Coquitlam/Buntzen Project Water Use Plan

Lower Coquitlam River Temperature Monitoring

Implementation Year 4

Reference: COQMON#6

Study Period: March 2008 – April 2011

Trow Associates Inc.
TEMPERATURE MONITORING PROGRAM
LOWER COQUITLAM RIVER
YEAR 4 REPORT
Version 4 (Final)

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EXECUTIVE SUMMARY

Trow Associates Inc. (Trow) was retained by BC Hydro to conduct a temperature monitoring program of the Lower Coquitlam River in Coquitlam, BC, with respect to assessing potential effects of the Coquitlam Reservoir operations on downstream river temperatures. The program’s field component provided over four years of collected data from stations along the Coquitlam reservoir-river system. For comparisons of natural lake-river systems (temperature gradients), data was collected also for the two natural systems, Chehalis and Chilliwack, which were chosen for accessibility, proximity to, and similarities with, the Coquitlam system. The data collection is intended for the provision of a statistical analysis, to test and report on the presence of dam operations effects on downstream temperatures within the Coquitlam system, and their relevance, if detected, to downstream freshwater aquatic life.

Methods used for this analysis include descriptive and inferential statistics. A key for interpreting the notched box plots (descriptive statistical summaries) used throughout this report is included at the beginning of the report. Inferential statistics includes analysis of variance (ANOVA) for comparison of mean temperatures from two or more data sets and multiple regression analysis to measure the significance of different parameters in statistical modeling of temperature data sets at stations of interest.

Organization of the analysis is centered on answering two key management questions. The questions and their answers have been addressed as follows:

<table>
<thead>
<tr>
<th>Question 1: Is there a significant correlation between lower Coquitlam River temperatures and Coquitlam Reservoir operations?</th>
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</table>

**Answer:**
- In the cold, high-discharge season of November 1 through December 31, the answer is ‘yes’.
  - Comparison of temperature means shows that there was no difference between mean temperatures of the reservoir surface and the discharge stratum during these months of the study period. Moreover, there was only a slight statistical drop in mean temperature between the reservoir surface and the downstream Patricia Footbridge station (approximately 0.8 °C) during this time of high discharge rates. However, based on the literature (e.g., Ahmadi-Nedushan et al., 2007), and confirmed by tests done for this study, a high negative correlation is expected between stream temperature and flow rate. (For Patricia Footbridge, during the warm, low-discharge season this correlation is -0.76 – shown in Figure 21 in the body of this report).
  - Based on five years of records (2004 through 2008), on average, for November and December approximately 51% of the flow passing through the Environment Canada station (downstream of Patricia Footbridge) is dam discharge. Regression analysis conducted for the Patricia footbridge station during the cold, high-discharge months found extremely high significance for the variable at.depth (temperature of the discharge stratum), and this variable is non-existent at this station during the warm
season at this station. (Or Creek is of even more extreme significance than at\_depth in the cold season, and is perhaps responsible for the slight drop of 0.8 °C.)

- In the warm, low-discharge season (June 1 through August 31), the answer is ‘yes’.
  - Comparison of temperature means shows that the monitoring station below the dam is cooler than the reservoir surface by approximately 3°C, and therefore a cooling effect is attributed to the variable at\_depth, since it is cooler than the station below the dam. Because of low discharge rates, however, the influence of at\_depth is lost on the downstream side of the cold confluence of Or Creek. Of all possible explanatory variables tested, Or Creek was shown to be the single most important explanatory variable affecting temperatures downstream from it.

**Discussion:** For the warm, low-discharge season, although there is a significant correlation between lower Coquitlam River temperatures and Coquitlam reservoir operations (i.e., the below dam station is approximately 3°C cooler), the significance is lost beyond Or Creek, because of low discharge rates. Moreover, although we observe this cooling effect at the station immediately below the dam, guidelines for maximum temperature thresholds published by the BC Ministry of Environment show that temperatures always exceeded the threshold for the category *Freshwater Aquatic Life – unknown fish distribution* for each summer we looked at. (Plots of these thresholds are included further in this report.)

For the cold, high-discharge season, although we observe warmer downstream temperatures than might be expected based on understanding of flow increases due to natural conditions, this warming effect does not raise temperatures above incubation temperature guidelines for the category *Freshwater Aquatic life – unknown fish distribution* published by the Ministry of Environment. In addition, potential impacts on Accumulated Thermal Units (ATUs) and incubation on downstream reaches beyond Or Creek do not appear evident when compared to the Chilliwack and Chehalis River systems. However, there are many other categories which could be checked; some may be more applicable to the Lower Coquitlam River than the categories plotted in this report.

**Question 2:** Is there a significant difference between the reservoir to river temperature gradient and lake to river temperature gradient(s) in similar but unregulated lower Fraser River tributaries?

**Answer:**

- Inferences based on the Chehalis system are weak due to lack of replication of seasons for Chehalis Lake.
- In the warm season, we found a significant difference between the Coquitlam system gradient and those of the natural systems.
  - The Coquitlam system gradient was 4.3 °C (lake to river, warm to cool) while the Chehalis system gradient was 0.6 °C and Chilliwack system gradient was 1.4 °C.
  - The temperature of the gradient midpoint for the Coquitlam system was 17 °C while both the Chehalis and Chilliwack systems had midpoint temperatures of approximately 13 °C.
o Through regression analysis, the steepness of the warm season gradient was shown to be largely attributable to Or Creek. The below dam station was approximately 3°C cooler, and this was caused by at depth discharge; however, this influence had no significance beyond Or Creek in the warm season (as discussed above).

- In the cold season, the Coquitlam system gradient showed a greater tendency to flatten than the Chehalis or Chilliwack systems.
  o The Coquitlam system gradient flattened by 85% while Chilliwack system flattened by 24% and Chehalis system steepened by 68%. As discussed, regression analysis showed the flattening of the Coquitlam system to be largely attributable to the higher discharge rates that occur in November and December.
  o Since Chehalis Lake lacks replication of seasons, the observed steepening of the Chehalis system is not statistically supported.

Discussion: The behaviour of the Coquitlam system reservoir-river temperature gradient appears to be significantly different than the two natural gradients (notwithstanding the apparent steepening of Chehalis in the winter). In the warm season, the Coquitlam gradient was much steeper than the other two, and its midpoint was much warmer than the other two. In fact, for the study period, the cool endpoint of the gradient, Patricia Footbridge station, was warmer than the warm endpoints (lakes) of the Chehalis and Chilliwack gradients in the summer, and the reservoir was warmest of all gradient endpoints –Figure 12). During November and December of the study period, both endpoints of the Coquitlam gradient dropped dramatically to a level slightly cooler than the warm endpoints of the two natural systems (Figure 13). High discharge rapidly transports the warmer temperatures of the reservoir discharge stratum to downstream stations (approximately 51% of flow at the hydrometric station came from dam discharge for these months). Even with these observed warmer temperatures, the station below the dam still exhibited temperatures that were below the incubation threshold for the category Freshwater Aquatic Life – unknown fish distribution publish in Ministry of Environment guidelines. In the summer, the apparent relative steepness of the Coquitlam gradient results from the contrast of relative high reservoir surface temperatures against the relative cold influence of Or Creek on temperature response at the gradient endpoint Patricia Footbridge station. During the summer months of the study period there appeared to be a cooling effect at the station immediately below the dam, but it is lost at the far downstream endpoint in the presence of the much cooler influence of Or Creek. Even with a cooling effect temperatures rose above ministry guidelines for the category Freshwater Aquatic Life – unknown fish distribution in the reach immediately below the dam.
# TABLE OF CONTENTS

1.0 INTRODUCTION .............................................................................................................. 1
  1.1 Background .................................................................................................................. 1
  1.2 Objective and Scope ..................................................................................................... 1
  1.3 Management Questions ............................................................................................... 2
   
2.0 METHOD .......................................................................................................................... 3
  2.1 Program Development .................................................................................................. 3
  2.2 Data Acquisition .......................................................................................................... 3
  2.3 Data Quantity ............................................................................................................... 4
  2.4 Data Quality ................................................................................................................ 5
  2.5 Analysis: Statement of Hypothesis ............................................................................. 5
  2.6 Conditional Statements Regarding This Analysis ....................................................... 6
   
3.0 ANALYSIS AND RESULTS ........................................................................................... 9
  3.1 Cold, high-discharge season, November 1 to December 31 .......................................... 13
    3.1.1 Comparison of mean temperatures within Coquitlam system – cold season ........ 13
    3.1.2 Regression analysis of upstream and downstream temperatures – cold season .... 18
  3.2 Warm, low-discharge season, June 1 to August 31 ..................................................... 25
    3.2.1 Comparison of mean temperatures within Coquitlam system – warm season ....... 25
    3.2.2 Regression analysis of Upstream and Downstream temperatures – warm season 29
  3.3 Comparison of Gradients of Coquitlam, Chehalis, and Chilliwack Systems ............... 37
  3.4 Gradient Comparison Figures ..................................................................................... 40
  3.5 Discussion .................................................................................................................... 42
    3.5.1 Potential cooling effect at first station below dam ................................................. 42
    3.5.2 Impact of cooling at first station below dam ......................................................... 43
    3.5.3 Comparison of Coquitlam gradient to natural gradients – potential warming effect 46
    3.5.4 Impact of cold season warming in reaches below dam ....................................... 52
    3.5.5 Plots of a 2007 warm season 5-day discharge spike .......................................... 55
   
4.0 CONCLUSIONS .............................................................................................................. 58

5.0 REFERENCES ................................................................................................................. 62

6.0 CLOSURE ....................................................................................................................... 65
LIST OF FIGURES (included)

Figure 1: available data for year-range 2004-2009 (please refer to p. vii for acronyms and variable names); the first 6 rows are: reservoir air temperature \textit{CQM-L1}; reservoir water temperature \textit{CQM-L2}; discharge stratum temperature \textit{at.depth}; reservoir surface elevation \textit{CQM-D2}; dam discharge \textit{CQM-D1}; discharge measured at downstream hydrometric station \textit{CQM-R7}.

Figure 2: \textit{unequal comparison} (different y scale) for four years, of reservoir elevation (m), dam discharge (cms), and downstream flow (cms) at Environment Canada hydrometric station (c.f. Figure 3 for \textit{equal comparison} – same y scale)

Figure 3: \textit{equal comparison} (same y scale) for four years, of reservoir elevation (m), dam discharge (cms), and downstream flow (cms) at Environment Canada hydrometric station (c.f. Figure 2 for \textit{equal comparison} – same y scale)

Figure 4: timeframe of regression analysis; no temperature data exists for summer 2009 for the reservoir \textit{(CQM-L2)} and discharge stratum \textit{(at.depth)}; no temperature data exists for river stations after November 25, 2009

Figure 5: \textit{cold, high-discharge season} profile using all Lower Coquitlam river stations and temperatures of the discharge stratum (dark green) and reservoir surface (1mbs – gold); considerable flattening of the gradient is evident compared to the warm season profile (Figure 8)

Figure 6: scatterplot matrix of Model 1; red lines are fitted non-parametric smoothed curves

Figure 7: scatterplot matrix of Model 5; red lines are fitted non-parametric smoothed curves

Figure 8: \textit{warm, low-discharge season} profile using all Lower Coquitlam river stations and the temperature regime of the discharge stratum (at.depth); overlapping notches (~ 95% confidence intervals) indicate insignificant differences (cf. same stations in cold season)

Figure 9: scatterplot matrix of Model 16; red lines are fitted non-parametric smoothed curves

Figure 10: monthly mean temperature of reservoir surface, discharge stratum, and below dam station averaged over all available months from 2004 to 2008 in the Coquitlam system

Figure 11: scatterplot matrix of Model 27; red lines are fitted non-parametric smoothed curves

Figure 12: \textit{warm, low-discharge season} gradients (average temperatures of systems endpoints)

Figure 13: \textit{cold, high-discharge season} gradients (average temperatures of systems endpoints)

Figure 14: percent change (change in slope) and vertical change (change in height of gradient midpoint) for Coquitlam, Chehalis and Chilliwack lake-river gradient systems (cf. Table 4)

Figure 15: \textit{Below Dam station (CQM-R6) 7-day moving average of maximum daily temperatures}: July 6, 2007 – October 4, 2007 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 10 = July 15; 17 = July 22; 77 = September 20; 82 = September 25 (\textit{MWMT = Mean Weekly Maximum Temperature})

Figure 16: \textit{Below Dam station (CQM-R6) 7-day moving average of maximum daily temperatures}: July 19, 2008 – August 26, 2008 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 4 = July 22; 13 = July 31; 38 = August 25 (\textit{MWMT = Mean Weekly Maximum Temperature})
Figure 17: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: July 3, 2009 – October 1, 2009 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 14 = July 16; 86 = September 26

Figure 18: monthly flow at Environment Canada hydrometric station averaged over 5 years (2004 - 2008)

Figure 19: dam discharge levels averaged over 5 years (2004 - 2008)

Figure 20: dam discharge contribution to downstream flow during cold, high-discharge months

Figure 21: water temperature at Patricia Footbridge station plotted against flow rate at Environment Canada station June – August 2007 – 2008 (Pearson's product-moment correlation = -0.76)

Figure 22: water temperature at Patricia Footbridge station and dam discharge rates June – August 2007 – 2009 (a 5-day spike in discharge in July 2007 has been removed from this data – cf. Figure 26)

Figure 23: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: November 12, 2007 – June 28, 2008 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 2 = November 13; 187 = May 16

Figure 24: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: October 21, 2008 – May 18, 2009 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 2 = October 22; 210 = May 18

Figure 25: ATUs in 2007/2008 and general dates expected for hatching and emergence stages (shaded areas) for incubating Coho salmon eggs. Time for start of spawning is for general reference only.

