flow period, sampling air instead of water temperature. When this occurs, it is often manifested in high-frequency automated temperature data as a sudden and very large increase in the amplitude of the diurnal temperature cycle. Such behaviour appears to occur intermittently in the Jacobsen Creek data from about July 26 onward, and more consistently in the LCR/216th Street data from about September 8 onward. In both cases, the record section deemed unreliable was deleted, and replaced with model-predicted temperatures. For Jacobsen Creek, these replacement temperatures were generated using a multiple linear regression model, which employed observed temperatures from six other small creeks in the thermistor network as predictors. The suite of predictor stations included East and West Twin Creeks, the creek between Thompson Creek and 176th Street, and Jenkins, Sam Hill, and Kuhn Creeks. These creeks were selected because: they are small systems, as opposed to the LCR mainstem, and thus were thought to be more physically and statistically appropriate surrogates; they were considered to have excellent data quality over the available record; and they showed the closest geographical proximity to Jacobsen Creek. For the LCR mainstem at 216th Street, a variety of possibilities were tried in a multiple linear regression framework. Ultimately, however, the best outcome obtained was found using a simple linear regression upon the LCR mainstem temperatures measured at the Boy Scout camp.

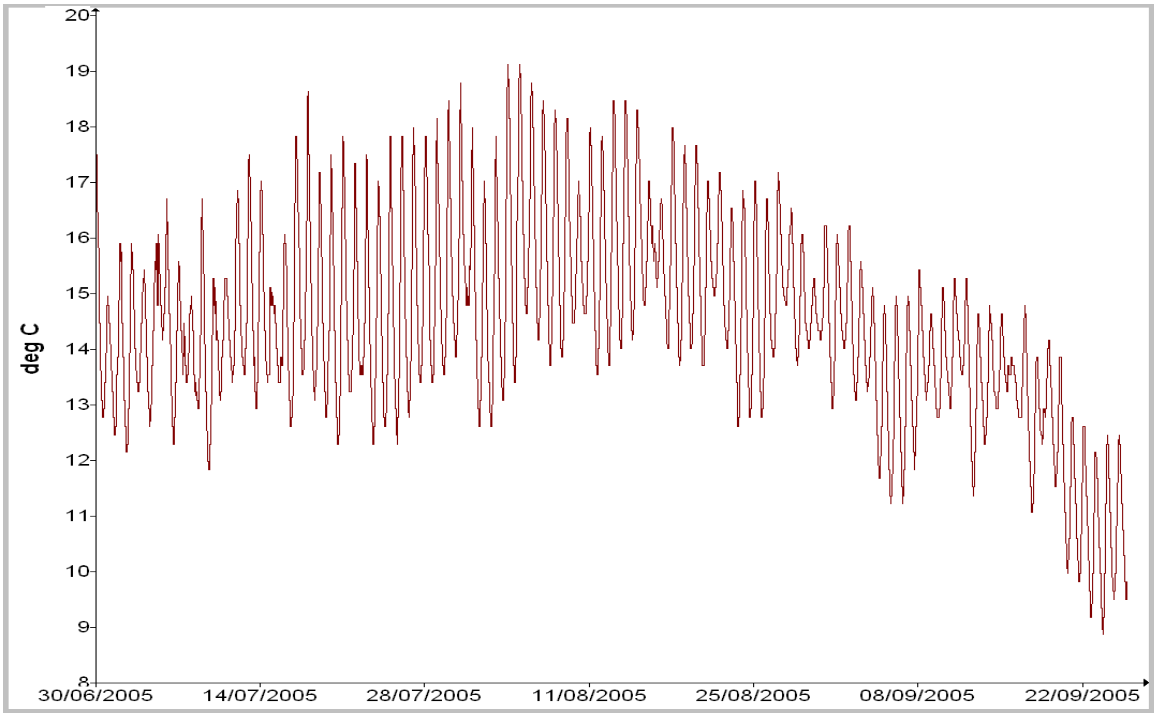

Figure A.1 *Creek between Thompson Creek and 176th St*

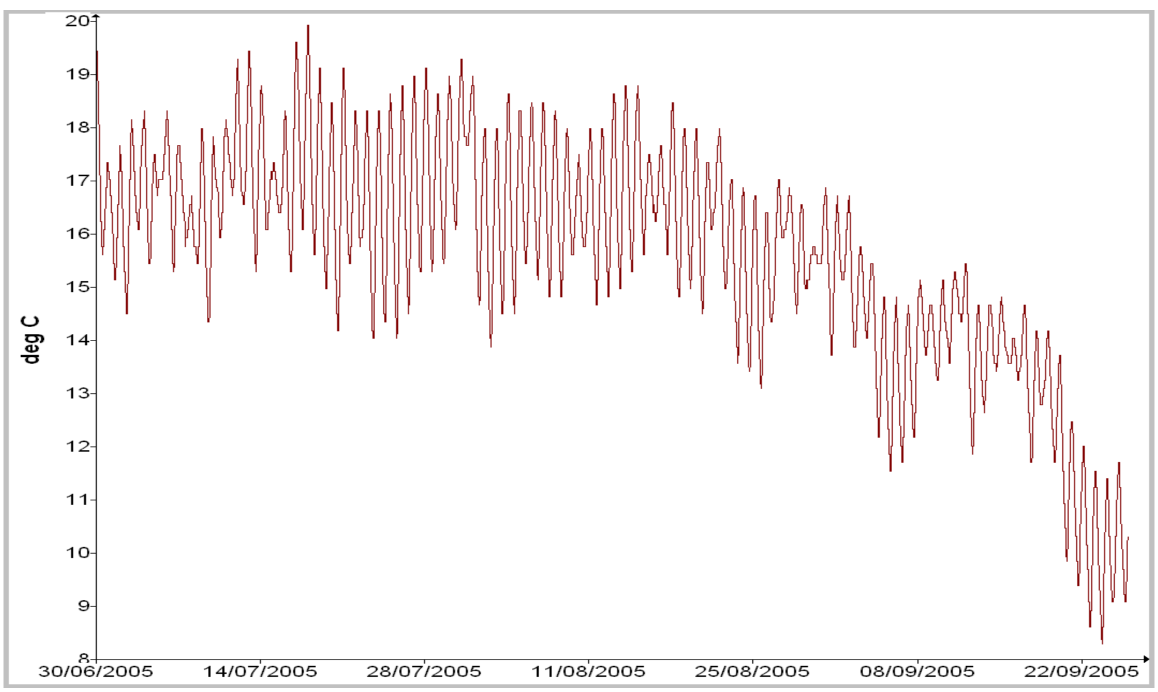

Figure A.2 *East Twin Creek at 184th St*

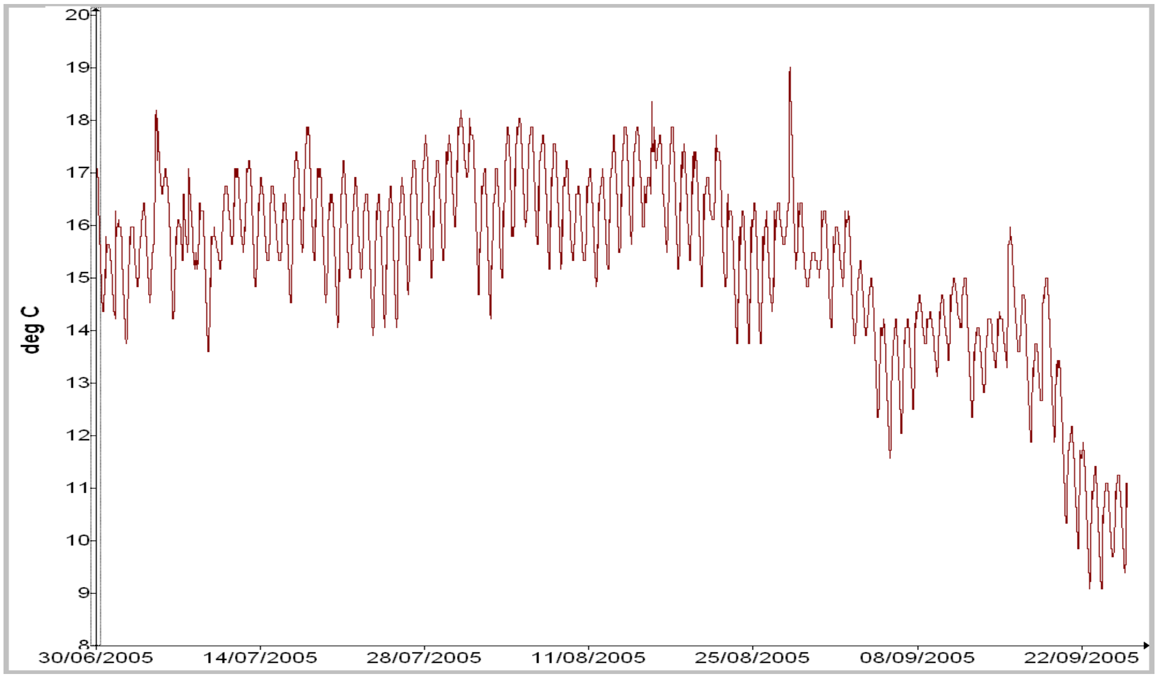

Figure A.3 *Fergus Creek at 168th St*

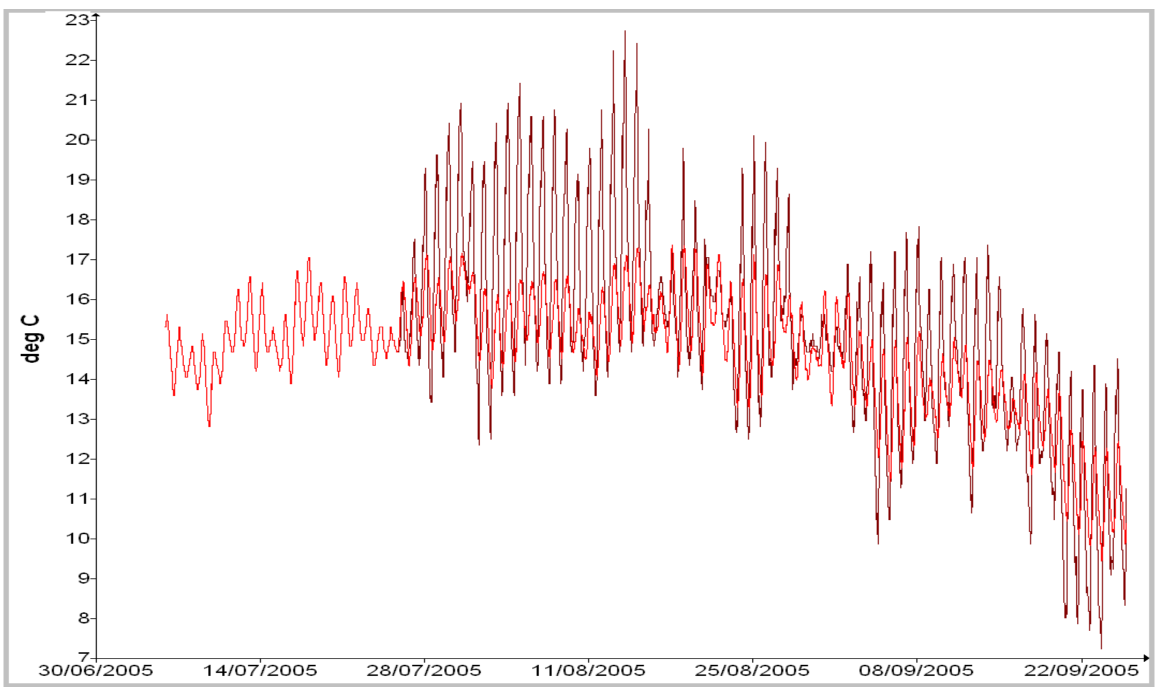

Figure A.4 *Jacobsen Creek at road to Puesta del Sol (bright red line gives corrected data)*

