Cheakamus Project Water Use Plan

CMSMON-6 Monitoring Groundwater in Side Channels of the Cheakamus River

Implementation Year 3

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Final Report

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Prepared by:

Tyler Gray¹, Jacek Scibek², Dan Mackie², Will Gaherty³, Diana M. Allen³

¹Pottinger Gaherty Environmental Consultants Ltd.
1200 – 1185 West Georgia Street
Vancouver, BC V6E 4E6
Tel: (604) 682-3707

²SRK Consulting (Canada) Inc.
2200 – 1066 West Hastings Street
Vancouver, BC V6E 3X2
Tel: (604) 681-4196

³Simon Fraser University, Department of Earth Sciences
8888 University Drive
Burnaby, BC V5A 1S6
Tel: (778) 782-3967

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Executive Summary

This report presents the final outcomes of a three-year study regarding groundwater-surface water interactions between Cheakamus River and side channels around the North Vancouver Outdoor School (NVOS) near Brackendale, BC. The study was carried out as one part of several parallel monitors by BC Hydro within the Cheakamus River Water Use Plan (WUP), as river flows are managed by releases at the Daisy Lake dam. January 2011 represented the end of three years of monitoring undertaken jointly by PGL and SRK.

The program was guided by four management questions:

1. How do seasonal NVOS and Tenderfoot Hatchery (TH) floodplain shallow groundwater flow direction, temperature, dissolved oxygen, and pH vary in response to Cheakamus River mainstem flows ≤ 40m³/s?
2. To what extent does seasonal NVOS and TH side channel hydrology depend on groundwater flow interactions with Cheakamus River mainstem flows ≤ 40m³/s?
3. To what extent do key fish habitat variables related to flow (average depth, average velocity, discharge) and water quality (temperature, dissolved oxygen, and pH) in NVOS and TH side channels depend on groundwater flow interactions with Cheakamus River mainstem flows ≤ 40m³/s?
4. To what extent does salmonid production vary in NVOS and TH side channels in relation to groundwater flow interactions with Cheakamus River mainstem flows ≤ 40m³/s, and to what extent has the implementation of the WUP affected salmonid production in the NVOS and TH side-channel habitats compared to the pre-WUP state?

Results of the monitoring program demonstrate a groundwater-surface water interface that is in a relatively stable state at low and moderate flows. Some physical parameters (e.g., water elevation) are statistically linked to lower river discharge, but the magnitude of variation is very small and of limited practical use for management. Other parameters are driven by processes other than river discharge, at least within the range of flows recorded in the three years.

Analysis of groundwater elevation shows an expected link between river stage (or discharge) and water levels in groundwater monitoring points or surface water in NVOS side channels. The current flows are characteristically lower than the previous in-stream flow order (IFO) by an amount that will lead to a measurable decrease in the water level, but for moderate flow differences the magnitude of water-level change is small (e.g., if comparing 20m³/s to 40m³/s, the magnitude of water-level variation is generally around 0.02 to 0.03m). Based on this analysis, the statistical relationship between river discharge and groundwater level persists at lower flows, but the practical significance of the relationship in terms of fish habitat seems quite limited.

Temperature data were used to calculate travel time of water discharging to ground from the river and subsequently upwelling into side channels. Even for short-distance shallow groundwater movement, the travel time is generally on the order of days, and in some locations weeks, and is affected very little by the pressure gradient of the river water. These travel times are not unusual, and create a system where sub-surface processes are a robust regulator of water quality. Conversely, water levels in NVOS monitoring points respond to changes in Cheakamus River
discharge on the order of hours; this is not indicative of travel time, but rather is the hydraulic response to a change in the pressure gradient.

Regarding habitat parameters measured, dissolved oxygen, pH, and temperature in NVOS sites are correlated to the values of those parameters in the river, but the values in the river are not in turn correlated to discharge within the range of flows observed from 2008 through 2011. Therefore, Cheakamus River flow within the relevant management range (e.g., 15 to 70 m³/s) will have no practical effect on pH, dissolved oxygen or temperature in upwelling groundwater or NVOS surface water. At very high flows the physical head pressure does in fact lead to a characteristic but transient decrease of hyporheic dissolved oxygen: long-residence groundwater with low DO is essentially “squeezed” out into the side channel in higher proportion than shallow, higher DO groundwater. In the case of extremely high storm flows, the transient decrease in side channel DO is also followed by a transient increase in dissolved oxygen, since very high and sustained storm events are capable of substantially shortening the travel time of deep groundwater entering the side channels, and resulting in higher DO. While the “flushing flow” threshold may be beyond the flow range meant for consideration in this monitor, it may be informative to explore whether the WUP is artificially reducing the frequency of flushing flows, or if the natural storm events that cause spill over the Daisy Lake dam are sufficiently large to make the extent of flow diversion inconsequential.

The duration of potentially informative fisheries data for Cheakamus groundwater processes is quite short. Statistical conclusions about the lack of an effect between the current WUP and fish productivity are not yet possible, though a correlation was identified between egg-to-fry survival and variability of water levels during incubation in BC Rail Channel. The extent of data to not warrant a final interpretation of whether this correlation represents a causal mechanism; however, with the conceptual model of physical processes provided, there should be some confidence that the fish habitat parameters previously thought most likely to be affected by low flows are within the same range – and water levels within an extremely similar range – compared to values under older water-use patterns.
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List of Acronyms

ccf - cross-correlation function
DFO - Fisheries and Oceans Canada
DO - dissolved oxygen
HSI - Habitat Suitability Index
IFO - In-stream Flow Order
masl - metres above sea level
NVOS - North Vancouver Outdoor School
PGL - Pottinger Gaherty Environmental Consultants Ltd.
QA/QC - quality assurance and quality control
SRK - SRK Consulting (Canada) Inc.
TH - Tenderfoot Hatchery
WSC - Water Survey of Canada
WUP - Water Use Plan

LIST OF MONITORING STATION ABBREVIATIONS
For locations and context of each, please refer to Figure 3 and Table 2, respectively.