Figure 26: 5-day spike in discharge in July 2007 (cf. Figure 22)

Figure 27: conditional plot showing 5-day spike in discharge during the 2007 warm season, Patricia Footbridge water temp plotted against dam discharge (bottom row) and Environment Canada hydrometric station discharge records; the discharge spike appears as a break in the natural inverse correlation of flow and stream temperature shown in the top row
LIST OF TABLES (included)

Table 1: differences in mean temperature – cold season
Table 2: differences in mean temperature – warm season
Table 3: warm season lake-river water temperature gradients with 95% confidence interval*
Table 4: cold season lake-river water temperature gradients with 95% confidence interval
Table 5: ANOVA – warm season average temperatures of gradient systems endpoints
Table 6: ANOVA – cold season average temperatures of systems endpoints

APPENDICES

Appendix A  Figure A-1: Relationship of Coquitlam Watershed to Comparison Watersheds in Lower Fraser Valley
Figure A-2: Coquitlam Watershed with Data Collection Locations
Figure A-3: Chilliwack Watershed with Data Collection Locations
Figure A-4: Chehalis Watershed with Data Collection Locations

Appendix B  TableB-1: Location Details and Summary of Available Data for All Systems

Appendix C  Interpretation & Use of Study and Report
**LIST OF ACRONYMS & VARIABLE NAMES**

Acronyms and variable names used in this report (organized as they appear on Figure 1) are presented below:

<table>
<thead>
<tr>
<th>ACRONYM &amp; VARIABLE NAMES</th>
<th>STATION DESCRIPTION</th>
<th>DETAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLS-R1</td>
<td>DFO Chehalis Hatchery</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CLS-L2</td>
<td>Chehalis Lake near outlet</td>
<td>lake water temperature</td>
</tr>
<tr>
<td>CLS-L1</td>
<td>Chehalis Lake</td>
<td>lake water temperature</td>
</tr>
<tr>
<td>CWK-R2</td>
<td>Chilliwack River upstream of Foley Creek confluence</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CWK-R1</td>
<td>DFO Chilliwack Hatchery</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CWK-L3</td>
<td>Chilliwack Lake at outlet (BCH logger)</td>
<td>lake water temperature</td>
</tr>
<tr>
<td>CQM-R1</td>
<td>reach 0 (Red Bridge)</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CQM-R2</td>
<td>reach 2 (Patricia Footbridge)</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CQM-R3</td>
<td>reach 3 (Hatchery)</td>
<td>river water temperature</td>
</tr>
<tr>
<td>CQM-R5</td>
<td>reach 3 (Or Creek)</td>
<td>river water temperature</td>
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<tr>
<td>CQM-R6</td>
<td>reach 4 (below dam)</td>
<td>river water temperature</td>
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<tr>
<td>CQM-R7</td>
<td>Env. Can. hydrometric stn. 08MH002</td>
<td>flow (cms)</td>
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<tr>
<td>CQM-D1</td>
<td>Coquitlam Res. discharge</td>
<td>discharge (cms)</td>
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<td>d.discharge</td>
<td>temperature of discharge stratum</td>
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<tr>
<td>CQM-L2</td>
<td>COQ2 thermistor chain</td>
<td>only the 1mbs data set (which represents the reservoir surface) is used in analysis</td>
</tr>
<tr>
<td>res.surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CQM-L1</td>
<td>above dam</td>
<td>air temperature</td>
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1.0 INTRODUCTION

Trow Associates Inc. (Trow) was retained by BC Hydro to conduct a temperature monitoring program of the Lower Coquitlam River in Coquitlam, BC, with respect to assessing potential effects of the Coquitlam Reservoir operations on downstream river temperatures. The monitoring program presented in this report utilizes a collection of data obtained over four years and is intended to provide a statistical analysis of data to assess the potential temperature effects downstream of the reservoir.

1.1 Background

Coquitlam Reservoir is a natural lake that was enlarged by the construction of a dam at the head of the Lower Coquitlam River. Waters from Coquitlam Reservoir are diverted through tunnels to Buntzen Lake, a reservoir that supplies water for two hydroelectric generation stations on Indian Arm, to the Greater Vancouver Water District’s (GVWD) drinking water system (note: the GVWD corporate entity also operates under the name Metro Vancouver). Releases of water are also directed to the Lower Coquitlam River to maintain the features and functions of this stream and its associated riparian habitat.

BC Hydro’s Coquitlam-Buntzen Water Use Plan (CBWUP), Monitoring Plan Terms of Reference (BC Hydro, 2006) – January 2006 (updated December 2007) specifies that a monitoring program be carried out to assess the effects of reservoir operations on downstream river temperatures in order to guide decisions made regarding the balancing of the three main demands on the Coquitlam-Buntzen system. These demands include habitat (primarily fish habitat) on the Lower Coquitlam River, domestic water supply, and hydroelectric power generation. Two components of the CBWUP monitoring program are infrastructure upgrades at the Coquitlam Reservoir, to allow regulated and variable flows from the low level outlets, and a series of monitoring programs, that will allow the assessment of various flow regimes being implemented over a nine year period. This Lower Coquitlam River temperature monitoring program is one of eight monitoring programs for the Coquitlam-Buntzen system.

1.2 Objective and Scope

The Lower Coquitlam River Temperature Monitoring Program (the Program) has the objective of determining if and how water temperatures in the Lower Coquitlam River are influenced by reservoir operations. This report evaluates the data provided to answer the management questions determined by the monitoring program’s management team.

Temperature monitoring has been conducted for four years (2006 through 2009) in various reaches of interest below the dam. Additional temperature monitoring by the GVWD in the Coquitlam Reservoir has also been conducted. Temperature data for adjacent and/or similar lake-headed tributaries to the lower Fraser River were also identified and used to analyze the degree of influence operations has on river temperature. The similar systems used for comparison in this program include: 1) the Chilliwack Lake and River and 2) the Chehalis Lake and River. These systems were selected because of similarities with the Coquitlam system in terms of size of lake and grade, channel width and length of river components.
1.3 Management Questions

The four years of this monitoring program generally involved the collection of, and a brief summary of, available data. The fourth year of this monitoring program also culminates in this analysis that is intended to answer the following two management questions:

1) Is there a significant correlation between lower Coquitlam River temperatures and Coquitlam Reservoir operations?
   and
2) Is there a significant difference between the reservoir to river temperature gradient and lake to river temperature gradient(s) in similar but unregulated lower Fraser River tributaries?
2.0 METHOD

The three main components of this study include the following:

- Temperature monitoring
- Information review and collation
- Analysis

Please note, temperature monitoring data were collected by various parties and submitted to, and/or requested by Trow throughout the monitoring program. Year 1, year 2, and year 3 temperature monitoring program reports (previously submitted) included a summation of yearly data with no statistical analysis. The year 4 report presents the statistical analysis of data compiled over the fourth year and preceding three years.

2.1 Program Development

The Lower Coquitlam River Monitoring Program was initiated in November 2005 with the installation of five water temperature data logger and one air temperature logger. Together with operations data (water releases to the Lower Coquitlam River) and water temperature data for Coquitlam Reservoir, obtained from the GVWD, these data were used to answer the first management question. In 2006, a search was conducted to locate data on water temperatures from one or more unregulated lake-river tributaries on the lower Fraser River. Candidate systems included the Harrison, Pitt, Chilliwack, Chehalis and Cultus systems. Data from the unregulated systems would be analyzed with lake and river water temperature data from the Coquitlam system to answer the second management question. See Figure A-1 for the location of the Coquitlam system in the lower Fraser Valley and Figure A-2 for details of the sampling locations in the Coquitlam system.

Although the Program was initially set up to run between January 2006 and December 2009, there was a substantial amount of data for some components of the Coquitlam system dating back to approximately the year 2000. It was decided that available historical data would be checked, formatted and stored with the 2006-2009 data. For details on this historical data and 2006 data please see the Year 1 Report.

The Year 1 Report noted that, of the candidate systems, only the Chehalis and the Chilliwack systems are suitable for comparison to the Coquitlam due to the similar size of their lakes, and the similar grade, channel width and length of their river components. See Figures A-3 and A-4 for details of the Chehalis and Chilliwack systems including the sampling locations.

2.2 Data Acquisition

Data on water releases to the Lower Coquitlam River, reservoir water surface elevation and water and air temperatures in the Lower Coquitlam River were provided by Living Resources. Water and air temperature data for Coquitlam Reservoir were provided by the GVWD (Metro Vancouver).
Water temperature data for Chilliwack River and Chehalis River were provided by Department of Fisheries and Oceans (DFO) fish hatcheries operated on each river. A limited amount of historical water temperature data was available from DFO for Chilliwack Lake, but no data from 2006 or earlier was identified for Chehalis Lake.

In response to the paucity of water temperature data available for Chilliwack and Chehalis Lakes, BC Hydro installed water temperature data loggers on both of these lakes in the summer of 2007. Due to uncertainty regarding the continuation of DFO water temperature monitoring program on Chilliwack River, BC Hydro also installed two water temperature data loggers in the Chilliwack River in the summer of 2007. In December 2007, the Monitoring Plan Terms of Reference were amended to extend the program to the end of 2009 to compensate for the lack of 2006 data from a comparison system.

2.3 Data Quantity
The year-range of data used in this report is 2004 through 2009. Table B-1 presents a summary of all received data for each of the three systems, ranging from years 2000 to 2009, and the stacked time series in Figure 1 show available data and gaps in the range 2004 through 2009.

As shown in Table B-1, data for year 2009 were acquired for both the Coquitlam Reservoir and the Lower Coquitlam River; however, due to ice flow problems there are no reservoir water temperature data for April to August 2009. There are also no river station data after November 25, 2009. Sample sizes in ensuing analyses therefore vary accordingly. For example, there are three complete November/December sets for the reservoir and at depth (2007, 2008, 2009), but only two complete sets for the same two months for the river stations (2007, 2008). Graphical data summaries (notched box plots, explained further in this report) and tests for difference in population means can have variable sample sizes and generally make use of all available complete months from within the year-range 2004 through 2009. Regression analyses, however, require data sets of equal dimensions.

The reservoir discharge stratum (at depth) temperatures are calculated from the CQM-L2 thermistor chain data. The 2009 thermistor chain data received were: 1, 4, 6, 7, 8, 9, 10, 12, 15, 20, 25, 30, 35, 40, 50, and 60 mbs (metres below surface).

As shown in Table B-1, available water temperature data for the Chilliwack system includes daily data for the Chilliwack River at the DFO hatchery (CWK-R1), and hourly data for the Chilliwack River (upstream from its confluence with Foley Creek; CWK-R2) and in Chilliwack Lake near its outlet to Chilliwack River (CWK-L3).

As shown in Table B-1 and Figure 1, the longest range of received data includes water temperatures for the Chehalis River at the DFO hatchery (CLS-R1). However, there is no replication of seasons available for Chehalis Lake (CLS-L2), which ranges only from June 2008 to April 2009. (The water temperature data logger on Chehalis Lake [station CLS-L1] was lost due to a debris slide on December 3, 2007, and BC Hydro contractors were not able to access Chehalis Lake to install a replacement logger until June of 2008.) Comparison of mean temperatures for the Chehalis gradient did not use the full set of river data, but rather a partial set.
matched to the same short period that was available for the lake. An opposite lake-to-river gradient resulted in comparison of the full river/partial lake match to the partial river/partial lake match. The full set was left out to minimize potential systematic error (i.e., the error would be cancelled through subtraction of one population mean from the other in testing for difference in population means). Because Chehalis Lake lacks replication the system to system comparison component of this analysis is not statistically supported.