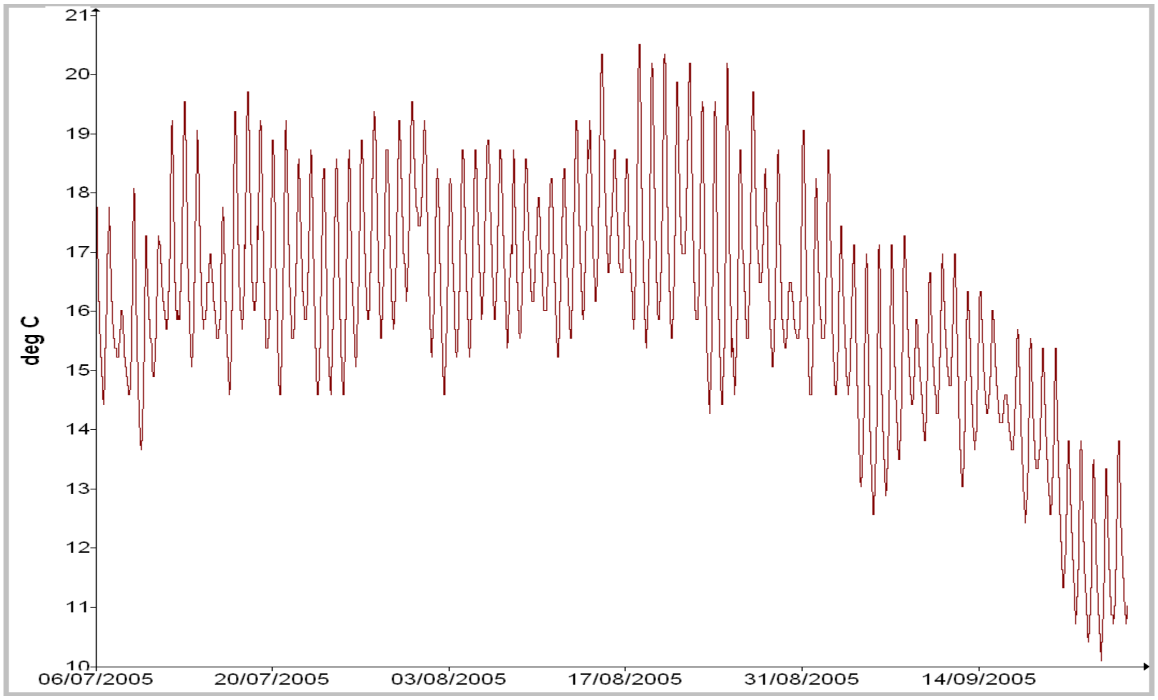

Figure A.5 *Jenkins Creek north of 8th Ave*

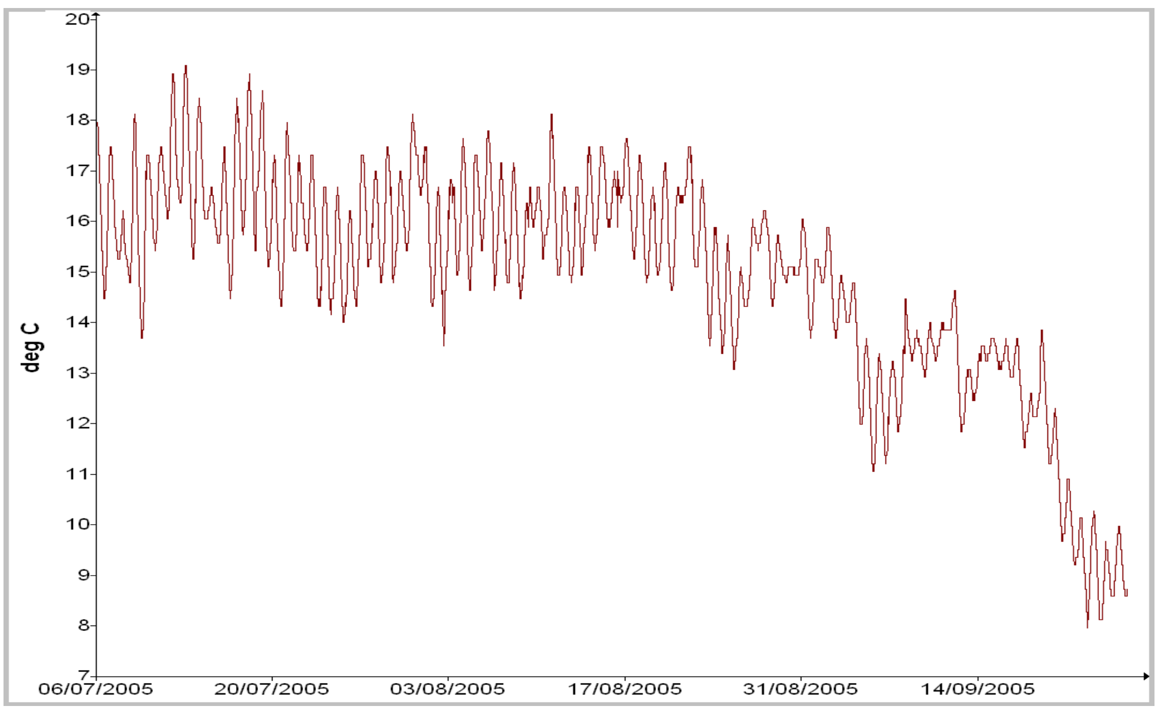

Figure A.6 *Kuhn Creek in Hazelmere Golf Course*

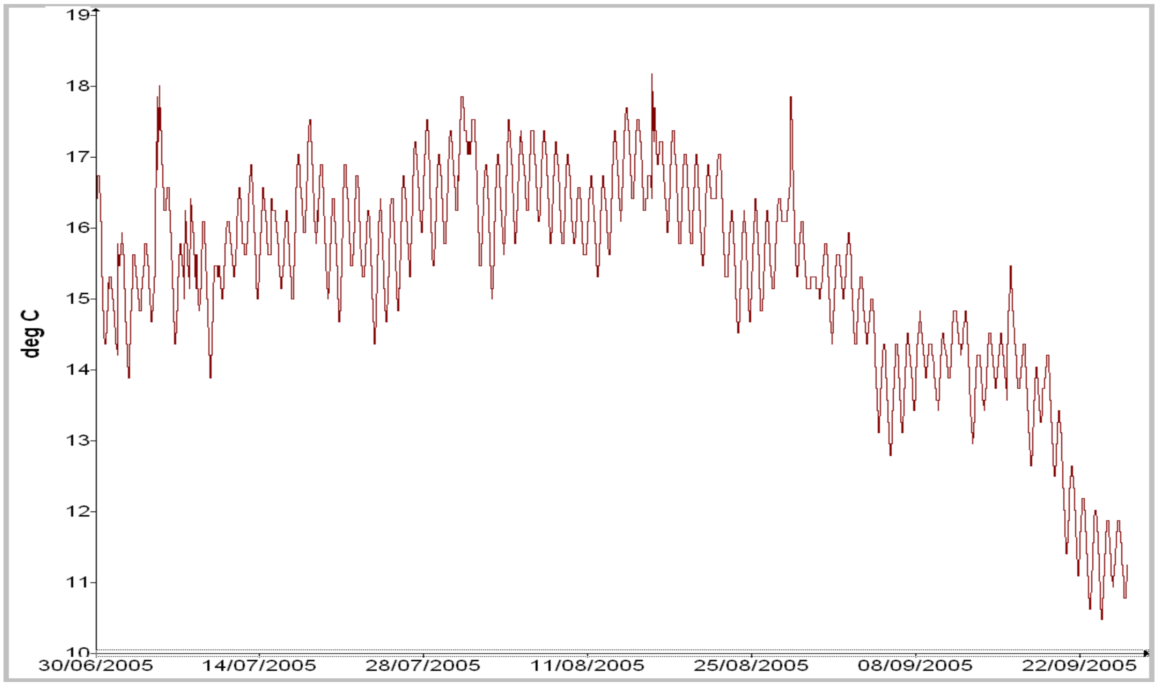

Figure A.7 *McNalley Creek north of 8th Ave*

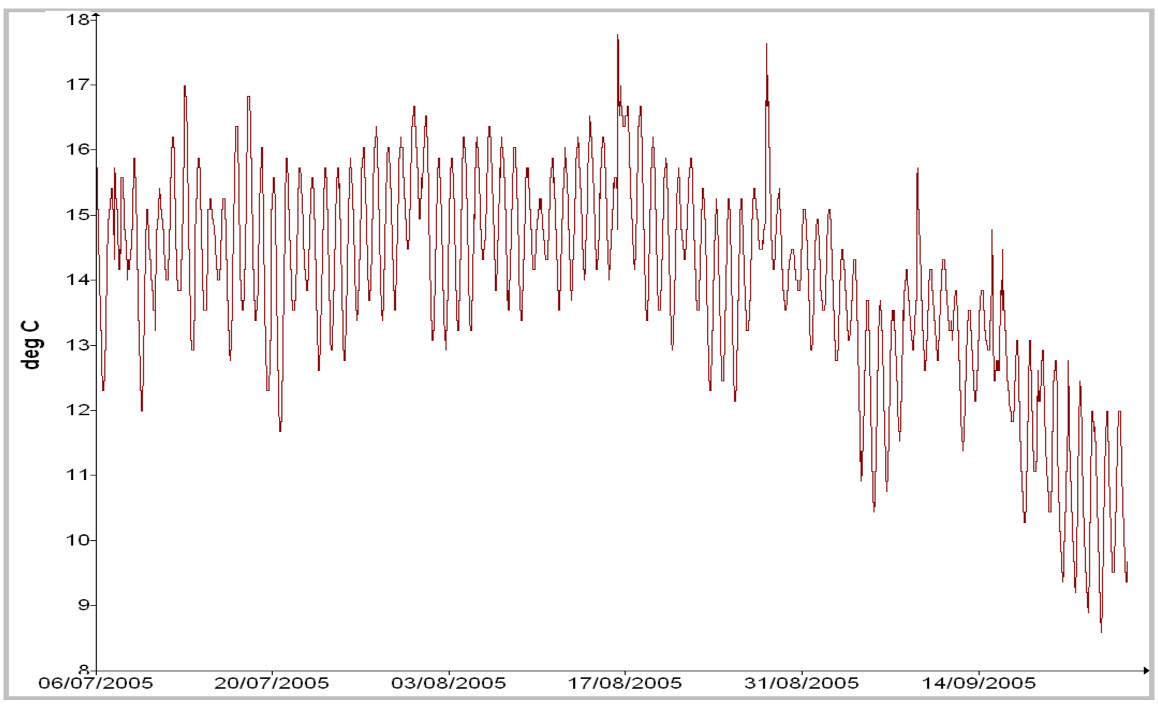

Figure A.8 *Sam Hill Creek at 176th St*

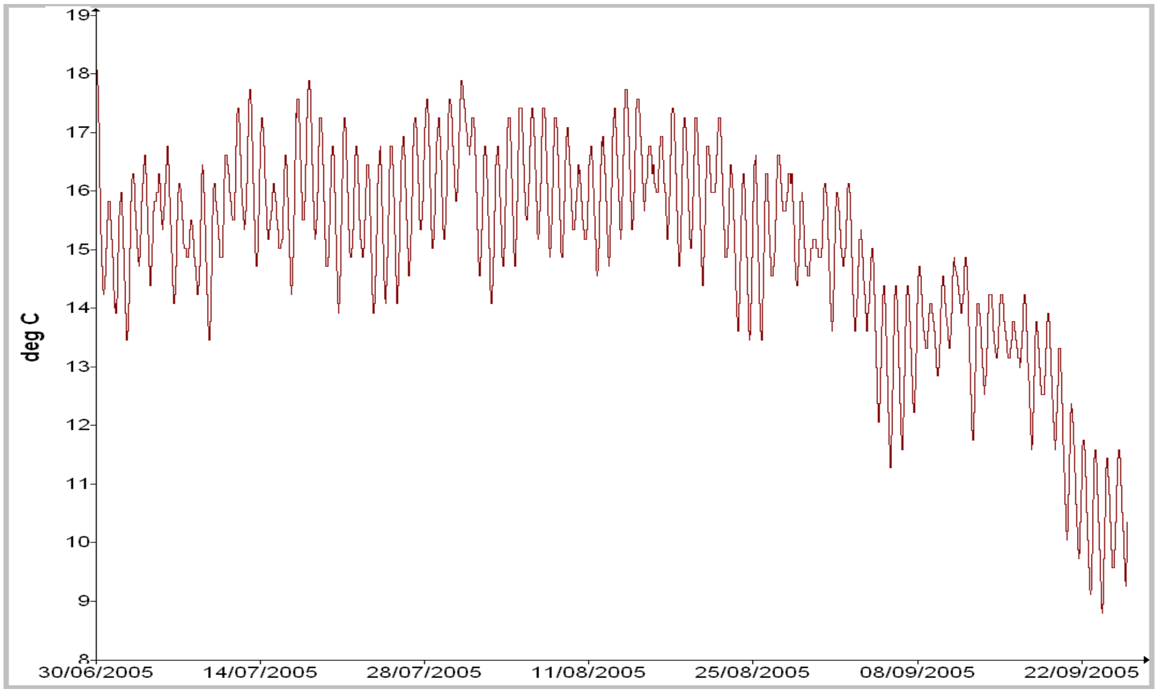

Figure A.9 *West Twin Creek at 184th St*

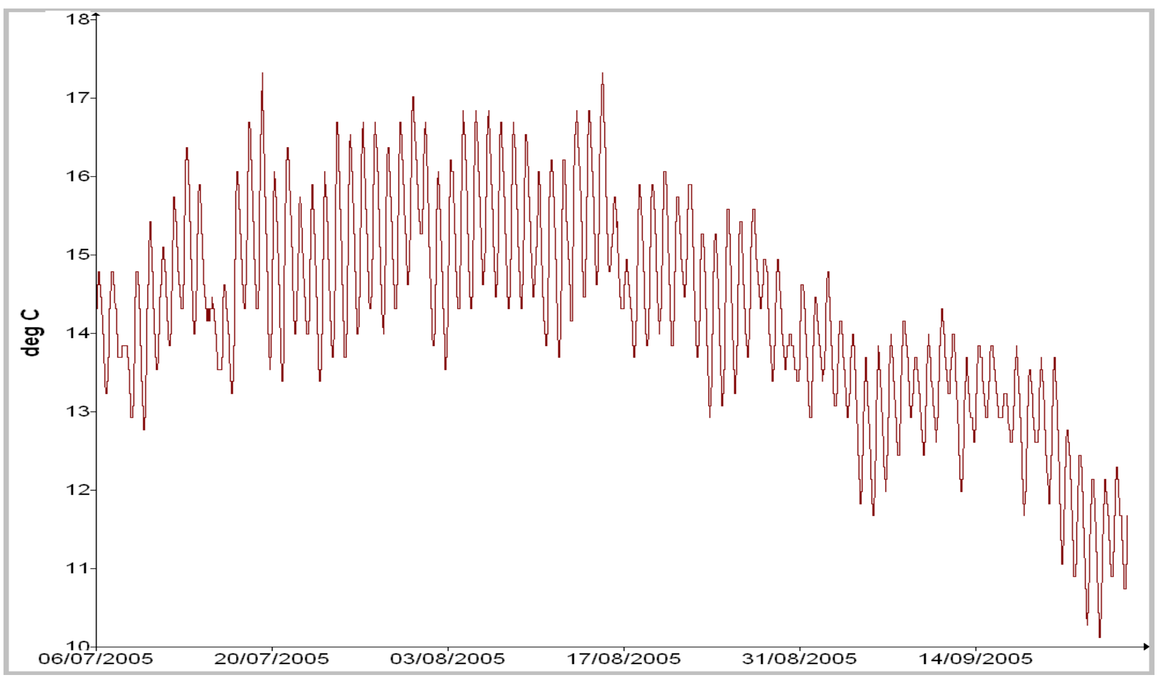

Figure A.10 *Little Campbell River at 16th Ave, west river loop*

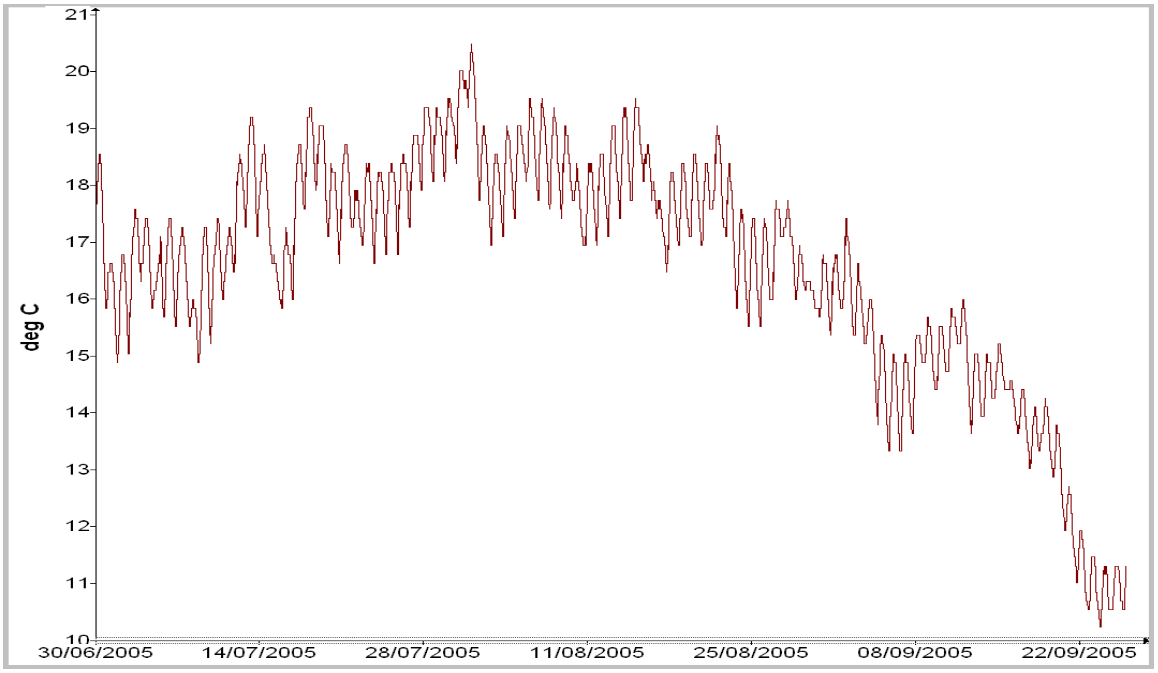

Figure A.11 *Little Campbell River at 172nd St*

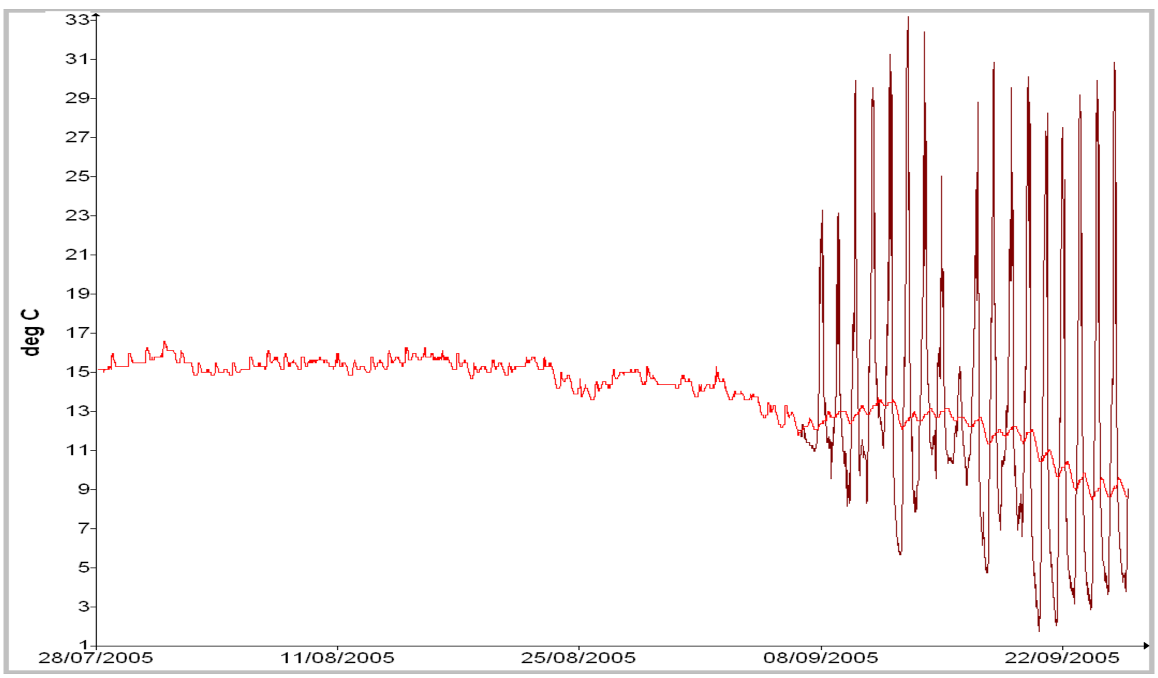

Figure A.12 *Little Campbell River at 216th St (bright red line gives corrected data)*

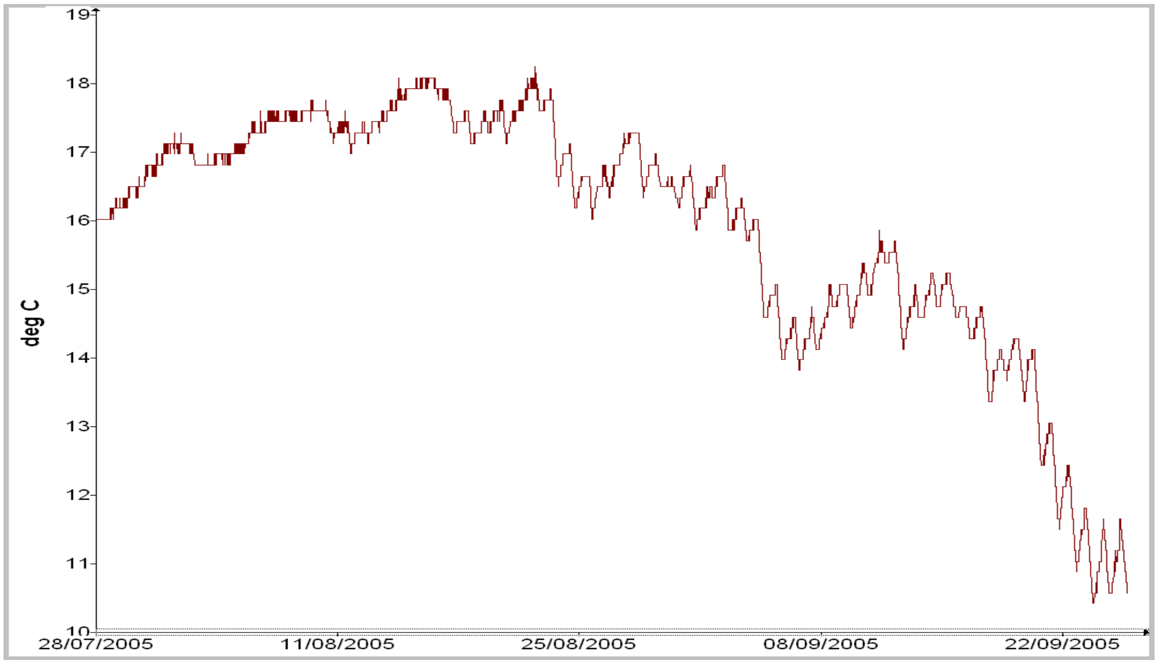

Figure A.13 *Little Campbell River at Boy Scout camp*

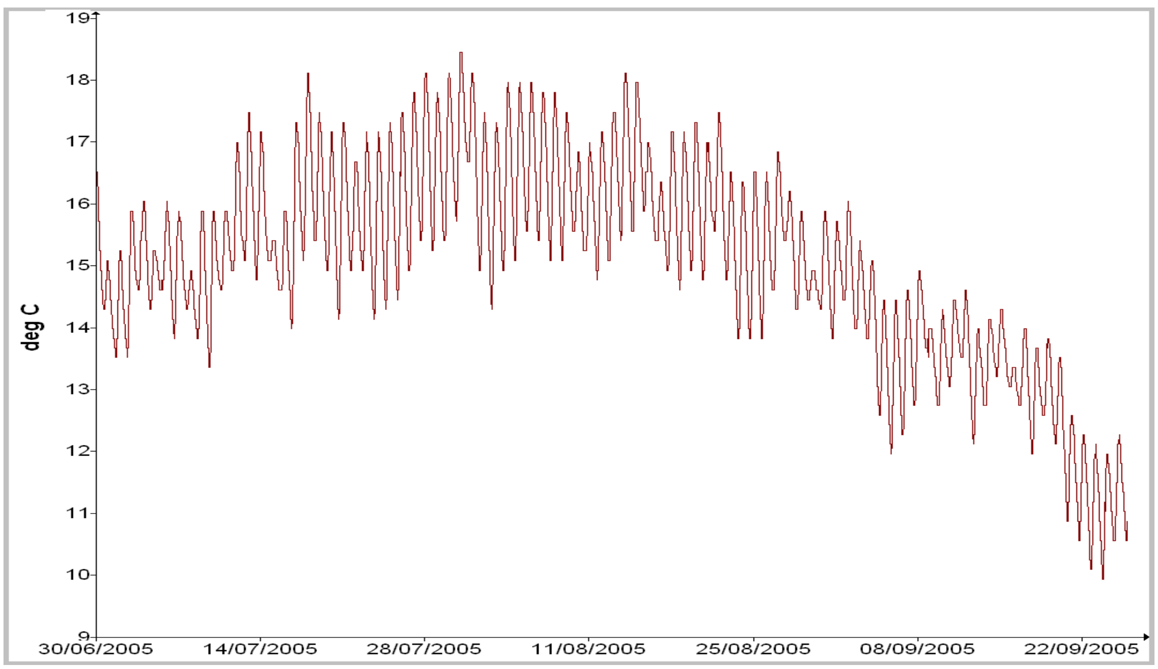