BCRDOG/BCRDOS - BC Rail Continuous DO Monitoring Station
D11 through D55 - In-stream piezometers
KDOG/KDOS - Kisutch Channel Continuous DO Monitoring Station
R4 through R13 - Regional floodplain steel piezometers
RBCH - BC Hydro Pond Floodplain Well
SGBCR - BC Rail Staff Gauge
SGCH - Cheakamus River Staff Gauge
SGKIS - Kisutch Channel Staff Gauge
SGUP - Upper Paradise Staff Gauge
TEND - Tenderfoot Hatchery
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1.0 INTRODUCTION

As part of the Cheakamus River Water Use Plan (WUP), Pottinger Gaherty Environmental Consultants Ltd. (PGL) and SRK Consulting (Canada) Inc. (SRK) jointly undertook Cheakamus River Monitoring Program #6 ("Monitor #6") on behalf of BC Hydro between January 2008 and January 2011.

The Cheakamus River is located in southwest BC, near the community of Squamish (Figure 1). Flows in the Cheakamus River are managed by BC Hydro's Daisy Lake Dam. The multi-disciplinary Cheakamus River WUP Monitors were initiated to evaluate potential physical and biological effects of the current WUP, which was instituted in 2006.

Cheakamus WUP minimum required flows at the Brackendale gauge are:

- 15.0m³/s from November 1 to March 31;
- 20.0m³/s from April 1 to June 30;
- 38.0m³/s from July 1 to August 15;
- 20.0m³/s from August 16 to August 31, unless directed by Comptroller to maintain 38.0m³/s for recreation; and
- 20.0m³/s from September 1 to October 31.

The Cheakamus River flows around the eastern border of the North Vancouver Outdoor School (NVOS). Within the NVOS grounds are a series of highly productive side channels, several of which are groundwater-fed. The NVOS side channels support spawning to various extents for anadromous chum, coho, pink, and steelhead stocks.

1.1 Context and Environmental Rationale

An overlying concern regarding Cheakamus River flow manipulation and resultant physical properties of the NVOS side channels is the implications for fish productivity. A growing body of literature is dedicated to the link between groundwater and fish habitat, and particular concerns emerged during the WUP consultation process regarding chum salmon in NVOS side channels and the potential effects of changing Cheakamus River water levels.

1.1.1 NOVS Channels and Chum Salmon

Surface water-groundwater linkages can affect such vital habitat attributes as dissolved oxygen (e.g., Malcom et al. 2009), temperature (e.g., Gesit et al. 2008), intra-gravel flow velocity (e.g., Greig et al. 2007), or overall surface water hydrology and habitat availability. These potential linkages can further be broken down into considerations for the quantity and quality of the habitat.

The consultation process for the Cheakamus WUP selected chum as a focal species for evaluating quantity and quality of fish habitat in the groundwater-fed side channels (Marmorek and Parnell, 2002). This selection was made largely due to the apparent preference of chum spawners for placing redds in areas of groundwater upwelling. Using chum as the focal species also was the most promising for meaningful data analysis, since chum data collection is relatively comprehensive and the absence of a resident fry life history stage simplifies the assessments.
The Cheakamus WUP consultation process generated concerns from some stakeholders about the influence of altered mainstem hydrology on habitat characteristics for chum. To illustrate the linkages between hyporheic flow and habitat quality within a redd, a conceptual model of the main factors influencing embryonic survival is depicted in Figure 2 (adapted from Greig et al., 2007). Potentially, a breakdown of hydraulic connectivity to mainstem flows could negatively impact the thermal regime, oxygen supply, or intra-gravel flow rates.

Given the outcomes of the WUP consultation process, the results of this monitoring program are interpreted in a general sense for aquatic life, but are particularly focused on chum salmon as an indicator species.

In the strictest terms, the quantity of fish habitat is defined exclusively by the amount of wetted area available for use. Because the NVOS side channels are groundwater-fed, Cheakamus River flows may impact the quantity of side channel habitat if groundwater upwelling processes are impacted. There was generally an expectation among Consultative Committee members during the WUP planning that the side channel habitat quantity was probably insensitive to the surface water-groundwater interactions, but to properly address the uncertainty, the link between side-channel hydrology and mainstem low flows was chosen for investigation.

Quality of habitat is defined by the parameters of relevance to fish populations at the various life history stages. For returning spawners, the quality may be defined primarily by substrate characteristics, water depth, velocity, and temperature. A multitude of studies have been undertaken to quantify appropriate flow characteristics by species and life history stage. For instance, previous studies for Pacific northwest chum have proposed highly suitable spawning conditions where velocity ranges between 0.05m/s and 0.6m/s and depth of at least 0.3m (Hale et al. 1985). The process of developing such “habitat suitability indices” may, however, be limited in applicability and is very dependent on whether metrics were derived from observed spawning in large river systems or slower-moving off-channel habitat.

Moving beyond surface water habitat characteristics, selective pressure for choosing redd locations with suitable hyporheic attributes is also relevant for some species. For incubation of reds, the hyporheic flow conditions are more important than surface flow for defining habitat quality: a certain threshold of interstitial velocity is required to deliver nutrients and remove metabolic waste from the area surrounding the egg sac. The required rate will be a function of the physical characteristics of the redd. A constant supply of oxygen and a temperature regime conducive to egg growth are also fundamental components of habitat quality for incubation.

Acute and chronic effects of oxygen depletion on all stages of anadromous fish are reviewed in detail in the BC Water Quality Guidelines (http://www.env.gov.bc.ca/wat/wq/BCguidelines/do/do-03.htm, last accessed April 14, 2011). The often-cited literature review by Bjornn and Reiser (1991) resulted in recommendations that DO for anadromous salmonids should remain above 5mg/L in the water column for most life stages, but should remain at or above 9mg/L in the water column (or 6mg/L in the interstitial hyporheic water if measurable) during incubation. The same guidelines propose surface water temperature thresholds of 7.2–12.8°C for spawning chum, and 4.4–13.3°C intragravel temperature for incubating chum. Recommended pH values range from 6 to 9.
Finally, for species with a freshwater residency period, flow characteristics (depth, velocity), site characteristics (substrate, overhead cover, temperature), and food availability are important characteristics for growth, survival and eventual reproduction. Suitability of water velocity and depth varies among species (and within species depending on individual fish size or particular site habitation by different breeding stocks), and by life history stage.

Oxygen, temperature, pH, velocity, and depth represent only a partial list of influential environmental variables, but include the ones considered by the Consultative Committee to have the highest likelihood to be linked to WUP decisions. For a more complete discussion of additional variables such as gradient and channel configuration see Chapman (1988).

There is interaction amongst the various habitat parameters listed above, and so the overall suitability of habitat is a function of these interactions. Furthermore, the relative importance of the parameters will vary by species, with different intrinsic preferences and life history requirements – in the case of chum, research generally supports the assertion that redds are often associated with areas of groundwater upwelling (Geist, 2000; Geist et al. 2008, Curry and Noakes, 1995; Leman 1993).