2.4 Data Quality

Generally the quality of the water temperature and air temperature data for the three systems under study was found to be relatively high. This was likely due in part to quality control and quality assurance procedures within the providing agencies (i.e. GVWD for Coquitlam Reservoir water and air temperatures, and DFO for Chehalis and Chilliwack River water temperature data). Data loggers installed by BC Hydro in the Coquitlam River, Chilliwack River, Chilliwack and Chehalis Lakes are placed in pairs at each location. Comparison of the two data streams increases the likelihood that anomalous values (created in most instances by the data logger being out of the water) are detected and corrected.

Some types of errors are more easily detected than others. Spurious values are frequently encountered at either end of a data series, when the logger is recording air temperature instead of water temperature. Values recorded while the data logger is traveling to or from the site are easily detected upon graphing and are deleted from the series. Other errors such as instrument shift are harder to detect and can only effectively be rooted out by a careful system of field checks and duplicate instrumentation.

2.5 Analysis: Statement of Hypothesis

The difference between natural and “operations” temperatures, for the purpose of this analysis, is defined as the difference between temperatures of the Coquitlam reservoir 1mbs stratum and the at depth or discharge stratum. Guided by this hypothesis, investigation of the first of the two management questions, “are dam operations correlated with downstream temperatures?” used two approaches. The first approach is a simple test for differences in mean lake surface temperature (Coquitlam reservoir 1mbs) with at depth (discharge stratum), and the station immediately below the dam. (This is also the only method used for the second management question regarding gradient differences across systems). If a significant difference were to be found, such that the below dam station temperature regime more closely resembled that of the discharge stratum than that of the reservoir surface – then this could be considered compelling evidence of a “dam operations” effect, at least for the upstream end. This simple approach would be used also for the downstream end of the Coquitlam system gradient, Patricia Footbridge station, although results would not be as reliable due to the influence of the upstream variable Or Creek, the coldest point source in the Coquitlam system (Figure 8). Unreliability could be diminished through use of regression modeling, the second approach used in this analysis.

Regression modeling in this analysis is based on examples found through a literature review of similar studies. Several of the studies were involved in examining the strength of stochastic models used to predict downstream temperatures. Regression modeling therefore provides a much more revealing study than simple comparison of population means, and can shed light on
complex predictor model spaces. Regression analysis, in the context of river temperature regimes, uses the relationship of independent data on variables such as flow and air temperature to predict river temperatures over different time scales. Most studies encountered did not include the objective of analyzing downstream temperatures for dam-caused thermal modifications. However, two of the studies encountered were directly concerned with dam effects and therefore became key resources for this report. One of the studies includes interseasonal variation through the use of time series models (Preece, Jones, 2002). The other, restricts its analysis to only the warm season of the year (Neumann, et al., 2002). This later approach was adopted for the analysis presented in this report.

Aside from guidance for the development of a regression model which included tests for dam effects, the two studies had little else in common with the Coquitlam study. For example, both of studies had a greater density of historical data (decades in the case of the time series study) which they partitioned into calibration and validation periods for refinement of their predictor models. Also, the objective of the single-warm season study was not to test for thermal modification but rather to provide a management decision tool for indicating when to increase flow to cool downstream reaches for the protection of fish stocks. The objective of the time series study was to investigate the deleterious effects of dam thermal modification. Those effects are in the form of cooler than natural temperatures in the summer and warmer than natural temperatures in the winter (Preece, Jones, 2002). Both effects are considered deleterious: the first delays upstream migration, and the second interferes with incubation (Preece, Jones, 2002). Perhaps the greatest difference between the two studies and the Coquitlam study is the number of monitoring stations, and especially the river distances involved: hundreds of kilometers in the case of the time series study.

2.6 Conditional Statements Regarding This Analysis

The goal of this study is to help provide understanding of the complex relationships which contribute to downstream temperature responses in the Lower Coquitlam River, especially as they relate to dam discharge, and to provide insight on the differences between those observed temperatures and guidelines published by the Ministry of Environment. The method for achieving this goal was formulated through answering the two guiding management questions:

1. Is there a significant correlation between lower Coquitlam River temperatures and Coquitlam Reservoir operations?
2. Is there a significant difference between the reservoir to river temperature gradient and lake to river temperature gradient(s) in similar but unregulated lower Fraser River tributaries?

Results for Question 2 follow the analysis for Question 1. However, as noted in the introduction, before proceeding with Question 1, it must be pointed out that there is a large disparity in data quantity for the Chilliwack and Chehalis systems compared to the Coquitlam system, especially for the Chehalis system, which lacks replication of season for the lake temperatures. The lack of replication for the Chehalis system reduces the reliability of the gradients comparison component of this analysis as a source for inferences. Available data and gaps in data coverage are shown in
Figure 1 which displays the entire data set (except CQM-R4) for all three systems from 2004 to 2010.

<table>
<thead>
<tr>
<th>CLS.R1</th>
<th>CLS.L2</th>
<th>CLS.L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWK.R2</td>
<td>CWK.R1</td>
<td>CWK.L3</td>
</tr>
<tr>
<td>CQM.R1</td>
<td>CQM.R2</td>
<td>CQM.R3</td>
</tr>
<tr>
<td>CQM.R5</td>
<td>CQM.R6</td>
<td>CQM.R7</td>
</tr>
<tr>
<td>CQM.D1</td>
<td>CQM.D2</td>
<td>at.depth</td>
</tr>
<tr>
<td>CQM.L2</td>
<td>CQM.L1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: available data for year-range 2004-2009 (please refer to p. vii for acronyms and variable names); the first 6 rows are: reservoir air temperature CQM-L1; reservoir water temperature CQM-L2; discharge stratum temperature at.depth; reservoir surface elevation CQM-D2; dam discharge CQM-D1; discharge measured at downstream hydrometric station CQM-R7.
Explanation of Notched Box Plots

Notched box plots are considered an excellent way of presenting statistical summaries for sample data sets and are extensively used throughout this report.

The central horizontal line is the sample median (50th percentile) and the lower and upper parts of the box are the second and third quartiles, bounded by the 25th and 75th percentiles respectively (i.e. fifty percent of the sample data lie within the box). The minimum and maximum sample values are shown by the low and high ends of the dashed vertical lines, if they lie within 1.5 times the interquartile range. Thus the dashed line can appear very short, but not longer than the 1.5 times interquartile range length (which is approximately equal to two standard deviations). Any data point beyond that is identified as an outlier, and is plotted as a small circle on the same vertical axis. Box plots are useful in showing how data is distributed on either side of the median. For example, the box plot on the right in the diagram above shows that its data are skew, with a larger range of values in the second quartile compared to the third.

Notches add utility to the box plot by showing if a difference between a pair of medians is significant. The notches represent the approximate 95% confidence interval. In the plot above, none of the notches overlap and so the site medians are very likely to be significantly different.
3.0 ANALYSIS AND RESULTS

Comparison of reservoir and river mean temperatures; regression analysis for explanation of river temperature regimes

To address management question 1 (within Coquitlam system) we first test for differences in mean temperatures of upstream and downstream gradient endpoint stations (variables below dam and Patricia, respectively) against those of the reservoir surface (1mbs) and discharge stratum (variables res.surface and at depth, respectively). Once significance has been determined we conduct regression analysis to examine the relationships among explanatory variables bearing upon the upstream and downstream temperature responses, within the context of seasonal discharge levels (explained below). Accordingly, there are four regression models: an upstream and downstream model for each season. We have organized our results on this basis:

3.1 Cold, high-discharge season, November 1 to December 31

3.1.1 Comparison of mean temperatures within Coquitlam system – cold season
3.1.2 Regression analysis of upstream and downstream temperatures – cold season
   3.1.2.1 Model for the Below Dam station – cold season
   3.1.2.2 Model for the Patricia Footbridge station – cold season

3.2 Warm, low-discharge season, June 1 to August 31

3.2.1 Comparison of mean temperatures within Coquitlam system – warm season
3.2.2 Regression analysis of Upstream and Downstream temperatures – warm season
   3.2.2.1 Model for the Below Dam station – warm season
   3.2.2.2 Model for the Patricia Footbridge station – warm season

Cold, high-discharge season and warm, low-discharge season

The year is isolated into two seasons to simplify the modelling process. The analysis is focused on winter and summer only, to centre on seasonal peak (or mean) temperature, when dam-caused thermal modification of downstream water temperatures (i.e., warmer than natural in winter, cooler than natural in summer), if it occurs, would be most detectable. In addition, on review of the data for the study years, it became apparent that discharge rate was characteristically high in November and December, and characteristically low from June through August. Furthermore, in early regression trials we generally found much higher explanatory power associated with discharge temperature than with discharge rate, especially for the downstream gradient endpoint Patricia Footbridge station; yet it is understood that the potential of discharge temperature is entirely dependent upon the presence or absence of discharge volume. Therefore, although we include discharge rate in the modelling process, we conduct the analysis based on assumed presence or absence of discharge volume (high-discharge, low-discharge). We are further constrained by this assumption to identify the cold season as November and December.
Figure 2 and Figure 3 are time series plots of annual reservoir elevation, discharge and downstream flow level cycles. (Figure 18 through Figure 20 show the same data as monthly average and correlation.)

Figure 2: unequal comparison (different y scale) for four years, of reservoir elevation (m), dam discharge (cms), and downstream flow (cms) at Environment Canada hydrometric station (c.f. Figure 3 for equal comparison – same y scale)
Figure 3: equal comparison (same y scale) for four years, of reservoir elevation (m), dam discharge (cms), and downstream flow (cms) at Environment Canada hydrometric station (c.f. Figure 2 for equal comparison – same y scale)

Figure 4 shows the timeframe of regression analysis of the Coquitlam Reservoir system. As noted in 2.3 Data Quantity, there are no reservoir water temperature data for the 2009 warm season. Within the timeframe there are sufficient data to provide for analysis of three cold seasons (2007, 2008, 2009) and two warm seasons (2007, 2008).
Analysis is first carried out for the cold, high-discharge season, to focus first on explanatory variables in the presence of high dam discharge rates. These relationships appear somewhat simpler than those of the warm, low-discharge season, which may be easier to see presented in this order.
3.1 Cold, high-discharge season, November 1 to December 31

3.1.1 Comparison of mean temperatures within Coquitlam system – cold season

There is no significant difference in mean water temperature between the reservoir surface (res.surface, CQM-L2) and upstream (below.dam, CQM-R6) and downstream (Patricia, CQM-R2) stations for the cold, high-discharge season, and no significant difference between the mean temperature of the reservoir surface and the discharge stratum (at.depth). Figure 5 summarizes all data for the Coquitlam system for the cold, high-discharge season of November and December. The overlapping notches, where they occur, are compelling evidence of lack of significance in differences between mean temperatures for the cold season (although the box plots are comparing population medians). The farthest downstream station, CQM-R1, was not used for analysis because of missing data (Figure 1). The Patricia Footbridge station (CQM-R2) is the downstream endpoint for the analysis.
Figure 5: cold, high-discharge season profile using all Lower Coquitlam river stations and temperatures of the discharge stratum (dark green) and reservoir surface (1mbs – gold); considerable flattening of the gradient is evident compared to the warm season profile (Figure 8)
The following are tests of upstream and downstream station variances against those of the reservoir surface (res.surface) and discharge stratum (at.depth). Tests for differences in the temperature means are shown at the end of the variance tests.

**Upstream Station Variance Test Set:**

1. at.depth
2. res.surface (CQM-L2)
3. below.dam (CQM-R6)

**Downstream Station Variance Test Set:**

1. at.depth
2. res.surface (CQM-L2)
3. Patricia (CQM-R2)
4. Or.creek (CQM-R5)

These procedures are done to quantify the box plot summaries shown in Figure 5 (although those summaries show sample medians rather than sample means). For each seasonal comparison of temperatures we must also test for equality of variance. Variance is pooled, in subsequent comparisons, if variance tests show unequal sample variances. The Fisher F test is suitable for comparisons of two samples, but for more than two samples it is necessary to use Bartlett’s test, Levene’s test, or the Fligner-Killeen test. These three variance tests decrease, respectively, in sensitivity to outliers (e.g., sampling errors). Or Creek is not the downstream endpoint for the gradient but is included for reference.

**Upstream Station Variance Test Set:**

1. at.depth (discharge stratum)
2. res.surface (CQM-L2)
3. below.dam (CQM-R6)

The cold season variances are:

<table>
<thead>
<tr>
<th>at.depth</th>
<th>below.dam</th>
<th>res.surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.662285</td>
<td>5.527520</td>
<td>2.814701</td>
</tr>
</tbody>
</table>

Bartlett’s test:

Bartlett's K-squared = 24.492, df = 2, p-value = 04.8046e-6
Levene’s test:

<table>
<thead>
<tr>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>23.179</td>
<td>2.448e-10.4</td>
</tr>
<tr>
<td>482</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fligner-Killeen test:

Fligner-Killeen:med chi-squared = 41.4431, df = 2, p-value = 1.003e-9

Where $Df =$ degrees freedom; $F$ value = $F$ statistic resulting from the comparison of variances; $p$-value and $Pr(>F)$ = the probability of the test result (e.g., $F$ statistic) occurring by chance

$\Rightarrow$ All three tests indicate highly significant differences in the population variances ($p < 0.05$).