Figure A.14 *Little Campbell River at Semiahmoo Fish And Game Club hatchery*

A.3.2 LCR Hydrolab

The checked raw and (for cases where corrections were deemed appropriate) corrected Hydrolab data are illustrated in **Figures A.15** through **A.20** below. In these figures, dark red indicates the raw time series; bright red indicates the corrected time series (which may overlie the raw data in certain portions of the graph); and blue indicates manual field sampling results.

Corrections were made only when they were judged clearly necessary, appropriate, and attainable with reasonable, albeit not guaranteed, accuracy. In such cases, the corrections were limited to adjustments of the automated data as necessary to match manual field measurements. Note that inter-parameter relationships in the automated data from this station to date are conspicuous by their apparent weakness or absence. For instance, it is common for specific conductivity and stage to show a strong correlation, but little relationship is evident here (compare **Figures A.15** and **A.17**). Thus, there appears little opportunity to use model-based validation, correction, or gap-filling for the LCR Hydrolab datasets available to date. It seems unclear at this juncture whether the lack of obvious inter-parameter relationships reflects instrumentation issues or the particular water quality dynamics of the Little Campbell River; further data acquisition and analysis may be required to fully resolve these questions.

The temperature and SC data were judged to be of excellent and very good quality, respectively, apart from gaps which occur through all of the parameters measured at this site. Thus, no corrections were undertaken. The DO data appeared to be of good quality, except for apparent instrument drift prior to November 24/05, and some very high concentrations on January 2/05. The latter correspond to oxygen saturations far above 100%, and could conceivably be due to the passage of air bubbles across the sensor. The drift was corrected, and the January 2/05 data were deleted. The pH, stage, and turbidity data were deemed to be of average quality. Offset and/or drift corrections were applied to the pH and stage time series. Note that for the latter parameter, the manual measurements of stream depth against the staff gauge were taken to be ground truth. Some of these measurements, as recorded in the station maintenance notes, were nominally negative. No corrections were unambiguously warranted for the turbidity data, so none were made. Note that, in a general sense, the very high turbidity values occasionally recorded by the automated station seem to be at least loosely corroborated by the available manual field measurements.