1.2 Study Objectives

The purpose of Monitor #6 is to evaluate the correlation(s) between flow in the Cheakamus River and hydraulic parameters in adjacent floodplain and groundwater-fed spawning channels, in and around the North Vancouver Outdoor School (NVOS) and Tenderfoot Hatchery (TH) sites in Brackendale (Figure 1). The program also explores how these hydraulic parameters may relate to salmonid productivity in the same area.

This study follows earlier work of Jordan-Knox (2003), who conducted detailed investigations into groundwater-surface water interactions in the NVOS study area in 2000 and 2001. Jordan-Knox’s results demonstrated strong connectivity between Cheakamus River stage and the aquifer feeding the side channels in Upper Paradise and Upper Kisutch, confirming that flow manipulations to the Cheakamus River had potential to alter flow and habitat in the groundwater-fed side channels. However, the study faced a limitation in the range of Cheakamus flows observed. The current WUP was not in place during the earlier work and it was recommended that future monitoring be carried out to determine the nature of hydrogeological relationships at the lower flows that were then being proposed (Jordan-Knox, 2003 pp. 122). The configuration of the side channels also changed between 2001 and 2007, increasing the surface water connectivity in the NVOS area. As this study is part of the broader Cheakamus WUP monitoring, the investigations are more focused on water management implications than the academic approach of Jordan-Knox (2003). The Monitor #6 program was derived from the results and recommendations from Jordan-Knox (2003) after consultation with multiple stakeholders within the Cheakamus WUP Consultative Committee.

To facilitate the study and to provide conclusions that are operationally relevant to Cheakamus water use by BC Hydro, the study program was guided by four management questions:

1. How do seasonal NVOS and TH floodplain shallow groundwater flow direction, temperature, dissolved oxygen (DO), and pH vary in response to Cheakamus River mainstem flows ≤ 40m³/s?
2. To what extent does seasonal NVOS and TH side-channel hydrology depend on groundwater flow interactions with Cheakamus River mainstem flows \( \leq 40 \text{m}^3/\text{s} \)?

3. To what extent do key fish habitat variables related to flow (average depth, average velocity, discharge) and water quality (temperature, DO, and pH) in NVOS and TH side channels depend on groundwater flow interactions with Cheakamus River mainstem flows \( \leq 40 \text{m}^3/\text{s} \)?

4. To what extent does salmonid production vary in NVOS and TH side channels in relation to groundwater flow interactions with Cheakamus River mainstem flows \( \leq 40 \text{m}^3/\text{s} \), and to what extent has the implementation of the WUP affected salmonid production in the NVOS and TH side-channel habitats compared to the pre-WUP state?

The monitoring approach to addressing these questions was initially established by a Request for Proposal released by BC Hydro in February 2007, and further shaped by amendments. Fieldwork commenced in January 2008 and was completed in early February 2011.

1.3 Overview of Channel Orientations and Interactions

The study site and various monitoring locations are shown in Figure 3. Three channels were selected as focal groundwater-fed channels for this project: Upper Paradise, Upper Kisutch, and BC Rail Channel. Six regional floodplain wells were also used.

In the time since Jordan-Knox’s 2003 report, additional work at NVOS has altered the physical arrangement of channels at NVOS. Gorbuscha Channel was added in 2003 and 2004. A submerged pipe intake conveys surface water directly into Gorbuscha, which runs nearer to the headwaters of Upper Paradise and Upper Kisutch channels than the Cheakamus River itself. A constant seepage of water out of the banks at the headwaters of Upper Paradise (Photo 3 of Appendix 1) likely illustrates a short transit-time contribution from Gorbuscha Channel. Seepage was also noted by Jordan-Knox in 2001, and so the extent to which Gorbuscha has altered surface water connectivity in Paradise Channel is unknown. Describing the relative contribution of this short-transit water to the longer-transit groundwater contributions was an aspect of this study.

Gorbuscha Channel construction involved an “overpass” over Upper Kisutch near stations D27/D28 (Figure 3, and see Photo 10 of Appendix 1). At this location it is also possible to observe what is likely surface flow contributions from Gorbuscha seeping directly through the banks and flowing into Upper Kisutch.

Immediately adjacent to the Gorbuscha Channel intake pipe discharge is a secondary intake into Sue’s Channel, constructed in 2007 (Figure 3). Sue’s Channel is confluent with Upper Paradise approximately 100m downstream of the latter channel’s headwaters. Backwatering from Sue’s Channel into Upper Paradise is evident, and while it does not backwater all the way to the top of Upper Paradise, the construction of Sue’s Channel in 2006 greatly reduced the length of Upper Paradise, which could be considered to be exclusively groundwater-fed.

Additional changes to the side-channel restoration in the area since 2003 include construction or restoration of Eagle Point, Mykiss Channel, Moody’s Channel, Bighouse, and Dave’s Pond (source: BC Hydro Bridge Coastal Rehabilitation Program); however, these changes have little bearing on the hydraulic properties of Paradise, Kisutch and BC Rail compared to the construction of Gorbuscha and Sue’s Channels.
BC Rail Channel drains influent groundwater from the north side of the Cheakamus River, joining the river on the left bank roughly opposite to NVOS (Figure 3). BC Rail Channel is also connected by a culvert to Dave’s Pond, which generally feeds surface flow into BC Rail Channel via a 600mm culvert (see Photos 19–21 of Appendix 1). Beaver activity had frequent impacts on water levels and velocities in BC Rail Channel in 2009 and 2010 (Photo 17 of Appendix 1). In 2009, damming repeatedly occurred on the upstream side of Dave’s Pond, whereas in 2010 a dam was repeatedly built and rebuilt further downstream in BC Rail Channel, approximately 50m downstream of the channel head. Unexpected site observations in May 2011 noted water flowing from BC Rail Channel into Dave’s Pond, due to the high water level from the downstream beaver dam. This observation was a clear means of verifying the strong groundwater upwelling at the head of BC Rail Channel, as strict reliance on the flow contributions from Dave’s Pond would negate the possibility for drainage from BC Rail Channel into Dave’s Pond.