**Downstream Station Variance Test Set:**

1. at.depth
2. res.surface (CQM-L2)
3. Patricia (CQM-R2)
4. Or.creek (CQM-R5)

The cold season variances are:

<table>
<thead>
<tr>
<th></th>
<th>at.depth</th>
<th>Or.creek</th>
<th>Patricia</th>
<th>res.surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.662285</td>
<td>5.635961</td>
<td>3.903740</td>
<td>2.814701</td>
</tr>
</tbody>
</table>

Bartlett’s test:

Bartlett's K-squared = 26.1705, df = 3, p-value = 8.785e-6

$\Rightarrow$ difference in variances ($p < 0.05$)

Levene's Test

<table>
<thead>
<tr>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14.006</td>
<td>7.7832e-9</td>
</tr>
<tr>
<td>599</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow$ difference in variances ($p < 0.05$)

Fligner-Killeen test:

Fligner-Killeen:med chi-squared = 43.1851, df = 3, p-value = 2.248e-9

$\Rightarrow$ difference in variances ($p < 0.05$)
Mean Temperatures (sd = standard deviation, n = sample size)

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>sd</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>at.depth</td>
<td>6.55</td>
<td>1.63</td>
<td>183</td>
</tr>
<tr>
<td>below.dam</td>
<td>6.41</td>
<td>2.35</td>
<td>119</td>
</tr>
<tr>
<td>res.surface</td>
<td>6.62</td>
<td>1.68</td>
<td>183</td>
</tr>
<tr>
<td>Patricia</td>
<td>6.08</td>
<td>1.98</td>
<td>122</td>
</tr>
<tr>
<td>Or Creek</td>
<td>4.00</td>
<td>2.37</td>
<td>115</td>
</tr>
</tbody>
</table>

Large-sample confidence interval calculation:

If population variances $\sigma_1^2$ and $\sigma_2^2$ are unknown but both $n_1$ and $n_2$ are 30 or more, the sample variances $s_1^2$ and $s_2^2$ can be used to estimate $\sigma_1^2$ and $\sigma_2^2$.

$$E(\bar{x}_1 - \bar{x}_2) = (\mu_1 - \mu_2),$$
$$s(\bar{x}_1 - \bar{x}_2) =$$
$$Z_{\alpha/2} \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$$

$E$ = point estimator, $\bar{x}_1$ = sample 1 mean, $\mu$ = true mean, $\alpha$ = significance level,

$s$ and $s^2$ = sample standard deviation and variance respectively (estimators of their true counterparts $\sigma$ and $\sigma^2$),

$Z$ = normal score.

Table 1: differences in mean temperature – cold season

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$\bar{x}_1 - \bar{x}_2$</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>res.surface – at.depth</td>
<td>0.07</td>
<td>-0.27</td>
</tr>
<tr>
<td>below.dam – res.surface</td>
<td>-0.21</td>
<td>-0.70</td>
</tr>
<tr>
<td>below.dam – at.depth</td>
<td>-0.14</td>
<td>-0.62</td>
</tr>
<tr>
<td>Patricia – res.surface</td>
<td>-0.54</td>
<td>-0.96</td>
</tr>
<tr>
<td>Patricia – at.depth</td>
<td>-0.47</td>
<td>-0.89</td>
</tr>
<tr>
<td>Or.creek – res.surface</td>
<td>-2.66</td>
<td>-3.16</td>
</tr>
<tr>
<td>Or.creek – at.depth</td>
<td>-2.59</td>
<td>-3.09</td>
</tr>
<tr>
<td>Patricia – Or.creek</td>
<td>2.12</td>
<td>1.57</td>
</tr>
</tbody>
</table>
RESULTS (note: no significance if confidence interval includes zero)

Significant Difference in Cold Season Temperature of Reservoir & Below Dam? No

Significant Difference in Cold Season Temperature of Reservoir & Patricia Footbridge? Slight

Large-sample estimation of the difference between means of all the four temperature data sets confirms the lack of significant difference (5% level [95% confidence intervals]) indicated by the notched boxplots of Figure 5. Patricia Footbridge station was slightly cooler than the Reservoir Surface and at.depth. Or Creek, which lies upstream of the Patricia station, was significantly cooler than all other stations.

3.1.2 Regression analysis of upstream and downstream temperatures – cold season

3.1.2.1 Model for the Below Dam station – cold season

Outline of Modelling Procedure:

- Stepwise reduction from most complex to simplest
- Beginning with the response (below.dam) and all possible explanatory variables
- Include curvature terms and interactions of the main effects

\[ \hat{T}_{R6} = \beta_0 + \beta_1 T_{L1} + \beta_2 T_{ad} + \beta_3 T_{L2} + \beta_{11} T_{L1} T_{L2} + \beta_{22} T_{ad} T_{L2} + \beta_{33} T_{L2}^2 \quad \text{Model 1} \]

Where \( \hat{T}_{R6} \) is predicted water temperature at station CQM-R6 (station below dam), \( \beta_{0...n} \) are coefficients, \( T_{L1} \) is air temperature at station CQM-L1, \( T_{L2} \) is water temperature at station CQM-L2 (reservoir 1mbs), \( T_{ad} \) is temperature of the discharge stratum (factor at.depth; interaction terms not shown).

The following is a scatterplot matrix showing relationships among the explanatory variables in Model 1, with inclusion of dam discharge rates (d.discharge; not included as factor in model).
In Figure 6, each variable is the y axis of its own row (e.g., on the bottom row below.dam is the y axis response of all other variables.)

- Relationships being tested are represented by the numbered plots on the bottom row.
- Although dam discharge d.discharge is shown in Figure 6, it is not included in Model 1 (i.e., it was found to have relatively no significance and was dropped out of the modelling process). There appears to be a pattern of temperature increase with increases in discharge rates above 30 cms; however, this observation was not tested in this analysis (see discussion of modelling process at beginning of Section 3.0).
- Multicollinearity arose from similarity of res.surface and at.depth. (Multicollinearity is error in coefficients due to high correlation of two or more predictor variables.) Because at.depth must be in the model (i.e., the term d.discharge – the only other term describing dam operations – was removed), all res.surface terms were removed to preclude multicollinearity.
Model 1 Summary (Below Dam station – cold season)

Coefficients:

|                      | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------------|----------|------------|---------|----------|
| (Intercept)          | 3.796760 | 2.200511   | 1.725   | 0.0876   |
| air.temp             | -2.166265| 0.397777   | -5.446  | 3.82e-07 ***|
| at.depth             | -0.470335| 5.976877   | -0.079  | 0.9374   |
| res.surface          | -0.087213| 5.887961   | -0.015  | 0.9882   |
| I(air.temp^2)        | -0.003049| 0.004070   | -0.749  | 0.4555   |
| I(at.depth^2)        | -2.169976| 6.642730   | -0.327  | 0.7446   |
| I(res.surface^2)     | -2.272899| 6.206290   | -0.366  | 0.7150   |
| air.temp:at.depth    | 0.112476 | 0.478623   | 0.235   | 0.8147   |
| air.temp:res.surface | 0.490555 | 0.471670   | 1.040   | 0.3009   |
| at.depth:res.surface | 4.566143 | 12.829527  | 0.356   | 0.7227   |
| air.temp:at.depth:res.surface | -0.039021 | 0.008269 | -4.719 | 7.87e-06 ***|

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Reading Model Summaries

Main effects are denoted as unmodified variables (e.g., air.temp); quadratic terms are denoted as I(..^2); interactions are denoted with colons, e.g. air.temp:at.depth:res.surface is a three way interaction.

The p value is an estimate of the probability of observing the t value (test statistic) by chance – if the null hypothesis were true (i.e., there is no significance for the explanatory variable). The overall correlation (coefficient of determination) is given by the adjusted R-squared value (e.g., Model 4). Some information has been left out of intermediate summaries since the purpose is only to show increasing significance (e.g., R-squared not always shown).
Through stepwise elimination of least significant variables, Model 1 was reduced in complexity to Model 4:

Model 4 Summary (Below Dam station – cold season)

Coefficients:

|                | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------|----------|------------|---------|---------|
| (Intercept)    | -4.30999 | 1.38799    | -3.105  | 0.002450 ** |
| air.temp       | -0.36868 | 0.10590    | -3.482  | 0.000730 *** |
| at.depth       | 2.05966  | 0.44174    | 4.663   | 9.3e-06 *** |
| I(at.depth^2)  | -0.07915 | 0.03562    | -2.222  | 0.028431 *  |
| air.temp:at.depth | 0.06297 | 0.01671    | 3.769   | 0.000273 *** |

---

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.689 on 104 degrees of freedom
(13 observations deleted due to missingness)
Multiple R-squared: 0.9148, Adjusted R-squared: 0.9115
F-statistic: 279.1 on 4 and 104 DF, p-value: < 2.2e-16

- All remaining terms are significant.
- The cold high-discharge season model is, as expected, much less complex than the summer low flow model for the below.dam station.
- It has five parameters, includes both main effects of at.depth and air.temp, a quadratic term (the least significant of the parameters) and the two-way interaction of the main effects.
- The model has a high correlation coefficient (Adjusted R-squared = 0.9115), and 104 degrees of freedom for error.

\[ \hat{T}_{R6} = -4.310 - 0.369 T_{L1} + 2.060 T_{ad} - 0.079 T_{ad^2} + 0.063 T_{L1ad} \]  

Equation 1

- Analysis of behaviour of residuals through diagnostic plots followed this stage. (Unless significant issues were observed inclusion of these plots has been omitted.)
### 3.1.2.2 Model for the Patricia Footbridge station – cold season

Outline of Modelling Procedure:

- Stepwise reduction from most complex to simplest
- Beginning with the response \((Patricia)\) and all possible explanatory variables
- Include curvature terms and interactions of the main effects

\[
\hat{T}_{R2} = \beta_0 + \beta_1 T_{L1} + \beta_2 T_{ad} + \beta_3 T_{R5} + \beta_4 T_{D2} + \beta_1 T_{L1\cdot2} + \beta_2 T_{ad\cdot2} + \beta_3 T_{R5\cdot2} + \beta_4 T_{D2\cdot2}
\]

Model 5

Where \(\hat{T}_{R2}\) is predicted water temperature at station \(CQM-R2\) (Patricia Footbridge station), \(\beta_0...n\) are coefficients, \(T_{L1}\) is air temperature at station \(CQM-L1\), \(T_{ad}\) is temperature of discharge stratum (factor \(at\cdotdepth\)), \(T_{R5}\) is water temperature at station \(CQM-R5\) (Or Creek), and \(D_2\) is dam discharge rate (interaction terms not shown).

The following is a scatterplot matrix showing relationships among the explanatory variables in Model 5.
In Figure 7, each variable is the y axis of its own row (e.g., on the bottom row Patricia is the y axis response of all other variables.)

- Relationships being tested are represented by the numbered plots on the bottom row.
- Although Env.Can (discharge at Environment Canada hydrometric station) is shown in Figure 7, it is not included in Model 5 because of similarity with dam discharge (d.discharge).