We suggest that station downloads and maintenance be performed somewhat more frequently if possible, to reduce data gaps and to obtain a slightly higher frequency of manual field measurements against which to validate and calibrate the automated station data.

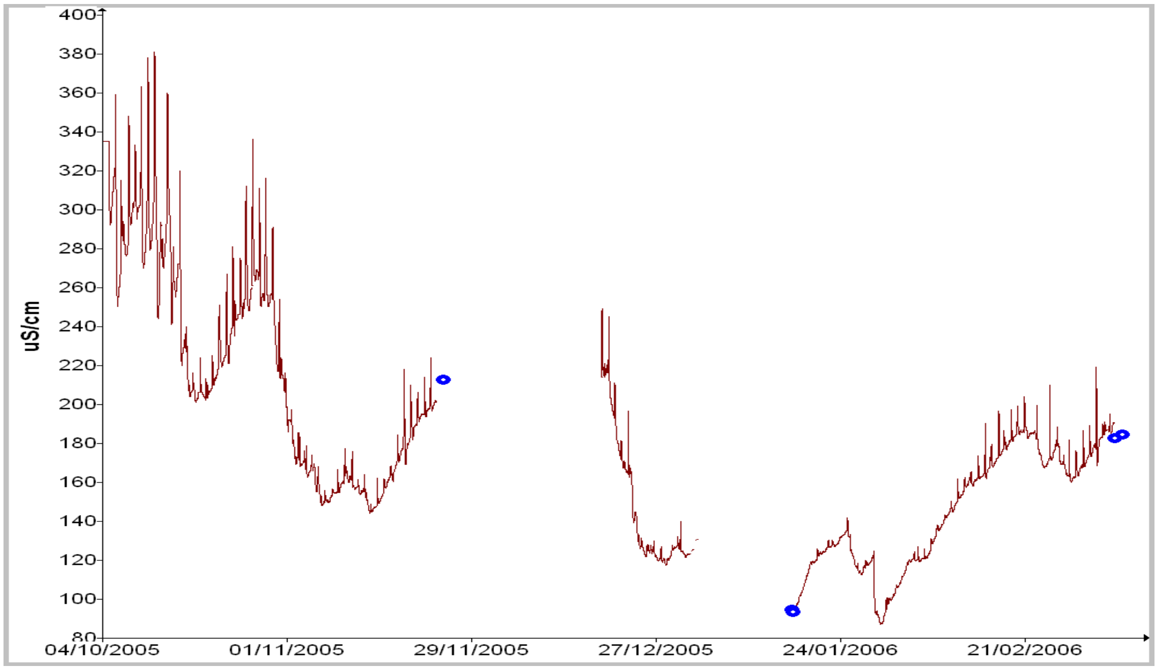

Figure A.15 *Hydrolab specific conductivity. Blue circles give manual field measurements.*

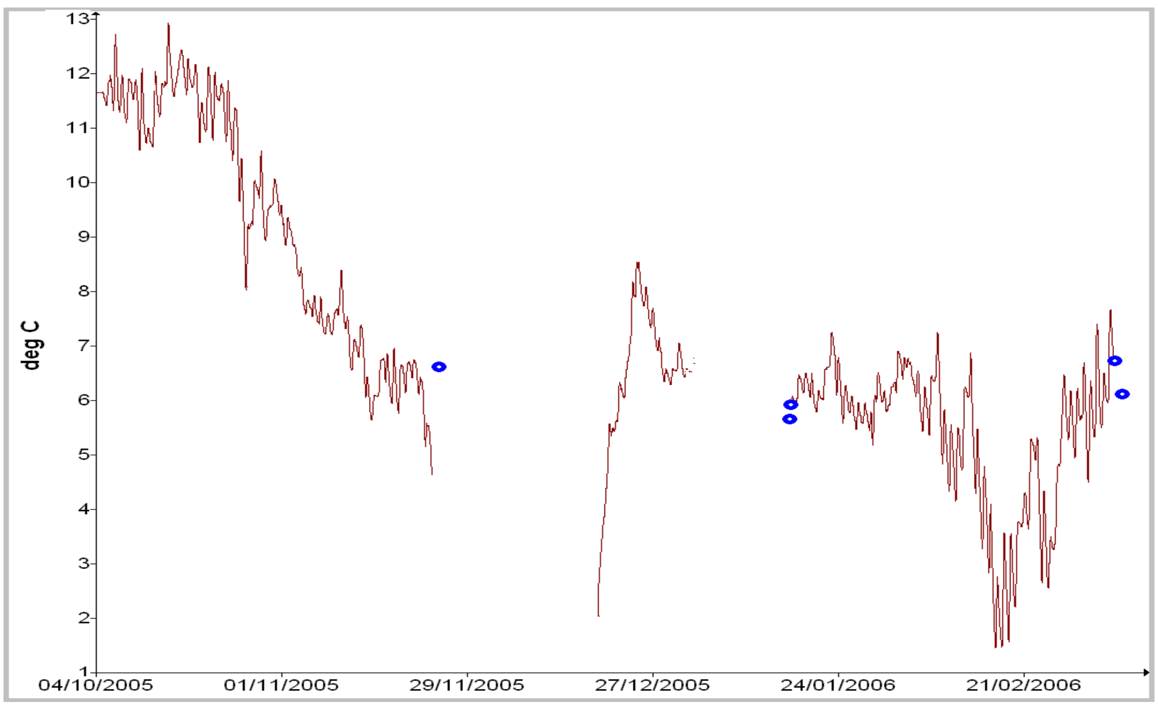

Figure A.16 *Hydrolab water temperature*

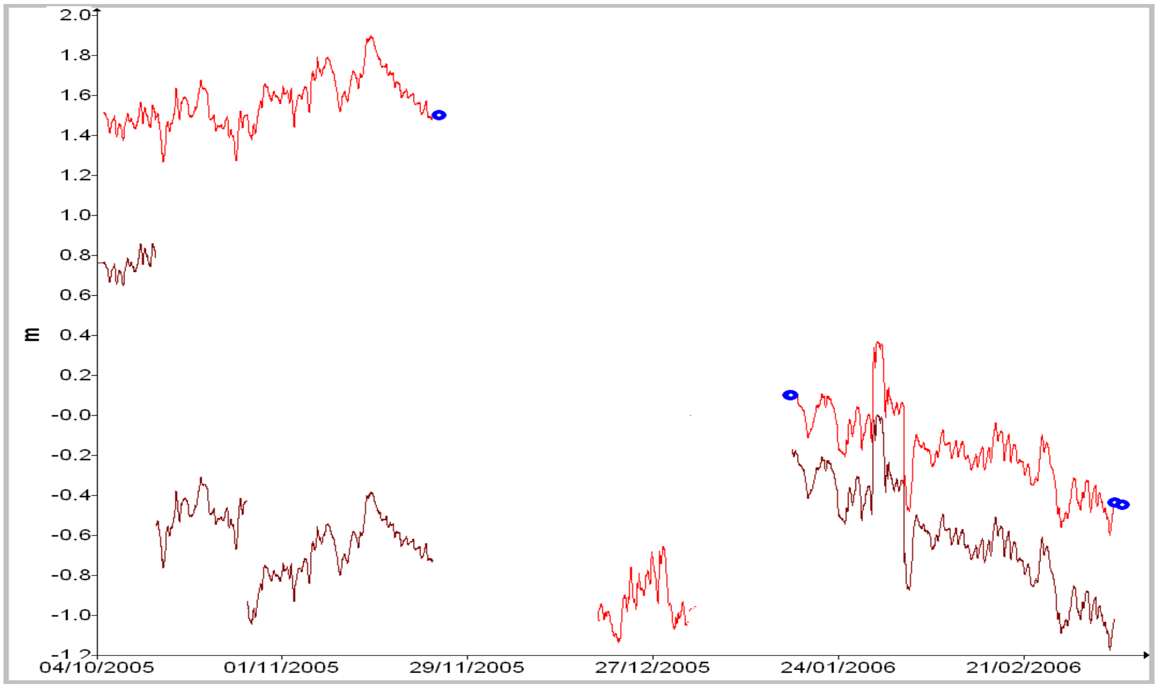

Figure A.17 *Hydrolab stage, adjusted to staff gauge. Bright red line gives corrected data.*