Two regional floodplain wells were monitored for water level, temperature, pH and DO: Tenderfoot Hatchery and the “BC Hydro” pond. The Tenderfoot Hatchery well is located just south of the pond that abuts the south side of the actual DFO hatchery. The well is an old 0.4m-diameter cast-iron well that intercepts relatively deep groundwater, and is more than 400m from the Cheakamus River. The BC Hydro pond is a small wetland beneath the transmission lines that run adjacent NVOS. The monitoring well is a 0.1m-diameter PVC pipe installed approximately 2m upland from the normal surface water level of the pond (Photo 22 of Appendix 1).
2.0 FIELD METHODS AND DATA COLLECTION

The groundwater monitor was able to build upon previous work at the NVOS location. In particular, the work by Jordan-Knox left a network of 72 in-stream and floodplain piezometers. A subset of the 72 piezometers was adopted for use in the groundwater monitor, and a small number of new sites were added to expand the study area.

A summary of the general approach utilized to address the management questions is shown in Table 1.

Table 1: Data collection approach for addressing management questions

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<td>Shallow groundwater flow direction vs. Cheakamus River flow</td>
<td>1</td>
<td>Bi-monthly surveys of water levels at in-stream and floodplain piezometers/wells; continuous water-level loggers in five nested in-stream pairs and two floodplain groundwater wells.</td>
</tr>
<tr>
<td>Shallow groundwater temperature vs. Cheakamus River flow</td>
<td>1</td>
<td>Bi-monthly grab-sample measurements; continuous loggers in five nested in-stream pairs, and two floodplain groundwater wells.</td>
</tr>
<tr>
<td>Shallow groundwater DO and pH vs. Cheakamus flow</td>
<td>1</td>
<td>Six grab samples per year and three-month continuous monitoring; one round of sampling for dissolved metals and anions.</td>
</tr>
<tr>
<td>Side channel discharge, average depth, average velocity, and wetted width vs. Cheakamus River flow</td>
<td>2 &amp; 3</td>
<td>Continuous loggers in three side-channel stilling wells (with staff gauges); bi-monthly flow transects and water level measurements</td>
</tr>
<tr>
<td>Side channel temperature vs. Cheakamus River flow</td>
<td>2 &amp; 3</td>
<td>Continuous temperature loggers in three side-channel stilling wells (staff gauges); six surface water grab samples per year.</td>
</tr>
<tr>
<td>Side channel DO and pH vs. Cheakamus River flow</td>
<td>2 &amp; 3</td>
<td>Six surface grab samples per year and one 3-month continuous monitoring period; ALSO – one round of sampling for dissolved metals and anions.</td>
</tr>
<tr>
<td>Relationship(s) between salmonid production and groundwater parameters</td>
<td>4</td>
<td>Exploratory data analysis at conclusion of study.</td>
</tr>
</tbody>
</table>

1 Compared to the original Terms of Reference, the scope of data collected for this objective was altered due to budgetary constraints in January 2008 prior to data collection beginning.
2.1 Monitoring Locations

Final monitoring locations are shown in Figure 3. The locations were established in January 2008 and underwent only minor changes over the first half of the study. Coordinate and elevation data of all sampling locations are provided in Appendix 2.

In Year 2 (April 2009 through January 2010), three new monitoring stations were installed and one modification was made from what was established in Year 1 (Table 2). At the completion of Year 1, discussions with Instream Fisheries Research Inc. (Instream) regarding fisheries monitoring conducted in parallel with our work indicated that, due to the very short (less than 200m) length of the groundwater-fed section of Upper Paradise Channel, it was proving impossible to obtain meaningful fisheries data in that reach. Conversely, good data were being collected in BC Rail Channel, which was the only one of the three side channels that did not have a downstream groundwater-monitoring station to match the upstream pair. Purchase of additional data loggers was not a possibility within the existing scope of work. Therefore, the data loggers that had previously been installed in D11/D12 (Upper Paradise Channel) were relocated to a newly installed pair of drivepoints near the downstream end of BC Rail Channel on June 15, 2009. The new BC Rail pair were labelled D54 (shallow groundwater drivepoint) and D55 (surface water stilling well).

The second new station was installed to facilitate the continuous DO/pH monitoring trial. Numerous discussions between PGL, SRK, BC Hydro, and Instream preceded the installation of the continuous DO/pH data loggers, to optimize timing and location of data logging for interpreting fisheries data. Three monitoring stations were ultimately chosen, two of which were in-stream and in areas of good spawning habitat. One of these in-stream pairs was at an existing BC Rail Channel monitoring station (SGBCR), although to denote the additional data collection the station name BCRDOG/BCRDOS was created for groundwater and surface water, respectively.

The third station, KDOG/KDOS, was installed in a new station near the head of Kisutch Channel on October 22, 2009, upstream from station D50/D51 (Figure 3).

The Tenderfoot Hatchery station was also modified in Year 2 for the continuous DO/pH logging: a DO/pH logger was installed from October 22, 2009 through January 18, 2010.

In Year 3 (April 2010 through February 2011), no new monitoring locations were added, but two minor changes were made to the extent of data collection. Flow measurements at the Upper Paradise channel were stopped after Year 2, as the water velocity was consistently below the detection limit and the results were therefore inaccurate. Secondly, a windstorm in September 2010 resulted in a fallen tree knocking out one of the steel floodplain piezometers (R8), and so water levels were not collected at that location for the final three site visits.
Table 2: Monitoring locations for Cheakamus River WUP Monitor #6