Model 5 Summary (Patricia Footbridge station – cold season)
Temperature Monitoring Program – Year 4
Lower Coquitlam River, Coquitlam, BC
Reference no. 061-02626-03

coefficients:

| estimate | std. error | t value | pr(>|t|) |
|----------|------------|---------|---------|
| (intercept) | -7.019e+00 | 4.630e+00 | -1.516 | 0.133 |
| air.temp | 1.619e-01 | 7.298e-01 | 0.222 | 0.825 |
| at.depth | 2.840e+00 | 1.977e+00 | 1.437 | 0.154 |
| or.creek | -7.599e-01 | 1.886e+00 | -0.403 | 0.688 |
| d.discharge | 1.583e-01 | 3.570e-01 | 0.443 | 0.659 |
| i(air.temp^2) | 2.106e-02 | 1.862e-02 | 1.131 | 0.261 |
| i(at.depth^2) | -7.356e-02 | 2.292e-01 | -0.321 | 0.749 |
| i(or.creek^2) | 6.133e-02 | 2.296e-01 | 0.267 | 0.790 |
| i(d.discharge^2) | 1.749e-03 | 1.458e-02 | 0.124 | 0.234 |
| air.temp:at.depth | 6.897e-02 | 1.499e-01 | 0.460 | 0.647 |
| air.temp:or.creek | -9.835e-02 | 1.460e-01 | -0.674 | 0.502 |
| at.depth:or.creek | -8.552e-02 | 4.443e-01 | -0.192 | 0.848 |
| air.temp:d.discharge | -5.833e-02 | 6.787e-02 | -0.859 | 0.393 |
| at.depth:d.discharge | -3.486e-02 | 6.230e-02 | -0.559 | 0.577 |
| or.creek:d.discharge | 3.035e-02 | 8.327e-02 | 0.364 | 0.716 |
| air.temp:at.depth:or.creek | 1.072e-03 | 1.281e-02 | 0.084 | 0.934 |
| air.temp:at.depth:d.discharge | 4.721e-03 | 1.156e-02 | 0.408 | 0.684 |
| air.temp:or.creek:d.discharge | 9.593e-03 | 1.125e-02 | 0.853 | 0.396 |
| at.depth:or.creek:d.discharge | 1.253e-05 | 1.248e-02 | 0.001 | 0.999 |
| air.temp:at.depth:or.creek:d.discharge | -9.995e-04 | 1.540e-03 | -0.649 | 0.518 |

Through 10 steps of elimination of least significant variables Model 5 was reduced in complexity to Model 15
With each step the main effect dam discharge decreased in significance (but not at.depth, not the quadratic term of dam discharge, and not an interaction term of dam discharge). The main effect d.discharge was therefore removed in early steps, in addition because it appeared prevent detection of better explanatory variables

Model 15 Summary (Patricia Footbridge station – cold season)

| estimate | std. error | t value | pr(>|t|) |
|----------|------------|---------|---------|
| (intercept) | -7.0661225 | 1.8885049 | -3.742 | 0.000314 *** |
| air.temp | 0.3546589 | 0.0628431 | 5.644 | 1.75e-07 *** |
| at.depth | 3.0686670 | 0.5599710 | 5.480 | 3.55e-07 *** |
| or.creek | -1.1502500 | 0.1717209 | -6.698 | 1.53e-09 *** |
| i(air.temp^2) | 0.0083172 | 0.0038612 | 2.154 | 0.033795 * |
| i(at.depth^2) | -0.1014107 | 0.0386688 | -2.623 | 0.010182 * |
| i(d.discharge^2) | 0.00030113 | 0.0008821 | 3.414 | 0.000947 *** |
| air.temp:d.discharge | 0.0125784 | 0.0052543 | -2.394 | 0.018655 * |
| at.depth:d.discharge | -0.0195398 | 0.0085027 | -2.298 | 0.023775 * |
| or.creek:d.discharge | 0.0303825 | 0.0113218 | 2.684 | 0.008609 ** |
Large increase in significance of Model 15 variables compared to Model 5
- Model 15 has 10 parameters; all main effects, including Or Creek, are extremely significant.
- The quadratic term for dam discharge is very significant as is the interaction between Or Creek and dam discharge levels
- Behaviour of Model 15 was tested through the residuals diagnostic plot; no difficulties were encountered – inclusion of this plot is omitted

3.2 Warm, low-discharge season, June 1 to August 31

3.2.1 Comparison of mean temperatures within Coquitlam system – warm season

The Below Dam station (CQM-R6) is significantly cooler than the reservoir surface (CQM-L2) and significantly warmer than the discharge stratum (factor at.depth) during the warm, low-discharge season. Similarly, the mean warm season temperature at the downstream station Patricia Footbridge is cooler than the reservoir surface and warmer than the discharge stratum. The mean temperature at Or Creek, which lies upstream of the Patricia Footbridge station, is significantly cooler than the discharge stratum (coldest mean temperature of all river stations). Figure 8 summarizes all data for the Coquitlam system for the warm, low-discharge season of June through August. Lack of overlap in notches (95% confidence interval) is compelling evidence of significance in mean temperature differences.
The following are tests of upstream and downstream station variances against those of the reservoir surface (res.surface) and discharge stratum (at.depth) for the warm, low-discharge season. Tests for differences in the temperature means are shown at the end of the variance tests.

Upstream Station Variance Test Set:

1. at.depth
2. res.surface (CQM-L2)
3. below.dam (CQM-R6)
Downstream Station Variance Test Set:

1. at.depth
2. res.surface (CQM-L2)
3. Patricia (CQM-R2)
4. Or.creek (CQM-R5)

As was done for the cold season these procedures are done for the warm season to quantifiy the box plot summaries shown in Figure 8. (Or Creek is not the downstream endpoint for the gradient but is included for reference.)

Upstream Station Variance Test Set:

1. at.depth
2. res.surface (CQM-L2)
3. below.dam (CQM-R6)

The warm season variances are:

<table>
<thead>
<tr>
<th></th>
<th>at.depth</th>
<th>below.dam</th>
<th>res.surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>variance</td>
<td>5.242800</td>
<td>11.682414</td>
<td>8.242821</td>
</tr>
</tbody>
</table>

Bartlett’s test:

Bartlett's K-squared = 28.5892, df = 2, p-value = 6.194e-07

⇒ Bartlett’s test indicates a strongly significant difference between the three variances (p = 6.194e-07).

Levene’s test:

<table>
<thead>
<tr>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>group</td>
<td>2</td>
<td>18.119</td>
</tr>
<tr>
<td></td>
<td>549</td>
<td></td>
</tr>
</tbody>
</table>

⇒ Levene’s test also indicates the very significant difference (p = 2.399e-08).

Fligner-Killeen test:

Fligner-Killeen:med chi-squared = 31.3432, df = 2, p-value = 1.563e-07

⇒ This extremely low p value is the most relevant result in the warm season analysis of variance, since the Fligner-Killeen test is the least sensitive to outliers.
Downstream Station Variance Test Set:

1. *at.depth*
2. *res.surface* (*CQM-L2*)
3. *Patricia* (*CQM-R2*)
4. *Or.creek* (*CQM-R5*)

The warm season variances are:

```
 at.depth  Or.creek   Patricia     res.surface
5.242800  10.477853 10.539154   8.242821
```

Bartlett’s test:

Bartlett's K-squared = 27.0964, df = 3, p-value = 5.62e-06

Levene’s test:

```
     Df F value  Pr(>F)   group
       3 10.168 1.445e-06 group
732
```

Fligner-Killeen test:

Fligner-Killeen:med chi-squared = 27.0056, df = 3, p-value = 5.871e-06

⇒ All tests show a highly significant difference in population variances for the four data sets.

*The test for differences in means uses the Large Sample model for 95% confidence interval calculation. The model is shown in the cold season section.*

Test for Difference in Mean Temperature (sd = standard deviation, n = sample size)

```
       mean    sd    n
  at.depth  12.23  2.29   184
below.dam  15.17  3.42   184
 res.surface 17.85  2.87   184
 Patricia  13.50  3.25   184
Or.creek   10.47  3.24   184
```
Table 2: differences in mean temperature – warm season

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Difference in Mean Temperature ($\bar{x}_1 - \bar{x}_2$)</th>
<th>95% Confidence Interval Lower</th>
<th>95% Confidence Interval Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>res.surface – at.depth</td>
<td>5.62</td>
<td>5.09</td>
<td>6.15</td>
</tr>
<tr>
<td>below.dam – res.surface</td>
<td>-2.68</td>
<td>-3.33</td>
<td>-2.04</td>
</tr>
<tr>
<td>below.dam – at.depth</td>
<td>2.94</td>
<td>2.34</td>
<td>3.53</td>
</tr>
<tr>
<td>Patricia – res.surface</td>
<td>-4.35</td>
<td>-4.97</td>
<td>-3.72</td>
</tr>
<tr>
<td>Patricia – at.depth</td>
<td>1.27</td>
<td>0.70</td>
<td>1.85</td>
</tr>
<tr>
<td>Or.creek – res.surface</td>
<td>-7.38</td>
<td>-8.01</td>
<td>-6.76</td>
</tr>
<tr>
<td>Or.creek – at.depth</td>
<td>-1.76</td>
<td>-2.34</td>
<td>-1.19</td>
</tr>
<tr>
<td>Patricia – Or.creek</td>
<td>3.04</td>
<td>2.37</td>
<td>3.70</td>
</tr>
</tbody>
</table>

RESULTS (note: no significance if confidence interval includes zero)

Significant Difference in Warm Season Temperature of Reservoir & Below Dam? Yes

Significant Difference in Warm Season Temperature of Reservoir & Patricia Footbridge? Yes

Large-sample estimation of the difference between temperature means shows that the Below Dam and Patricia Footbridge stations are significantly cooler than the Reservoir Surface (1mbs), and also that Or Creek is significantly colder than all other stations. These results confirm the lack of overlap in the notched box plots of (Figure 8).

3.2.2  Regression analysis of Upstream and Downstream temperatures – warm season

3.2.2.1 Model for the Below Dam station – warm season

Outline of Modelling Procedure:

- Stepwise reduction from most complex to simplest
- Beginning with the response ($below.dam$) and all possible explanatory variables
- Include curvature terms and interactions of the main effects

$$\hat{T}_{R6} = \beta_0 + \beta_1 T_{L1} + \beta_2 T_{L2} + \beta_3 T_{ad} + \beta_{11} T_{L1}^2 + \beta_{22} T_{L2}^2 + \beta_{33} T_{ad}^2$$  Model 16

Where $\hat{T}_{R6}$ is predicted water temperature at station $CQM-R6$ (station below dam), $\beta_{0..n}$ are coefficients, $T_{L1}$ is air temperature at station $CQM-L1$, $T_{L2}$ is water temperature at station $CQM-L2$ (reservoir 1mbs), and $T_{ad}$ is temperature of discharge stratum (factor at.depth; interaction terms not shown).

The following is a scatterplot matrix showing relevant relationships among the explanatory variables in Model 16.
Figure 9: scatterplot matrix of Model 16; red lines are fitted non-parametric smoothed curves

- In Figure 9, each variable is the y axis of its own row (e.g., on the bottom row below.dam is the y axis response of all other variables.)
- Relationships being tested are represented by the numbered plots on the bottom row
Model 16 Summary (Below Dam station – warm season)

Coefficients:

|                                | Estimate | Std. Error | t value | Pr(>|t|) |
|--------------------------------|----------|------------|---------|----------|
| (Intercept)                    | 58.292441| 14.485395  | 4.024   | 8.53e-05 *** |
| air.temp                       | -2.964534| 1.001949   | -2.959  | 0.003521 ** |
| res.surface                    | -3.516810| 1.093036   | -3.217  | 0.001544 ** |
| at.depth                       | -4.938541| 1.400291   | -3.527  | 0.000539 *** |
| I(air.temp^2)                  | 0.011947 | 0.014084   | 0.848   | 0.397492  |
| I(res.surface^2)               | 0.009282 | 0.056670   | 0.164   | 0.870086  |
| I(at.depth^2)                  | -0.122265| 0.050702   | -2.411  | 0.016935 * |
| air.temp:res.surface           | 0.107584 | 0.055220   | 1.948   | 0.053000 . |
| air.temp:at.depth              | 0.364353 | 0.113751   | 3.203   | 0.001619 ** |
| res.surface:at.depth           | 0.446202 | 0.109697   | 4.068   | 7.21e-05 *** |
| air.temp:res.surface:at.depth  | -0.017110| 0.004881   | -3.505  | 0.000581 *** |

→ Complexity of the model was reduced in 10 steps to Model 26:

Model 26 Summary (Below Dam station – warm season)

Coefficients:

|                                | Estimate | Std. Error | t value | Pr(>|t|) |
|--------------------------------|----------|------------|---------|----------|
| (Intercept)                    | 4.66923  | 0.29995    | 15.567  | < 2e-16  *** |
| I(res.surface^2)               | -0.07512 | 0.01573    | -4.775  | 3.72e-06 *** |
| I(at.depth^2)                  | -0.15281 | 0.03304    | -4.624  | 7.18e-06 *** |
| at.depth:res.surface           | 0.26272  | 0.04587    | 5.728   | 4.23e-08 *** |

---

Signif. codes:  0 ’***’ 0.001 ’**’ 0.01 ’*’ 0.05 ’.’ 0.1 ’ ’ 1

Residual standard error: 1.133 on 179 degrees of freedom
Multiple R-squared: 0.892,    Adjusted R-squared: 0.8902
F-statistic: 493 on 3 and 179 DF, p-value: < 2.2e-16

\[ \hat{T}_{R6} = 4.669 - 0.075 T_{L2}^2 - 0.153 T_{ad}^2 + 0.263 T_{adL2} \]

Equation 2

→ By the end of the stepwise reduction air temperature has lost significance relative to an interaction between reservoir surface temperatures and those of at.depth and their two quadratic terms (a non-linear response). The model has 179 degrees of freedom for the error, and a high overall correlation of 0.89.