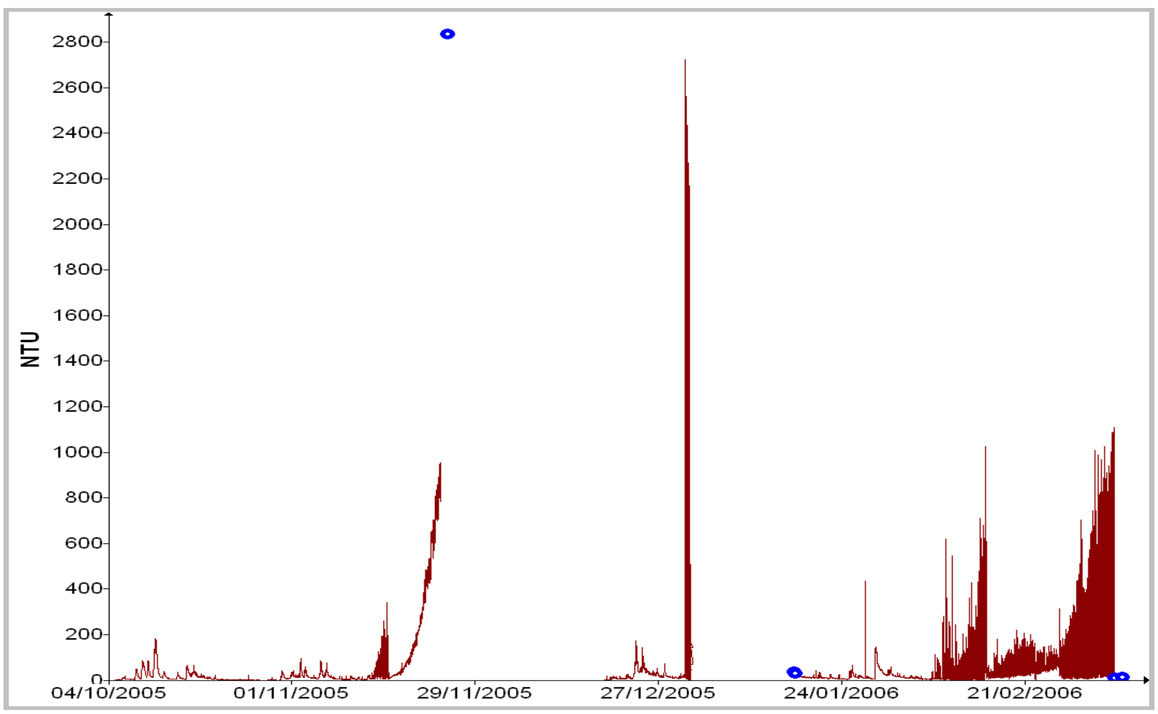

Figure A.18 *Hydrolab turbidity*

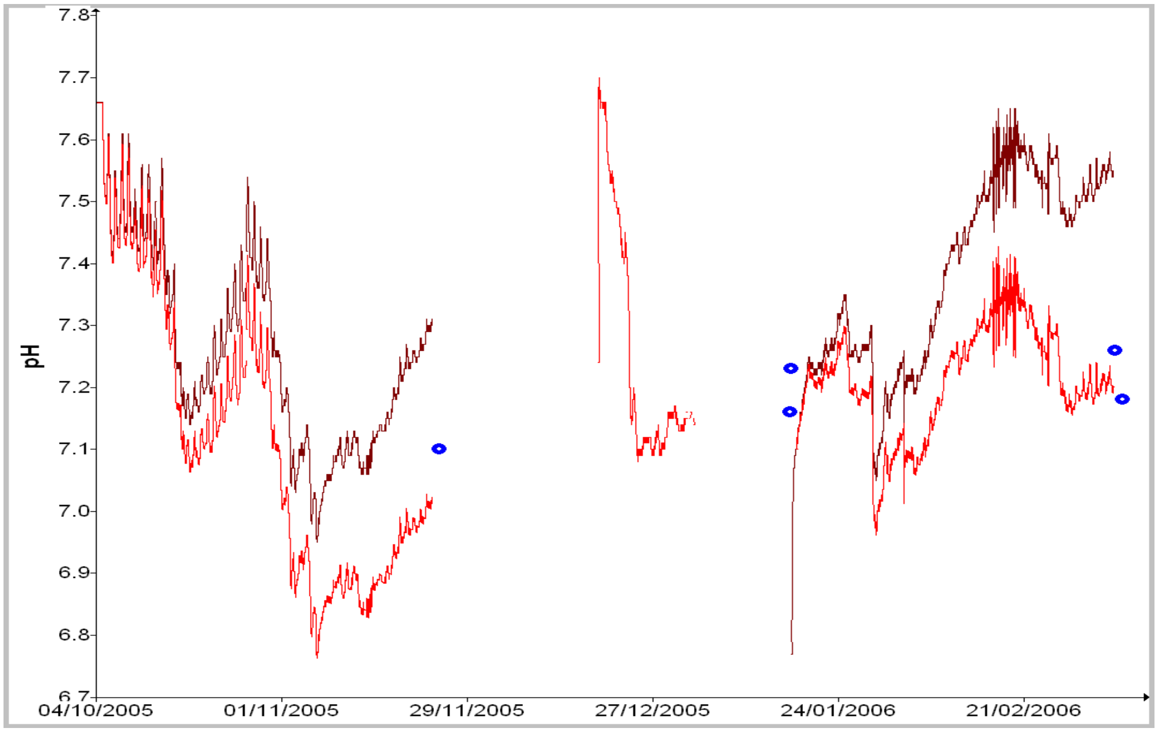

Figure A.19 *Hydrolab pH. Bright red line = corrected data. pH on 11/24/05 = 7.0 (not shown)*