<table>
<thead>
<tr>
<th>Code</th>
<th>Date Installed</th>
<th>Description</th>
<th>Data Collection</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGCH</td>
<td>January 2008</td>
<td>Cheakamus River Staff Gauge</td>
<td>Water level/temperature logger, surface water pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>North end of Paradise Valley Road bridge. 19mm diameter stainless steel drivepoint with logger, and wooden staff gauge (staff gauge washed out in late 2009, data logger and drivepoint remain stable)</td>
</tr>
<tr>
<td>SGBCR</td>
<td>January 2008</td>
<td>BC Rail Channel Staff Gauge</td>
<td>Water level/temperature logger, discharge and surface water pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>100mm diameter PVC stilling well</td>
</tr>
<tr>
<td>SGUP</td>
<td>January 2008</td>
<td>Upper Paradise Channel Staff Gauge</td>
<td>Water level/temperature logger, discharge and surface water pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>100mm diameter PVC stilling well</td>
</tr>
<tr>
<td>BCRDOG /BCRDOS</td>
<td>October 2009</td>
<td>Continuous DO/pH monitoring stations in BC Rail Channel</td>
<td>DO/pH measurements every six hours, November 2009 through January 2010</td>
<td>50mm diameter PVC shallow groundwater drivepoint, and 75mm diameter PVC stilling well. Located at SGBCR.</td>
</tr>
<tr>
<td>KDOG /KDOS</td>
<td>October 2009</td>
<td>Continuous DO/pH monitoring station in Kisutch Channel</td>
<td>DO/pH measurements every six hours, November 2009 through January 2010</td>
<td>50mm diameter PVC shallow groundwater drivepoint, and 75mm diameter PVC stilling well. Located upstream of SGKIS and D50/D51.</td>
</tr>
<tr>
<td>SGKIS</td>
<td>January 2008</td>
<td>Kisutch Channel Staff Gauge</td>
<td>Water level/temperature logger, discharge and surface water pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>100mm diameter PVC stilling well</td>
</tr>
<tr>
<td>D11/D12</td>
<td>Existing</td>
<td>Shallow/deep well pair in Paradise Channel</td>
<td>In 2008, water level/temperature loggers, groundwater pH/DO every two months, one-time dissolved metals and anions lab sample. In 2009/2010, manual water level every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>D21/D22</td>
<td>Existing</td>
<td>Shallow/deep well pair in Upper Paradise Channel</td>
<td>Manual water levels every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>D23/D24</td>
<td>Existing</td>
<td>Shallow/deep well pair in Upper Paradise Channel</td>
<td>Water level/temperature loggers, groundwater pH/DO every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>D27/D28</td>
<td>Existing</td>
<td>Shallow/deep well pair in Upper Paradise Channel</td>
<td>Manual water levels every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>Code</td>
<td>Date Installed</td>
<td>Description</td>
<td>Data Collection</td>
<td>Notes</td>
</tr>
<tr>
<td>------</td>
<td>----------------</td>
<td>-------------</td>
<td>-----------------</td>
<td>-------</td>
</tr>
<tr>
<td>D39/D40</td>
<td>Existing</td>
<td>Shallow/deep well pair in Kisutch Channel</td>
<td>Manual water levels every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>D45/D46</td>
<td>Existing</td>
<td>Shallow/deep well pair in Kisutch Channel</td>
<td>Water level/temperature loggers, groundwater pH/DO every two months</td>
<td>19mm diameter steel drivepoint piezometers</td>
</tr>
<tr>
<td>D50/D51</td>
<td>January 2008</td>
<td>Shallow/deep well pair in Kisutch Channel</td>
<td>Water level/temperature loggers, groundwater pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>19mm diameter stainless steel drivepoint piezometers</td>
</tr>
<tr>
<td>D52/D53</td>
<td>January 2008</td>
<td>Shallow/deep well in BC Rail Channel</td>
<td>Water level/temperature loggers, groundwater pH/DO every two months; one-time dissolved metals and anions lab sample.</td>
<td>19mm diameter stainless steel drivepoint piezometers</td>
</tr>
<tr>
<td>TEND</td>
<td>Existing (Modified for Year 2)</td>
<td>Regional floodplain well at Tenderfoot Creek Hatchery</td>
<td>Water level/temperature logger, groundwater pH/DO every two months; continuous pH/DO probe for three months.</td>
<td>Large (approx 250mm diameter) steel well</td>
</tr>
<tr>
<td>R4</td>
<td>Existing</td>
<td>Floodplain well located near North Vancouver Outdoor School buildings</td>
<td>Manual water level every two months</td>
<td>19mm diameter steel drivepoint piezometer</td>
</tr>
<tr>
<td>R8</td>
<td>Existing</td>
<td>Floodplain well north of Paradise Channel</td>
<td>Manual water level every two months</td>
<td>19mm diameter steel drivepoint piezometer</td>
</tr>
<tr>
<td>R13</td>
<td>Existing</td>
<td>Floodplain well</td>
<td>Manual water level every two months</td>
<td>19mm diameter steel drivepoint piezometer</td>
</tr>
<tr>
<td>R24</td>
<td>Existing</td>
<td>Floodplain well</td>
<td>Manual water level every two months</td>
<td>19mm diameter steel drivepoint piezometer</td>
</tr>
<tr>
<td>RBCH</td>
<td>January 2008</td>
<td>Floodplain well near BC Hydro tower</td>
<td>Water level/temperature logger, groundwater pH/DO every two months; one-time dissolved metal and anions lab sample.</td>
<td>100mm diameter PVC well</td>
</tr>
<tr>
<td>D54/D55</td>
<td>June 2009 (Installed in Year 2)</td>
<td>Shallow groundwater/surface water well pair in Kisutch Channel</td>
<td>Water level/temperature logger, groundwater and surface water pH/DO every two months</td>
<td>19mm diameter stainless steel drivepoint piezometer/stilling well.</td>
</tr>
<tr>
<td>BARO1/2</td>
<td>January 2008</td>
<td>Barometric loggers located at North Vancouver Outdoor School</td>
<td>Barometric pressure used to correct water-level logger readings from wells</td>
<td>Loggers stored in Fire Shed near Main Building</td>
</tr>
</tbody>
</table>
2.2 Fieldwork Chronology

February 2011 represented the completion of the third and final year of data collection. Work onsite commenced in January 2008, with eight field visits in 2008, ten in 2009 and seven in 2010/2011 (Table 3).

Table 3: Summary of fieldwork chronology 2008–2011

<table>
<thead>
<tr>
<th>Date</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 8, 2008</td>
<td>Site visit with BC Hydro, PGL, SRK</td>
</tr>
<tr>
<td>Jan 17, 2008</td>
<td>Purge sediment from piezometers and collect survey data</td>
</tr>
<tr>
<td>Jan 21, 2008</td>
<td>Install all loggers; side-channel flow transects, in situ DO, pH, water-level measurements.</td>
</tr>
<tr>
<td>Mar 13, 2008</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>May 27, 2008</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>July 22, 2008</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Sept 30, 2008</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Dec 2, 2008</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Jan 20, 2009</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Apr 7, 2009</td>
<td>Side channel flow transects, manual water-level measurements, download data loggers.</td>
</tr>
<tr>
<td>Apr 30, 2009</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Jun 15, 2009</td>
<td>Installation of D54/D55; flow transects; download data loggers; in situ DO, pH, water-level measurements.</td>
</tr>
<tr>
<td>Aug 24, 2009</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; download data loggers.</td>
</tr>
<tr>
<td>Oct 22, 2009</td>
<td>Install continuous DO/pH loggers at Tenderfoot, BC Rail Channel, Kisutch Channel</td>
</tr>
<tr>
<td>Nov 2, 2009</td>
<td>Download and check all data loggers (including DO/pH), in situ DO, pH, water-level measurements.</td>
</tr>
<tr>
<td>Dec 8, 2009</td>
<td>Flow transects; download DO/pH continuous data loggers.</td>
</tr>
<tr>
<td>Jan 21, 2010</td>
<td>Download data loggers; in situ DO, pH, water-level measurements</td>
</tr>
<tr>
<td>Apr 9, 2010</td>
<td>Side channel flow transects, in situ DO, pH, water-level measurements; final download of data loggers. Cease flow transects in Upper Paradise from this date forward.</td>
</tr>
</tbody>
</table>
### 2.3 Data Collection Methods