→ The importance of the non-linear response to at.depth is shown by the extremely low probability (7.18e-06) of its occurrence by chance alone. There is even greater importance of the interaction of at.depth with res.surface. Figure 10 shows what these relationships look like averaged over six years (2004 through 2008).
3.2.2.2 Model for the Patricia Footbridge station – warm season

Outline of Modelling Procedure:

- Stepwise reduction from most complex to simplest
- Beginning with the response (Patricia) and all possible explanatory variables
- Include curvature terms and interactions of the main effects
\[ \hat{T}_{R2} = \beta_0 + \beta_1 T_{L1} + \beta_2 T_{ad} + \beta_3 T_{R5} + \beta_4 T_{R7} + \beta_{11} T_{L1}^2 + \beta_{22} T_{ad}^2 \]
\[ + \beta_{33} T_{R5}^2 + \beta_{44} T_{R7}^2 \]

Model 27

Where \( \hat{T}_{R2} \) is predicted water temperature at station CQM-R2 (Patricia Footbridge station), \( \beta_{0\ldots n} \) are coefficients, \( T_{L1} \) is air temperature at station CQM-L1, \( T_{ad} \) is temperature of discharge stratum (factor \textit{at.depth}), \( T_{R5} \) is water temperature at station CQM-R5 (Or Creek), \( T_{R7} \) is discharge measured at station CQM-R7 (Environment Canada hydrometric station; interaction terms not shown).

The following is a scatterplot matrix showing relationships among the explanatory variables in Model 27.
Figure 11: scatterplot matrix of Model 27; red lines are fitted non-parametric smoothed curves

- In Figure 11, each variable is the y axis of its own row (e.g., on the bottom row Patricia is the y axis response of all other variables.)
- Relationships being tested are represented by the numbered plots on the bottom row
- There is a much higher apparent correlation with Or Creek during the warm season than the cold (cf. Figure 7)

Model 27 Summary (Patricia Footbridge station – warm season)
Coefficients:                      Estimate  Std. Error t value  Pr(>|t|)  
(Intercept)                    10.7071493  6.2705375   1.708 0.089687 .  
air.temp                       -0.6769324  0.4354071  -1.555 0.122016   
at.depth                       0.0231649  0.7689449   0.030 0.976005   
Or.creek                      -0.8532257  0.8146366  -1.047 0.296529   
Env.Can                        -3.6537233  1.2733895  -2.869 0.004677 ** 
I(air.temp^2)                 -0.0049435  0.0036385  -1.359 0.176196   
I(at.depth^2)                 -0.0746014  0.0269663  -2.766 0.006343 ** 
I(Or.creek^2)                -0.0730120  0.0202299  -3.609 0.000412 ***  
I(Env.Can^2)                  0.0219514  0.0106385   2.063 0.040710 *  
air.temp:at.depth             0.0670463  0.0403567   1.661 0.098628 .  
air.temp:Or.creek             0.1024038  0.0410404   2.495 0.013616 *  
at.depth:Or.creek             0.2159326  0.0628400   3.436 0.000754 ***  
air.temp:Env.Can              0.2320561  0.0913857   2.539 0.012073 *  
at.depth:Env.Can              0.3007054  0.1216473   2.472 0.014498 *  
Or.creek:Env.Can              0.4134701  0.1836960   2.251 0.025775 *  
air.temp:at.depth:Or.creek   -0.0069135  0.0031618  -2.187 0.030247 *  
air.temp:at.dpth:Env.Can     -0.0231196  0.0087541  -2.641 0.009096 **  
air.temp:Or.creek:Env.Can    -0.0243874  0.0114491  -2.130 0.034714 *  
at.depth:Or.creek:Env.Can   -0.0348101  0.0136571  -2.549 0.011760 *  
air.temp:at.depth:Or.creek:Env.Can  0.0022867  0.0009152   2.499 0.013490 *
• Model 27 was reduced in 10 steps to Model 37:

Model 37 Summary (*Patricia Footbridge station – warm season*)

Coefficients:

| Term                        | Estimate | Std. Error | t value | Pr(>|t|) |
|-----------------------------|----------|------------|---------|----------|
| (Intercept)                 | 2.555e+00| 6.688e-01 | 3.820   | 0.000188 *** |
| air.temp                    | 6.718e-02| 2.583e-02 | 2.600   | 0.010144 * |
| Or.creek                    | 1.239e+00| 8.603e-02 | 14.402  | < 2e-16 *** |
| Env.Can                     | -6.815e-01| 1.422e-01 | -4.791  | 3.64e-06 *** |
| I(at.depth^2)               | -4.852e-02| 1.074e-02 | -4.519  | 1.17e-05 *** |
| I(Or.creek^2)               | -8.174e-02| 1.082e-02 | -7.556  | 2.61e-12 *** |
| Or.creek:at.depth           | 1.101e-01 | 2.155e-02 | 5.110   | 8.72e-07 *** |
| Env.Can:at.depth            | 1.101e-01 | 2.155e-02 | 5.110   | 8.72e-07 *** |
| air.temp:Env.Can:at.depth   | 1.354e-01 | 2.117e-02 | 6.397   | 1.53e-09 *** |
| Or.creek:Env.Can:at.depth   | 1.028e-02 | 1.647e-03 | -6.241  | 3.46e-09 *** |

---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2888 on 167 degrees of freedom
Multiple R-squared: 0.9927,     Adjusted R-squared: 0.9923
F-statistic: 2272 on 10 and 167 DF,  p-value: < 2.2e-16

• Model 37 is the most complex model encountered in the analysis; it has 11 parameters; three are main effects, two are curved variables, two are two-way interactions, two are three-way interactions, and one is a four-way interaction.

• at.depth, as a main effect, was removed early (cf. cold season Model 15).

• All parameters (except for air.temp) have extremely high significance.
3.3 Comparison of Gradients of Coquitlam, Chehalis, and Chilliwack Systems

The following table summarizes warm season lake-river water temperature gradients with 95% confidence interval.

Table 3: warm season lake-river water temperature gradients with 95% confidence interval*

<table>
<thead>
<tr>
<th>Gradient System and endpoints</th>
<th>average of daily mean temperatures Jun. 1 to Aug. 31 $\bar{x}$</th>
<th>standard deviation $s$</th>
<th>sample variance $s^2$</th>
<th>sample size $n$</th>
<th>lake-river gradient and 95% C.I.</th>
<th>gradient midpoint (simple avg.)</th>
<th>approx. gradient distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coquitlam Reservoir to Patricia Footbridge</td>
<td>18.70</td>
<td>2.88</td>
<td>8.30</td>
<td>460</td>
<td>4.27 ± 0.48</td>
<td>16.57</td>
<td>11.17</td>
</tr>
<tr>
<td>Chehalis Lake to Chehalis River</td>
<td>13.44</td>
<td>3.12</td>
<td>9.70</td>
<td>88</td>
<td>0.60 ± 0.79</td>
<td>13.14</td>
<td>14.30</td>
</tr>
<tr>
<td>Chilliwack Lake</td>
<td>12.84</td>
<td>3.08</td>
<td>9.51</td>
<td>184</td>
<td>1.44 ± 0.43</td>
<td>13.05</td>
<td>13.16</td>
</tr>
<tr>
<td>Chilliwack River</td>
<td>13.77</td>
<td>2.84</td>
<td>8.09</td>
<td>276</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilliwack River</td>
<td>12.33</td>
<td>2.28</td>
<td>5.21</td>
<td>276</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Large sample confidence interval calculation

$$E(\bar{x}_1 - \bar{x}_2) = (\bar{\mu}_1 - \bar{\mu}_2),$$

$$s_{(\bar{x}_1 - \bar{x}_2)} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \cdot Z_{\alpha/2}$$

$E = \text{point estimator, } \bar{x}_1 = \text{sample 1 mean, } \bar{\mu} = \text{true mean, } \alpha = \text{significance level,}$

$s$ and $s^2 = \text{sample standard deviation and variance respectively (estimators of their true counterparts } \sigma \text{ and } \sigma^2), \ Z = \text{normal score.}$
The following table summarizes cold season lake-river water temperature gradients with 95% confidence interval, and the percent change (percent of slope) and gradient midpoints (simple mean of two endpoint station temperatures).

**Table 4: cold season lake-river water temperature gradients with 95% confidence interval**

<table>
<thead>
<tr>
<th>Gradient System and endpoints</th>
<th>average of daily mean temperatures November 1 to December 31 ((\bar{x}))</th>
<th>lake-river gradient and 95% C.I. (°C)</th>
<th>% change, warm season to cold season</th>
<th>gradient midpoint (simple avg.)</th>
<th>gradient midpoint difference warm - cold season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coquitlam Reservoir to Patricia Footbridge</td>
<td>7.02</td>
<td>0.66 ± 0.37</td>
<td>0.66 – 4.27 (\frac{4.27}{4.27})</td>
<td>flattened by 85%</td>
<td>6.69</td>
</tr>
<tr>
<td>Chehalis Lake to Chehalis River</td>
<td>7.15</td>
<td>1.90 ± 0.76</td>
<td>0.60 – 1.90 (\frac{1.90}{1.90})</td>
<td>steepened by 68%</td>
<td>6.20</td>
</tr>
<tr>
<td>Chilliwack Lake</td>
<td>7.52</td>
<td>1.09 ± 0.49</td>
<td>1.09 – 1.44 (\frac{1.44}{1.44})</td>
<td>flattened by 24%</td>
<td>6.97</td>
</tr>
</tbody>
</table>

*Figure 14 is a graphic representation of this table*
### Table 5: ANOVA – warm season average temperatures of gradient systems endpoints

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum sq</th>
<th>MEAN SQ</th>
<th>F</th>
<th>PR(&gt;f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>2</td>
<td>6377.5</td>
<td>3188.8</td>
<td>297.63</td>
<td>&lt; 2.2e-16 ***</td>
</tr>
<tr>
<td>Residuals</td>
<td>1557</td>
<td>16681.6</td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Significance Codes:**
- **0’***’ 0.001 ‘***’ 0.01 ‘**’ 0.05 ‘.’ 0.1 ‘’ 1

**Summary**

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>sd</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chehalis</td>
<td>13.03349</td>
<td>3.100635</td>
<td>272</td>
</tr>
<tr>
<td>Chilliwack</td>
<td>13.05121</td>
<td>2.674994</td>
<td>552</td>
</tr>
<tr>
<td>Coquitlam</td>
<td>17.09563</td>
<td>3.713102</td>
<td>736</td>
</tr>
</tbody>
</table>

**Interpretation:**

1. One or more of the systems are significantly different in average temperature between gradient endpoints during the warm season. 2. Further test: large sample difference test confirms that Chehalis and Chilliwack are not significantly different, at -0.02 ± 0.4, and that the Coquitlam system is significantly different from Chehalis and Chilliwack (e.g., -4.04 ± 0.35 Chilliwack vs. Coquitlam).

Note: Summary Means in these ANOVA tables are the arithmetic averages of all daily temperatures for the both ends of each gradient. The means (gradient midpoints) in Table 3 and Table 4 are simple averages of the gradient endpoints.

### Table 6: ANOVA – cold season average temperatures of systems endpoints

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum sq</th>
<th>MEAN SQ</th>
<th>F</th>
<th>PR(&gt;f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>2</td>
<td>111.49</td>
<td>55.744</td>
<td>15.086</td>
<td>3.728e-07 ***</td>
</tr>
<tr>
<td>Residuals</td>
<td>781</td>
<td>2885.81</td>
<td>3.695</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Significance Codes:**

<table>
<thead>
<tr>
<th></th>
<th>df = degrees freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chehalis</td>
<td>sq = squares of errors</td>
</tr>
<tr>
<td>Chilliwack</td>
<td>sd = standard deviation</td>
</tr>
<tr>
<td>Coquitlam</td>
<td>n = sample size</td>
</tr>
</tbody>
</table>

**Summary**

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>sd</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chehalis</td>
<td>5.913720</td>
<td>2.428144</td>
<td>152</td>
</tr>
<tr>
<td>Chilliwack</td>
<td>6.970495</td>
<td>1.767875</td>
<td>180</td>
</tr>
<tr>
<td>Coquitlam</td>
<td>6.805481</td>
<td>1.784439</td>
<td>452</td>
</tr>
</tbody>
</table>

**Interpretation:**

1. One or more of the systems are significantly different in average temperature between gradient endpoints during the cold season. 2. Further test: large sample difference test confirms that the Chehalis system is significantly different from the Chilliwack and Coquitlam systems (-1.06 ± 0.46, -0.89 ± 0.42, respectively) and that there is no difference between the Chilliwack and Coquitlam systems, at -0.17 ± 0.30. This shows that the Coquitlam system has changed the most (i.e., vertical movement of system endpoints) and that the change is one of flattening.
3.4 Gradient Comparison Figures

Figure 12 through Figure 14 are notched box plot comparisons of systems (Coquitlam, Chehalis and Chilliwack) and gradient endpoints in warm season and cold season.