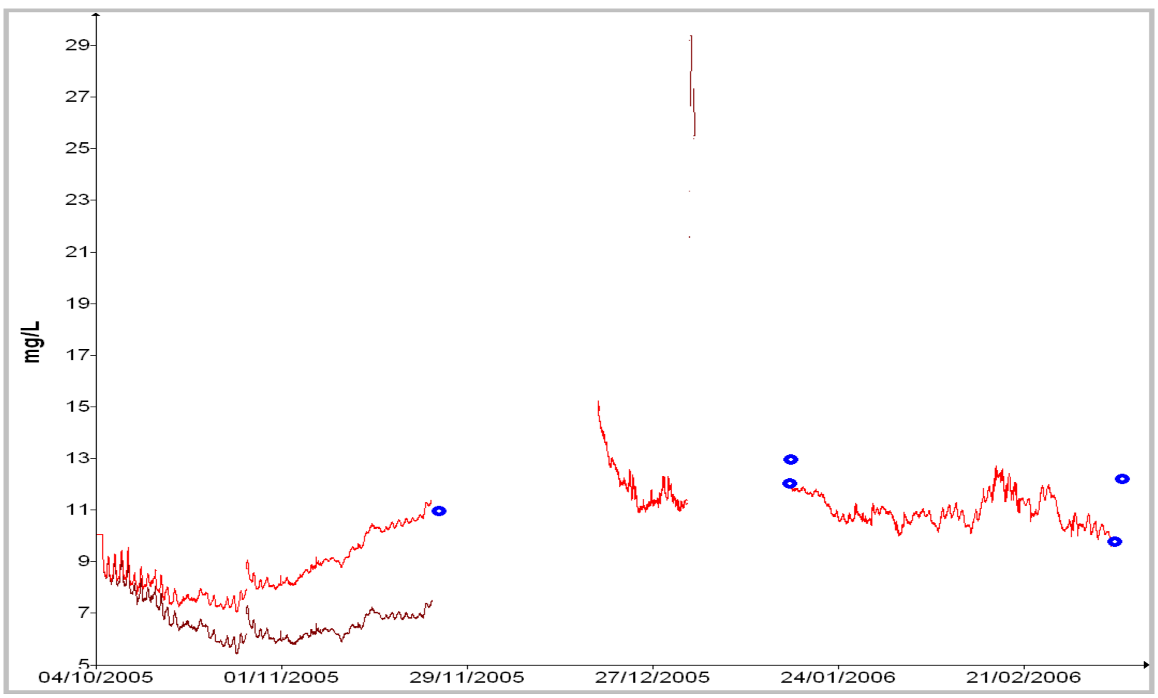

Figure A.20 *Hydrolab dissolved oxygen. Bright red line gives corrected data.*

A.4 Statistical Summary

A.4.1 Thermistor Network

The minimum, mean, and maximum values at each station over its full record length as available to AI at the time of writing are given in **Table A.2**. However, because the record lengths are variable between stations and temperature is season-dependent, it may be difficult to make meaningful comparisons between stations on the basis of the results in **Table A.2**.

Therefore, in **Table A.3** we list a more comprehensive suite of summary statistics, calculated over the period of record common to all the thermistor stations (July 28/05-September 26/05). Note that we do not include the Hydrolab water temperature measurements here because its 2005 record begins much later than for the thermistor network (October 5).

Table A.4 shows the inter-station mean and range for a number of these statistical metrics, across all the LCR mainstem stations (top row), and across all the tributary stations (bottom row). In all tables, if the data for a given station were corrected, then summary statistics were generated using the corrected data.

Table A.2 *2005 minimum, mean, and maximum temperatures over full, currently available record for each station. See* ***Table A.1*** *for complete station names.*

Location	min	ave	max
Fergus Cr	9.1	15.3	19.0
East Twin Cr	8.3	15.6	19.9
West Twin Cr	8.8	15.0	18.1
Creek / Thompson & 176th	8.9	14.4	19.1
McNalley Cr	10.5	15.4	18.2
Jacobsen Cr	9.4	14.7	17.4
Jenkins Cr	10.1	16.1	20.5
Sam Hill Cr	8.6	14.0	17.8
Kuhn Cr	8.0	14.9	19.1
LCR at 216th St	8.5	13.9	16.6
LCR at 172nd St	10.2	16.6	20.5
LCR at Boy Scout camp	10.4	15.9	18.2
LCR at hatchery	9.9	15.1	18.5
LCR at 16th Ave	10.1	14.3	17.3

Table A.3 *Statistical summary of 2005 thermistor network data over mutually common period of currently available record (July 28-Sep 26, 2005). Abbreviations are as follows: min = minimum; 5‰ = 5th percentile; ave = average (mean); med = median (50th percentile); 95‰ = 95th percentile; max = maximum; rng = range (maximum-minimum); std = standard deviation; IQR = interquartile range (75th percentile-25th percentile). See* ***Table A.1*** *for full station names.*

Location	min	5‰	ave	med	95‰	max	rng	std	IQR
Fergus Cr	9.1	10.9	15.1	15.5	17.7	19.0	9.9	2.0	2.7
East Twin Cr	8.3	10.5	15.0	15.3	18.3	19.3	11.0	2.2	2.8
West Twin Cr	8.8	10.7	14.7	15.0	17.3	17.9	9.1	1.9	2.5
Cr / Thompson & 176th	8.9	10.9	14.4	14.5	17.7	19.1	10.3	1.9	2.2
McNalley Cr	10.5	116	15.2	15.6	17.4	18.2	7.7	1.7	2.2
Jacobsen Cr	9.4	11.2	14.5	14.7	16.8	17.4	7.9	1.7	2.3
Jenkins Cr	10.1	11.8	15.9	16.0	19.1	20.5	10.4	2.1	2.5
Sam Hill Cr	8.6	10.4	13.8	14.0	16.2	17.8	9.2	1.7	2.2
Kuhn Cr	8.0	9.5	14.4	14.9	17.3	18.1	10.2	2.2	2.8
LCR at 216th St	8.5	9.5	13.9	14.5	15.8	16.6	8.1	1.8	2.6
LCR at 172nd St	10.2	11.3	16.3	16.8	19.2	20.5	10.3	2.4	3.5
LCR at Boy Scout camp	10.4	11.7	15.9	16.5	17.9	18.2	7.8	1.8	2.5
LCR at hatchery	9.9	11.5	14.9	15.1	17.6	18.5	8.5	1.8	2.5
LCR at 16th Ave	10.1	11.7	14.1	14.2	16.4	17.3	7.2	1.4	1.9

Table A.4 *Mean values of the individual station minima, average, and maxima (as listed in* ***Table A.3****) across all LCR mainstem thermistors; mean values of individual station minima, averages, and maxima across all tributary stations; and range of minimum, average, and maximum temperatures across all five LCR stations, and across all nine tributary stations.*

Location	Mean value of:			Range in:		
	min	ave	max	min	ave	max
LCR mainstem stations	9.8	15.3	18.2	1.9	2.4	3.9
Tributary stations	9.1	14.8	18.6	2.5	2.1	3.1

On the basis of the available data, the three warmest locations in terms of maximum observed temperature appear to be Jenkins Creek, the LCR mainstem at 172nd Street, and East Twin Creek (**Table A.3**). The ranking can change somewhat depending on the specific statistical metric, however. For instance, in terms of mean temperature, the three warmest locations were evidently Jenkins Creek, the LCR mainstem at 172nd Street, and the LCR mainstem at the Boy Scout camp.

Interestingly, overall (**Table A.4**) the LCR mainstem appears to show very slightly warmer temperatures, and slightly greater spatial variability in temperature, relative to the tributary creeks monitored. However, whether these contrasts are statistically significant and, if so, why that temperature pattern arises, remains to be assessed pending (in part) additional data acquisition.

The highest observed instantaneous temperature anywhere in the network was 20.5^o, so it seems unlikely that acutely lethal temperatures were encountered by salmonids in the monitored portions of the LCR system in the summer of 2005. However, chronic temperature risks, which begin to be incurred at lower temperatures relative to acute risks (see Section II of this report), may have been widespread. Note that the temperatures observed here might be elevated relative to pristine conditions due to historical activities in the watershed, including but not limited to removal of riparian vegetation and shading. As noted in Section II, chronic risks could grow worse under poor watershed management practices and potential climatic changes, but could by the same token be mitigated and reversed by restoration activities.

A.4.2 Multi-Parameter Station

Statistical summaries for each Hydrolab parameter over its full record length as available to AI at the time of writing (nominally, October 5/05 through March 7/05) are given below in **Table A.5**.

Table A.5 *Statistical summary of 2005 Hydrolab data over currently available period of record. Abbreviations are as in caption to* ***Table A.3****. Units are: m for stage, ^{o}C for temperature, μS/cm for specific conductivity, mg/L for dissolved oxygen, and NTU for turbidity.*

Location	min	5‰	ave	med	95‰	max	rng	std	IQR
pH	6.8	6.9	7.2	7.2	7.5	7.7	0.9	0.2	0.2
Stage	-1.1	-1.0	0.5	0.0	1.7	1.9	3.0	1.0	1.8
Temperature	1.5	3.3	7.2	6.5	11.9	12.9	11.5	2.6	3.2
Specific conductivity	87	108	178	168	292	381	294	55	72
Dissolved oxygen	7.0	7.5	10.1	10.5	12.1	15.2	8.2	1.5	2.6
Turbidity	0.0	0.6	66.1	13.6	377	2723	2723	173	31.9

On the basis of the available data, it appears that the only monitored water quality parameters which obviously exhibited potentially problematic levels at this location over the fall and winter of 2005-2006 were DO and turbidity. Dissolved oxygen reached a protracted minimum in the 7-8 mg/L range in about late October. Turbidity occasionally reached some very high values, which may reflect bank slumps into the creek under heavy rainfall and/or human disturbance.

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