The existing piezometers that were chosen for the study were filled with sediment during a flood event in 2003, and required purging to be usable for this study. These piezometers were purged in January 2008, and each monitoring well was then surveyed for elevation data at the outset of the study (survey data provided in Appendix 2).

#### 2.3.1 Water Level and Temperature Logging

A total of 18 Solinst Leveloggers were installed for use in this study. Two loggers recorded barometric data at the NVOS main building, for the purpose of correcting water level data for atmospheric pressure. Of the remaining 16 loggers, 10 were in nested in-stream pairs, 4 were in surface water stilling wells at staff gauge locations, and 2 were in regional floodplain groundwater wells (Table 2). Each of these 16 loggers recorded water level and temperature at 15-minute intervals.

Loggers were downloaded on 18 occasions to a hand-held field unit and subsequently uploaded to a laptop. Three minor difficulties were encountered with respect to the data loggers:

- On one occasion (December 2, 2009), numerous drivepoints were frozen making removal of the loggers (or manual measurement of water levels for that matter) impossible. However, all data collected by the loggers was downloaded during the subsequent visit.
- In June of 2009, the wire suspending the logger in D45 broke due to corrosion. The logger was retrieved, but the cap and hanger were damaged during removal. The logger was not reinstalled until the subsequent field visit in August when a replacement part was available.
- In August 2010, the logger in D51 stopped collecting data due to a battery failure. This is the only logger that failed over the course of the program.

Completeness of temperature and water-level logger data is portrayed graphically in Figure 4.
Manual water-level measurements were undertaken on 18 occasions coinciding with the
download visits. In addition to recording water levels at the 16 wells containing loggers, water
levels were also read at three additional nested in-stream piezometer pairs (D39/D40; D21/D22;
D27/D28), and four floodplain piezometers (R13, R4, R8, and R24; see Figure 3). Water levels
were measured with a Heron water-level probe, to the nearest thousandth of a metre. For the
wells in which loggers were installed, water levels were always measured prior to removal of the
logger to guard against minor water-level fluctuations that may be induced by logger removal.

Manual temperature readings were taken at the same time as manual DO and pH readings, as
described below.

2.3.2 Dissolved Oxygen and pH

In addition to water temperature, DO and pH were two key fish habitat variables being monitored.
Data were collected via automated logger for a three-month period in Year 2, as well as in situ
“grab sample” measurement through all three years.

2.3.2.1 Grab Sampling

The scope of work included bi-monthly measurements of DO and pH from five nested in-stream
piezometer pairs, as well as from surface water in each of the three side channels and the
Cheakamus mainstem and two floodplain wells (i.e., in all locations where a water-level/temperature logger was installed). For grab samples, measurements were taken with a
WTW Oxi 330i meter (DO) and a WTW 320 pH and temperature meter during most visits. On two
occasions, a YSI Pro Plus meter was used for DO measurements – the first time as a quality
assurance/quality control (QA/QC) measure to have replicate measurements from different
sensors, and the second time because the WTW Oxi 330i was not available.

All wells (whether carbon steel, stainless steel, or PVC) were purged prior to taking DO, pH, and
temperature measurements.

Purging of wells is of particular importance in the carbon steel piezometers that have been in
place for almost a decade, as rusting is considerable. To better address this issue, methods for
DO collection were changed in April 2009 to improve accuracy. Data collected in 2008 involved
continuous purging of wells into a 1L plastic container with the sensor placed inside. Final
readings were recorded when DO output stabilized for approximately 10 seconds. This method
did not involve recording the volume of water purged from the well, and in April 2009 it was
observed that “stable” DO readings sometimes occurred after very little well development, but
subsequently changed again after purging more water. This observation partially explained some
of the odd DO values recorded in 2008. Methods adopted from April 2009 through the remainder
of the study required purging 3L of water from the 19mm in-stream piezometers using a peristaltic
pump. Readings of DO, pH and temperature were taken after each 1L, but the 3L value was
considered final. Spot checks were frequently done with an additional 4L or 5L development
volume to ensure that DO values were unchanged from the 3L value. The 3L volume also
corresponds to approximately three well volumes, depending on the water levels on the particular
day. For a small sub-set of the in-stream piezometers (most frequently D23 and D24), the
extremely slow recharge proved an impediment to achieving the desired purge volume: standing
water in the pipe would be purged and then would not recharge sufficiently to test within the
available sampling timeframe. DO values from these wells therefore were not obtained on some
visits.
For the larger floodplain wells in which water quality was sampled (RBCH and TEND), a submersible pump was utilized to run flowing water through a sampling container until DO, pH, and temperature readings had all stabilized. Development volume for these larger wells exceeded 100L during each visit but precise volume was not recorded.

2.3.2.2 Continuous DO and pH Logging

A three-month monitoring period was undertaken between October 22, 2009 and January 18, 2010 in which pH, DO and temperature were monitored via five automated YSI Sonde multi-parameter data loggers. A schematic of the logger setup is shown on Figure 5. Leading up to this component of the monitoring program, numerous discussions were held between PGL, SRK, BC Hydro, and Instream. Considerations into the timing and locations of the monitoring included (but were not limited to):

- Hyporheic water quality is well accepted to be closely related to egg-to-fry survival, though surface water quality is also of high management interest;
- Chum salmon may preferentially select redd locations in areas of groundwater upwelling;
- Overlapping the monitoring with as much of the chum (and to a lesser extent coho) incubation periods as possible would be advantageous when comparing against eventual egg-to-fry survival metrics;
- Upper Paradise Channel has to date not provided robust fisheries data compared to Kisutch and BC Rail Channels; and
- Budgetary constraints limited the rental of loggers to no more than the originally agreed-upon three-month periods.