![Box plots comparing water temperature for different systems and seasons.](image)

Figure 12: *warm, low-discharge season* gradients (average temperatures of systems endpoints)
Figure 13: cold, high-discharge season gradients (average temperatures of systems endpoints)
3.5 Discussion

The hypothesis for the analysis of this report defines the difference between natural and operations temperatures as the difference between temperatures of the Coquitlam reservoir 1mbs stratum and the discharge stratum (variable at.depth). Two downstream stations are compared with this difference, and further analyzed, to assess the influence of operations temperatures. One station is immediately below the dam and one is at the farthest available monitored point downstream. Following this comparison and analysis the gradient established through the process is compared with those of two other systems (Chehalis and Chilliwack).

3.5.1 Potential cooling effect at first station below dam

A prominent feature observed in the regression modelling process was the increase of complexity of the temperature response plane in the summer season, especially at the Patricia Footbridge station. Many subtle interactions among explanatory variables are apparent in the warm season, which are not seen during the cold season, in the presence of high discharge rate and its associated explanatory variable at.depth (discharge stratum temperature). The variable at.depth reaches highest significance in the cold season, at which time it is important at both ends of the Coquitlam river gradient (below the dam and at the Patricia Footbridge station). However, in the warm, low-discharge season, although its influence is strong immediately below the dam, it attenuates with distance downstream, and is lost, as a main effect, downstream of Or Creek, which appears to be the single most important explanatory variable affecting warm season temperatures at Patricia Footbridge station (Model 37).

In the summer, if we think of the station immediately below the dam (response variable below.dam) as being completely recharged by dam releases (explanatory variable at.depth), and if we discount the potential effects of variables such as wind, solar radiation, shading, residence
time of water at low flow, rain etc., then the results of tests of mean temperature differences (Section 3.2.1) imply a cooling effect of roughly 3°C at the below dam station caused by dam operations \((\text{at.dept})\). However, downstream reaches beyond Or Creek (explanatory variable \(\text{or.creek}\)) are likely far more significantly affected by that source, which was shown through difference tests to be colder than \(\text{at.dept}\) in both seasons. This drop in temperature is shown in the notched box plot summaries in Figure 5 and Figure 8. Or Creek is influential at downstream reaches even in the cold season, but its significance, as detected in Model 37 for the Patricia Footbridge station, reaches an extreme in the summer low-discharge season \((p < 2e-16)\). Conversely, Model 37 shows no significance for the variable \(\text{at.dept}\) in the warm season for Patricia Footbridge station.

### 3.5.2 Impact of cooling at first station below dam

British Columbia Ministry of Environment has published water quality guidelines for temperature available at:


To assess the potential for impacts of cooling on fish populations during the warm season, we plotted guidelines for the category *Freshwater Aquatic Life – streams with unknown fish distribution*. It is plotted against the 7-day moving average of maximum daily temperatures recorded at the below dam station. (The 7-day moving average is the basis of the ministry-published Mean Weekly Maximum Temperature (MWMT) guideline, defined as the average of the warmest daily maximum temperatures for seven consecutive days.)

Moving average plots cover each of the warm seasons in the study period (2007 through 2009). The plots indicate that temperatures in the below dam station rose above published guideline thresholds, despite the apparent cooling effect detected in that station (Figure 15, Figure 16).
max daily temp = 19°C
MWMT = 18°C

Figure 15: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: July 6, 2007 – October 4, 2007 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 10 = July 15; 17 = July 22; 77 = September 20; 82 = September 25 (MWMT = Mean Weekly Maximum Temperature)
Figure 16: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: July 19, 2008 – August 26, 2008 and MOE water temperature guidelines for Freshwater Aquatic Life – Streams with unknown fish distribution; Points: 4 = July 22; 13 = July 31; 38 = August 25 (MWMT = Mean Weekly Maximum Temperature)
3.5.3 Comparison of Coquitlam gradient to natural gradients – potential warming effect

The cross-system gradient comparison is included despite the absence of replication of seasons for the Chehalis system (Chehalis Lake). Since there is no replication, inferences based on the Chehalis gradient are not supported.

Comparison of warm season gradients showed that the Coquitlam system was significantly steeper (warm-to-cool, lake-to-river) in the summer than either the Chehalis or Chilliwack systems (4.3°C, 0.6°C, and 1.4°C respectively – Table 3). For the cold, high-discharge season we found a greater amount of levelling out (rotation) for the Coquitlam gradient than for the two
natural systems. From its summer value of 4.3°C it flattened to 0.7°C. Chehalis and Chilliwack were 1.9°C and 1.1°C respectively (Table 4). This levelling out was consistent with findings from the within system (Coquitlam profile) analysis for the months of November and December, which indicated that there was, on average, virtually no difference between discharge temperatures and surface (1mbs) temperatures during the high-discharge months for the study period, and that this uniformity was borne rapidly down to the Patricia Footbridge station, which is the downstream end of the Coquitlam gradient. Since the Coquitlam gradient endpoint temperatures are virtually the same in the cold season, and since these are the same as the reservoir surface, then according to the hypothesis downstream temperatures can be said to be natural. However, this effect may itself be unnatural, because the midpoint of the Chehalis and Chilliwack gradients have a shallower rise and fall (seasonal difference) than the Coquitlam gradient, and they don’t show the same rotational character (85% flattening for Coquitlam compared to 24% for Chilliwack; Chehalis actually steepened by 68% – Table 4, Figure 12 through Figure 14). As mentioned, however, in the case of Chehalis there is no replication for the lake, so this observation is not statistically supported.

The greater rotation of the Coquitlam system gradient is explained, at least in part, by the high discharge rates which occurred during November and December in the study period. For those months, on average (based on 2004 through 2008 data), over half (51%) of the flow passing through the Patricia Footbridge was dam discharge. Figure 18 shows the annual cycle of flow changes at the Environment Canada hydrometric station; Figure 19 and Figure 20 show how much of the flow is attributable to dam releases. A warm, low-discharge season plot of Patricia Footbridge temperatures against discharge recorded at the Environment Canada hydrometric station shows that increases in natural flow correlate with decreases in temperature (consistent with the literature review – Figure 21). However, the same plot of Patricia Footbridge temperatures against discharge rate for the same period shows no correlation, at least at low discharge rates (Figure 22).
Figure 18: monthly flow at Environment Canada hydrometric station averaged over 5 years (2004 - 2008)
Figure 19: Dam discharge levels averaged over 5 years (2004 - 2008)
Figure 20: dam discharge contribution to downstream flow during cold, high-discharge months of study period
Figure 21: Water temperature at Patricia Footbridge station plotted against flow rate at Environment Canada station June – August 2007 – 2008 (Pearson's product-moment correlation = -0.76)
3.5.4 Impact of cold season warming in reaches below dam

Using the same ministry published guidelines as we did for the warm season, we plotted temperature thresholds for the single category *Freshwater Aquatic life – unknown fish distribution* against the 7-day moving average for the below dam (CQM-R6) station. For the cold season for this category, the guideline is *maximum incubation temperature*. Measured against this guideline, there appears to be no deleterious effect caused by cold season high-discharge rates, at least for the study period – Figure 23, Figure 24).
Please note that water temperature guideline plots herein are non-specific and should be recalculated with known fish distribution data. The MOE website has much more detailed information and guidelines for known species distributions.

Figure 23: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: November 12, 2007 – June 28, 2008 and MOE water temperature guidelines for *Freshwater Aquatic Life – Streams with unknown fish distribution*; Points: 2 = November 13; 187 = May 16
Figure 24: Below Dam station (CQMR6) 7-day moving average of maximum daily temperatures: October 21, 2008 – May 18, 2009 and MOE water temperature guidelines for *Freshwater Aquatic Life – Streams with unknown fish distribution*; Points:  2 = October 22; 210 = May 18

In addition, in order to assess potential impacts of cold season warming impacts, water temperature data (from September 15, 2007 to March 29, 2008) was converted into accumulated thermal units (ATUs), where one degree Celsius in one day is equal to one ATU. The calculated ATUs and potential dates expected for hatch and emergence stages for incubating Coho salmon eggs are presented in Figure 25. The estimated eyed, hatch and emergence stage timing is based on ATU data for Coho salmon available from DFO.
Based on this and previously mentioned information, it appears the observations of cooling by Or Creek could potentially delay egg incubation and/or create greater variability in the stages of egg development. Overall, ATUs on downstream reaches (i.e. beyond Or Creek) appear similar to other systems at both the Chilliwack River and Chehalis River.

![ATUs in 2007/2008 and general dates expected for hatching and emergence stages (shaded areas) for incubating Coho salmon eggs. Time for start of spawning is for general reference only.](image)

3.5.5 **Plots of a 2007 warm season 5-day discharge spike**

While there may be correlation of discharge rate and temperature at higher discharge rates, as previously noted, however, this is not evident for low discharge rates (e.g., Figure 22). The data included a 5-day spike in discharge in the middle of the 2007 low-flow season (Figure 26). Figure 27 shows the effect of this spike at the Patricia Footbridge station. It is clear that the sudden imposition of discharge cuts across the natural correlation of temperature and flow with transport of the temperature of its source (explanatory variable \( at\_depth \)). This may result in a sudden change in temperature, and this can be fatal to fish. The Ministry of Environment has published guidelines on maximum hourly rates of change at:

Figure 26: 5-day spike in discharge in July 2007 (cf. Figure 22)
Figure 27: conditional plot showing 5-day spike in discharge during the 2007 warm season, Patricia Footbridge water temp plotted against dam discharge (bottom row) and Environment Canada hydrometric station discharge records; the discharge spike appears as a break in the natural inverse correlation of flow and stream temperature shown in the top row.
4.0 CONCLUSIONS

Based on the methods used in this study, the answers to the two management questions have been addressed as follows:

<table>
<thead>
<tr>
<th>Question 1: Is there a significant correlation between lower Coquitlam River temperatures and Coquitlam Reservoir operations?</th>
</tr>
</thead>
</table>

**Answer:**
- In the **cold, high-discharge** season of November 1 through December 31, the answer is ‘yes’.
  - Comparison of temperature means shows that there was no difference between mean temperatures of the reservoir surface and the discharge stratum during these months of the study period. Moreover, there was only a slight statistical drop in mean temperature between the reservoir surface and the downstream Patricia Footbridge station (approximately 0.8 °C) during this time of high discharge rates. However, based on the literature (e.g., Ahmadi-Nedushan et al., 2007), and confirmed by tests done for this study, a high negative correlation is expected between stream temperature and flow rate. (For Patricia Footbridge, during the warm, low-discharge season this correlation is -0.75 – shown on Figure 21.) Based on five years of records (2004 through 2008), on average, for November and December approximately 51% of the flow passing through the Environment Canada station (downstream of Patricia Footbridge) is dam discharge. Regression analysis conducted for the Patricia footbridge station during the cold, high-discharge months found extremely high significance for the variable at.depth (temperature of the discharge stratum), and this variable is non-existent during the warm season at this station. (Or Creek is of even more extreme significance than at.depth in the cold season, and is perhaps responsible for the slight drop of 0.8 °C.)
- In the **warm, low-discharge** season (June 1 through August 31), the answer is ‘yes’.
  - Comparison of temperature means shows that the monitoring station below the dam is cooler than the reservoir surface by approximately 3°C, and therefore a cooling effect is attributed to the variable at.depth, since it is cooler than the station below the dam. Because of low discharge rates, however, the influence of at.depth is lost on the downstream side of the cold confluence of Or Creek. Of all possible explanatory variables tested, Or Creek was shown to be the single most important explanatory variable affecting temperatures downstream from it.

**Discussion:** For the warm, low-discharge season, although there is significant correlation between lower Coquitlam River temperatures and Coquitlam reservoir operations (i.e., the below dam station is approximately 3°C cooler), the significance is lost beyond Or Creek, because of low discharge rates. Moreover, although we observe this cooling effect at the station immediately below the dam, guidelines for maximum temperature thresholds published by the BC Ministry of
Environment show that temperatures always exceeded the threshold for the category *Freshwater Aquatic Life – unknown fish distribution* for each summer we looked at.
For the cold, high-discharge season, although we observe warmer downstream temperatures than might be expected based on understanding of flow increases due to natural conditions, this warming effect does not raise temperatures above incubation temperature guidelines for the category *Freshwater Aquatic life – unknown fish distribution* published by the Ministry of Environment. In addition, potential impacts on Accumulated Thermal Units (ATUs) and incubation on downstream reaches beyond Or Creek do not appear evident when compared to the Chilliwack and Chehalis River systems. However, there are many other categories which could be checked; some may be more applicable to the Lower Coquitlam River than the categories plotted in this report.