The outcome of the collaborative fieldwork planning was to focus the monitoring period on November through January. Not only would this timing coincide with chum incubation, but it would also capture winter low-flow conditions punctuated by occasional fall or winter storms, which provides useful contrast in the dataset. It was decided that the five data loggers would be allocated so as to put one in a deep groundwater-monitoring location (TEND), and a surface-water/shallow groundwater pair located at good spawning habitat in both Kisutch and BC Rail Channels.

On October 22, 2009, personnel from PGL, SRK, BC Hydro, and Instream reviewed the proposed installation locations for suitability according to the criteria above. The surface water loggers were placed into 75mm-diameter PVC stilling wells, with wire-mesh screening over the submerged perforations (Figure 5). To install the groundwater loggers, pits were shovelled out to a depth of 300 to 400mm below the creek bed elevation – this depth is also consistent with standard redd depth for chum salmon (DeVries, 1997). PVC stand pipes (50mm) were then installed and backfilled so that the screened perforations (and sensor loggers) were both fully covered by creek bed material (Figure 5). Loggers were calibrated and programmed to read DO, pH, and temperature every six hours. On two follow-up field visits (November 2 and December 2, 2009), logger data were downloaded and readings compared to grab sample readings for QA/QC purposes. The loggers were removed on January 18, 2010.

An important assumption in the continuous monitoring program is that a continuously upwards hydraulic gradient exists at the groundwater-monitoring locations, such that groundwater is upwelling towards and past the sensor (Figure 5). This ensures that the buried sensors measure actual hyporheic water rather than measuring solely surface water. Part of the QA/QC field protocol included comparing DO and pH in water pumped from the buried PVC pipes to adjacent
surface water, using a hand-held meter. In the absence of an upward gradient, the two measurements would be expected to be similar.

2.3.3 Flow Transects

All flow transects utilized a standard propeller-current Swoffer flow meter. The Swoffer flow meter will register water velocity exceeding 0.01m/s, but confidence in accuracy decreases below the device’s officially reported detection limit of 0.03m/s.

Although not legally surveyed, transect locations remained for the most part the same over the three years of the study. Flow measurements at Kisutch Channel in particular used precisely the same location for every flow measurement, at a constriction in the channel 8m downstream of the staff gauge (see Figure 3), where velocity was always well above the Swoffer detection limit. At BC Rail Channel, flow measurements were also taken from the same location on each occasion, approximately 10m downstream of the staff gauge. After the winter of 2009/10, some bedload movement was evident in BC Rail Channel, possibly due to high velocities during beaver dam breaching or simply from normal spawning scour with high escapement that year. Owing to both the build-up of gravel in the original flow transect location and occasional flow velocities below the detection limit, duplicate flow measurements in BC Rail Channel were often taken at a second location 15m upstream of the staff gauge.

Flow measurements in Upper Paradise Channel were taken on 12 occasions in 2008 and 2009, but were halted in 2010. Discharge in Upper Paradise is consistent but very low, with flow velocity below the Swoffer detection limit in at least part of the cross-section during every site visit. The interim results from Upper Paradise reviewed after Year 2 identified that no statistically valid rating curve would be forthcoming. Moreover, because flow was visibly evident but not measurable with the Swoffer, the calculations that were resulting were known to be badly underestimated but not by a quantifiable amount. Prior to starting Year 3, a potential switch to an alternate type of flow meter (a Price variety) was investigated, but the velocity detection limit would have been similarly problematic. An ultrasonic Doppler flow meter would be suitable for measuring flow in Upper Paradise, but exceeded the approved budget for fieldwork in this study.

Measurements used the standard cross-sectional area-velocity method (RISC, 2009). This methodology involves dividing the width of each transect location into approximately 30 equidistant cells and recording the depth and average velocity in each. Estimated flow is then the sum product of the velocity multiplied by the area of each transect cell.

2.3.4 Water Chemistry Samples

The study Terms of Reference required a one-time collection of samples from surface water and groundwater for laboratory analysis, to compare dissolved metals and anions results to those obtained by Quinn Jordan-Knox (2003).

On January 21, 2010, the following locations were sampled:

- Three from upper BC Rail Channel (D52 and D53, and surface water);
- Three from upper Kisutch Channel (D50 and D51, and surface water);
- Two from Upper Paradise Channel (D11 and surface water);
• Two from Cheakamus River mainstem (surface water beneath the bailey bridge, plus one
duplicate sample for QA/QC);
• One from the floodplain BC Hydro well (RBCH monitoring station); and
• One blank for QA/QC purposes.

The intended scope of sampling was to also include an additional sample from D12 in the Upper
Paradise Channel, and from two other floodplain wells (R8 and R4). However, none of these
three wells were able to supply even half of the required water volume for laboratory submission.

For each sample, three bottles were collected: a 500mL amber glass vial with HNO₃ (for
dissolved metals), a 250ml plastic bottle with H₂SO₄ (nitrate and nitrite together), and a 500ml
plastic bottle without preservative (dissolved anions). Samples were preserved in a chilled cooler
overnight and delivered to CanTest Laboratories the following morning. Analytical methods
employed by CanTest are included with the results package appended to this report
(Appendix 3).

It should be noted that some thought was given to including stable isotope analysis in the water
chemistry sampling – this was in fact a preliminary recommendation in the Year 1 interim report.
After soliciting opinion from SRK geochemists, it was decided that the scale of sampling likely
required to properly characterize source waters over time (i.e., glacier fed vs. precipitation; waters
with long or short residence times in Daisy Lake), and the possibility of not being able to detect
any measurable, meaningful results from a one-time sample, did not justify the additional costs
that would be required to carry out this task. As a result, sampling was undertaken according to
the original Terms of Reference.

2.4 Database Management

After each site visit, automated logger data was backed up by PGL and transferred to SRK for
processing. In situ water levels, temperatures, DO, and pH levels were recorded by PGL on a
Microsoft Excel spreadsheet, and discharge measurements were calculated from the flow
transect data using the velocity-area method.

SRK has compiled all data collected in Monitor #6 into a Microsoft Access database. This
database is a key deliverable of the project, and CD copies will be sent to BC Hydro in the
summer of 2011, with instructional documentation for any future use of the data.

2.5 External Data

In addition to flow model results and water chemistry data collected by Jordan-Knox (2003), data
integrated into this analysis were also provided by BC Hydro and Instream, and by Water Survey
of Canada (WSC).