<table>
<thead>
<tr>
<th>Question 2: Is there a significant difference between the reservoir to river temperature gradient and lake to river temperature gradient(s) in similar but unregulated lower Fraser River tributaries?</th>
</tr>
</thead>
</table>

**Answer:**
- Inferences based on the Chehalis system are weak due to lack of replication of seasons for Chehalis Lake.
- In the warm season, we found a significant difference between the Coquitlam system gradient and those of the natural systems.
  - The Coquitlam system gradient was 4.3 °C (lake to river, warm to cool) while the Chehalis system gradient was 0.6 °C and Chilliwack system gradient was 1.4 °C.
  - The temperature of the gradient midpoint for the Coquitlam system was 17 °C while both the Chehalis and Chilliwack systems had midpoint temperatures of approximately 13 °C.
  - Through regression analysis, the steepness of the warm season gradient was shown to be largely attributable to Or Creek. The below dam station was approximately 3°C cooler, and this was caused by at depth discharge; however, this influence had no significance beyond Or Creek in the warm season (as discussed above).
- In the cold season, the Coquitlam system gradient showed a greater tendency to flatten than the Chehalis or Chilliwack systems.
  - The Coquitlam system gradient flattened by 85% while Chilliwack system flattened by 24% and Chehalis system steepened by 68%. As discussed, regression analysis showed the flattening of the Coquitlam system to be largely attributable to the higher discharge rates that occur in November and December.
  - Since Chehalis Lake lacks replication of seasons, the observed steepening of the Chehalis system has no statistical significance.

**Discussion:** The behaviour of the Coquitlam system reservoir-river temperature gradient appears to be significantly different than the two natural gradients (notwithstanding the apparent steepening of Chehalis in the winter). In the warm season, the Coquitlam gradient was much steeper than the other two, and its midpoint was much warmer than the other two. For the study
period, the cool endpoint of the gradient, Patricia Footbridge station, was warmer than the warm endpoints (lakes) of the Chehalis and Chilliwack gradients in the summer, and the reservoir was warmest of all gradient endpoints – Figure 12). During November and December of the study period both endpoints of the Coquitlam gradient dropped dramatically to a level slightly cooler than the warm endpoints of the two natural systems (Figure 13). High discharge rapidly transports the warmer temperatures of the reservoir discharge stratum to downstream stations (approximately 51% of flow at the hydrometric station came from dam discharge for these months). Even with these observed warmer temperatures the station below the dam still exhibited temperatures that were below the incubation threshold for the category Freshwater Aquatic Life – unknown fish distribution publish in Ministry of Environment guidelines. In the summer, the apparent relative steepness of the Coquitlam gradient results from the contrast of relative high reservoir surface temperatures against the relative cold influence of Or Creek on temperature response at the gradient endpoint Patricia Footbridge station. During the summer months of the study period there appeared to be a cooling effect at the station immediately below the dam, but it is lost at the far downstream endpoint in the presence of the much cooler influence of Or Creek. Even with a cooling effect, temperatures rose above ministry guidelines for the category Freshwater Aquatic Life – unknown fish distribution in the reach immediately below the dam.
5.0 REFERENCES


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6.0 CLOSURE

We trust this report meets your requirements at this time. Please review the “Interpretation & Use of Study and Report” included as Appendix B. If you have any questions or comments regarding this report, please contact the undersigned.

Yours truly,

TROW ASSOCIATES INC. Reviewed by:

THIS IS A COPY. THIS IS A COPY.

Environmental Scientist (Biology) Environmental Engineer
APPENDIX A

FIGURES

(Figures A-1 through A-4)
APPENDIX B

TABLE

(Table B-1)
| System          | Parameter     | Station ID | Station Description      | Latitude | Longitude | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|----------------|---------------|------------|--------------------------|----------|-----------|------|------|------|------|------|------|------|------|------|------|------|
| Coquitlam      | water temperature | CQM-L2    | COQ2 thermistor chain     | 49, 22, 31 | 122, 47, 56 | n/a  | n/a  | n/a  | n/a  | h    | q    | q    | q    | q    | q    | q    | q    | q    |
| Reservoir      | air temperature | CQM-L1    | above dam                | 49, 21, 12 | 122, 46, 29.9 | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   |
| water discharge| CQM-D1        | at dam     |                         | 49, 21, 12 | 122, 46, 29.9 | h    | h    | h    | d    | d    | d    | d    | d    | d    | d    | d    |
| surface elevation | CQM-D2      | at dam     |                         | 49, 21, 12 | 122, 46, 29.9 | h    | h    | h    | d    | d    | d    | d    | d    | d    | d    |
| Lower          | water temperature | CQM-R6    | reach 4 (below dam)      | 49, 21, 10 | 122, 46, 23.9 | h*   | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
| Coquitlam      | air temperature | CQM-R5    | reach 3 (Or Creek)       | 49, 20, 29 | 122, 46, 16.4 | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
| River          | air temperature | CQM-R3    | reach 3 (Hatchery)       | 49, 20, 16 | 122, 46, 17.39 | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
|             | water discharge | CQM-R2    | reach 2 (Patricia Footbridge) | 49, 16, 33 | 122, 46, 36.5 | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
|             | water temperature | CQM-R1    | reach 0 (Red Bridge)     | 49, 15, 02 | 122, 47, 47.3 | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
|             | air temperature | CQM-R4    | reach 3 (Gord's Cabin)   | 49, 19, 12 | 122, 46, 13.1 | n/a  | n/a  | n/a  | h    | h    | h    | h    | h    | h    | h    |
|             | water discharge | CQM-R7    | Env. Can. hydrometric stn. 08MH0 | 49, 15, 56 | 122, 46, 51 | d    | d    | d    | d    | d    | d    | d    | d    | d    | d    |
| Chilliwack     | water temperature | CWK-L1    | Chilliwack Mid-lake (stn.1) | 49, 03, 14 | 121, 24, 52 | n/a  | i    | i    | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  |
| Lake          | water temperature | CWK-L2    | Chilliwack Lake at outlet (stn.2) | 49, 04, 58 | 121, 27, 13 | n/a  | i    | i    | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  |
|             | water temperature | CWK-L3    | Chilliwack Lake at outlet (BCH logger) | 49, 04, 54 | 121, 26, 59.2 | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | h    | h    |
| Chilliwack     | water temperature | CWK-R1    | DFO Chilliwack Hatchery  | 49, 04, 50 | 121, 42, 42.0 | n/a  | n/a  | n/a  | n/a  | n/a  | h    | h    | d    | n/a  | n/a  |
| River         | water temperature | CWK-R2    | upstream of Foley Creek confluence | 49, 05, 59 | 121, 37, 42 | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | h    | h    |
| Chehalis       | water temperature | CLS-L2    | Chehalis Lake near outlet | 49, 24, 17 | 122, 01, 55 | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | n/a  | h    | h    |
| River         | water temperature | CLS-R1    | DFO Chehalis Hatchery    | 49, 17, 26 | 121, 56, 28.3 | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   | mm   |

Notes:
- n/a: data not available
- #: lost-not replaced
- q: data recorded every quarter hour
- h: data recorded every hour
- 5: data recorded every 5 minutes
- mm: data available as daily minimum/maximum
- d: data available as daily averages
- i: data with irregular availability; spot values
- CQM-L2: no data for the 2009 summer period (April - August)
- CQM-R1 to R6: no data for the 2009 winter period (November - December)
APPENDIX C

INTERPRETATION & USE OF STUDY AND REPORT
INTERPRETATION & USE OF STUDY AND REPORT

1. STANDARD OF CARE

This study and Report have been prepared in accordance with generally accepted engineering consulting practices in this area. No other warranty, expressed or implied, is made. Engineering studies and reports do not include environmental consulting unless specifically stated in the engineering report.

2. COMPLETE REPORT

All documents, records, data and files, whether electronic or otherwise, generated as part of this assignment are a part of the Report which is of a summary nature and is not intended to stand alone without reference to the instructions given to us by the Client, communications between us and the Client, and to any other reports, writings, proposals or documents prepared by us for the Client relative to the specific site described herein, all of which constitute the Report.

IN ORDER TO PROPERLY UNDERSTAND THE SUGGESTIONS, RECOMMENDATIONS AND OPINIONS EXPRESSED HEREIN, REFERENCE MUST BE MADE TO THE WHOLE OF THE REPORT. WE CANNOT BE RESPONSIBLE FOR USE BY ANY PARTY OF PORTIONS OF THE REPORT WITHOUT REFERENCE TO THE WHOLE REPORT.

3. BASIS OF THE REPORT

The Report has been prepared for the specific site, development, building, design or building assessment objectives and purpose that were described to us by the Client. The applicability and reliability of any of the findings, recommendations, suggestions, or opinions expressed in the document are only valid to the extent that there has been no material alteration to or variation from any of the said descriptions provided to us unless we are specifically requested by the Client to review and revise the Report in light of such alteration or variation.

4. USE OF THE REPORT

The information and opinions expressed in the Report, or any document forming the Report, are for the sole benefit of the Client. NO OTHER PARTY MAY USE OR RELY UPON THE REPORT OR ANY PORTION THEREOF WITHOUT OUR WRITTEN CONSENT. WE WILL CONSENT TO ANY REASONABLE REQUEST BY THE CLIENT TO APPROVE THE USE OF THIS REPORT BY OTHER PARTIES AS ‘APPROVED USERS’. The contents of the Report remain our copyright property and we authorise only the Client and Approved Users to make copies of the Report only in such quantities as are reasonably necessary for the use of the Report by those parties. The Client and Approved Users may not give, lend, sell or otherwise make the Report, or any portion thereof, available to any party without our written permission. Any use which a third party makes of the Report, or any portion of the Report, are the sole responsibility of such third parties. We accept no responsibility for damages suffered by any third party resulting from unauthorised use of the Report.

5. INTERPRETATION OF THE REPORT

a. Nature and Exactness of Descriptions: Classification and identification of soils, rocks, geological units, contaminant materials, building envelopment assessments, and engineering estimates have been based on investigations performed in accordance with the standards set out in Paragraph 1. Classification and identification of these factors are judgmental in nature and even comprehensive sampling and testing programs, implemented with the appropriate equipment by experienced personnel, may fail to locate some conditions. All investigations, or building envelope descriptions, utilizing the standards of Paragraph 1 will involve an inherent risk that some conditions will not be detected and all documents or records summarising such investigations will be based on assumptions of what exists between the actual points sampled. Actual conditions may vary significantly between the points investigated and all persons making use of such documents or records should be aware of, and accept, this risk. Some conditions are subject to change over time and those making use of the Report should be aware of this possibility and understand that the Report only presents the conditions at the sampled points at the time of sampling. Where special concerns exist, or the Client has special considerations or requirements, the Client should disclose them so that additional or special investigations may be undertaken which would not otherwise be within the scope of investigations made for the purposes of the Report.

b. Reliance on Provided information: The evaluation and conclusions contained in the Report have been prepared on the basis of conditions in evidence at the time of site inspections and on the basis of information provided to us. We have relied in good faith upon representations, information and instructions provided by the Client and others concerning the site. Accordingly, we cannot accept responsibility for any deficiency, misstatement or inaccuracy contained in the report as a result of misstatements, omissions, misrepresentations or fraudulent acts of persons providing information.

c. To avoid misunderstandings, Trow Associates Inc. (Trow) should be retained to work with the other design professionals to explain relevant engineering findings and to review their plans, drawings, and specifications relative to engineering issues pertaining to consulting services provided by Trow. Further, Trow should be retained to provide field reviews during the construction, consistent with building codes guidelines and generally accepted practices. Where applicable, the field services recommended for the project are the minimum necessary to ascertain that the Contractor’s work is being carried out in general conformity with Trow’s recommendations. Any reduction from the level of services normally recommended will result in Trow providing qualified opinions regarding adequacy of the work.

6.0 ALTERNATE REPORT FORMAT

When Trow submits both electronic file and hard copies of reports, drawings and other documents and deliverables (Trow’s instruments of professional service), the Client agrees that only the signed and sealed hard copy versions shall be considered final and legally binding. The hard copy versions submitted by Trow shall be the original documents for record and working purposes, and, in the event of a dispute or discrepancy, the hard copy versions shall govern over the electronic versions. Furthermore, the Client agrees and waives all future right of dispute that the original hard copy signed version archived by Trow shall be deemed to be the overall original for the Project.

The Client agrees that both electronic file and hard copy versions of Trow’s instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except Trow. The Client warrants that Trow’s instruments of professional service will be used only and exactly as submitted by Trow.

The Client recognizes and agrees that electronic files submitted by Trow have been prepared and submitted using specific software and hardware systems. Trow makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.