2.5.1 Cheakamus River Discharge

During the project duration, BC Hydro has supplied data relating to flow releases from the Daisy
Lake Dam, and flow data from the flow gauge on the Cheakamus River at Brackendale (8GA043)
operated by the WSC. These data are fundamental in the overall interpretation of the study, as it
is the response of the hydraulic parameters to the mainstem Cheakamus discharge that is of
primary interest in this study.
The final discharge dataset for Cheakamus River (08GA043 Cheakamus River near Brackendale gauge) was obtained from WSC as continuous hourly data for complete period from 2007 to January 2011. The discharge record for 2011 is preliminary unapproved data and subject to revision, and was not used in analysis, although water level and temperature monitoring at NVOS site drivepoints was terminated in February 2011. The portion of data for 2011 was not used in statistical analysis with river discharge but it is shown on time series graphs of seasonal variation.

The logger at the 08GA043 river gauge is a Valcom type which samples water level every 5 minutes and logs every 15 minutes. It also logs the maximum and minimum water level for the day. WSC calculates hourly discharge from the stage-discharge curve maintained at that location.

2.5.2 Daily Air Temperature

For statistical analysis of air temperature and its relationship to other parameters, air temperature (mean daily and hourly) was taken from the Environment Canada weather station at Squamish (station ID 10476F0, Squamish Auto – “automatic”). This weather station has a long period of record, is located a short distance from the NVOS site, and is at similar elevation and valley-bottom setting as the NVOS site.

We also examined air temperature from the Squamish Upper weather station (station ID 1047672), which is upstream of NVOS site and at a higher elevation. This station only has a daily data record and it is not as continuous as the Squamish weather station, and so is less representative of NVOS site conditions.

2.5.3 Geo-spatial Data

The external spatial datasets available for this program included:

- Digital orthophotos of Cheakamus Valley, georeferenced to UTM coordinate system, obtained from BC Hydro;
- Regional digital elevation model from Natural Resources Canada, Government of Canada;
- A site plan of NVOS and spawning channel shapes – from NVOS and BC Hydro; and
- Surficial geology, existing piezometer and drivepoint sampling locations, results and interpretations of geophysical surveys and other information relating to the previous conceptual model of the hydrogeologic flow system at NVOS [from Simon Fraser University (Jordan-Knox 2003 thesis digital files)]. This information was used as background information for conceptual model development.

2.5.4 Fisheries Data

Instream has been overseeing parallel fisheries WUP monitors in the NVOS side channels. Monitoring covering juvenile outmigration for five anadromous species (coho, chum, pink, Chinook and steelhead) commenced in 2000, whereas enumeration of escapement for chum adults began only in autumn 2007. Comprehensive details on data collection and analytical techniques are provided in the annual reports by Instream.

Fish populations – particularly for anadromous species – are notorious for requiring long time series for detecting causative environmental relationships, largely due to the complexity of the life histories involved. For evaluating potential linkages between groundwater-surface water interactions and fisheries production in the NVOS side channels, chum are a particularly useful
species to evaluate. Not only are chum known to seek out groundwater-fed redd locations, but there is no freshwater residency for fry. Therefore, if groundwater-linked effects are present, they will be comparatively more detectable for an effect on chum egg survival, though other influential factors such as predation and density-dependent effects are also relevant. Egg-to-fry survival data are available for four years in which both adult chum escapement and resultant juvenile outmigration were evaluated (Table 4). Adult escapement for side channels in the NVOS did not differentiate between the groundwater-fed portions and the surface-water fed reaches. Therefore, the most relevant data for exploration of links between fisheries data and groundwater data is BC Rail Channel, but the quality of fisheries data against which to compare flow release data will improve with additional years of fish monitoring.

Table 4: Summary of spawning and migration timing and egg-to-fry survival for chum

<table>
<thead>
<tr>
<th>Year</th>
<th>BC Rail Channel</th>
<th>NVOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spawners</td>
<td>SpawnD50</td>
</tr>
<tr>
<td>2007–2008</td>
<td>595</td>
<td>Nov 9</td>
</tr>
<tr>
<td>2008–2009</td>
<td>1,279</td>
<td>Nov 12</td>
</tr>
<tr>
<td>2009–2010</td>
<td>3,243</td>
<td>Nov 14</td>
</tr>
<tr>
<td>2010–2011</td>
<td>367</td>
<td>Nov 5</td>
</tr>
</tbody>
</table>

Data courtesy of Instream Fisheries Research Inc.

2.6 Data Limitations

Considering the extent of data collected and the duration of the study, there were relatively few logistical or technical issues with the data collected. However, some issues were encountered to place limitations on the data. A number of these were noted in preceding sections describing methods. To summarize:

- Field methods for DO grab-sample collection in Year 1 did not yield reliable results, and methods were revised for Year 2 and Year 3. DO data from 2008 in situ sampling were therefore excluded from the analysis.
- DO sensor malfunctions occurred during a small number of field days. On these dates, DO data were only obtained from a sub-set of all the monitoring locations. On October 28, 2010 the sensor malfunctioned during the second sample of the day and could not be repaired in the field; DO results on that day were limited to TEND.
- One logger stopped functioning in September 2010. The time series for water level and temperature at D51 (head of Kisutch Channel) therefore terminates approximately three months before the remaining loggers. (The logger has since been repaired and so all loggers are functional and available for future use by BC Hydro.)
- Many loggers reached memory capacity in February 2010 and were re-set in April 2010. There is therefore a data gap for continuous water level and temperature data for approximately three weeks in early 2010 (Figure 4).
• On one occasion (December 2, 2009), numerous drivepoints were frozen, making removal of the loggers (or manual measurement of water levels for that matter) impossible. However, all data collected by the loggers was downloaded during the subsequent visit.

• In June of 2009, the wire suspending the logger in D45 broke due to corrosion. The logger was retrieved, but the cap and hanger were damaged during removal. The logger was not reinstalled until the subsequent field visit in August when a replacement part was available.

• Discharge estimates from Upper Paradise Channel were badly underestimated due to water velocity consistently below the Swoffer detection limit. Flow measurements at this location were discontinued in 2010, and no rating curve was developed at the SGUP location.

• “Sensor drift” is a common issue with automated loggers, but is detectable and correctable. This correction was necessary for 2008 data but not thereafter, and is not considered to place any limitation on the water-level or temperature data.

• Upper Paradise Channel receives surface flow contributions from Sue’s Channel (fed via intake pipe from Gorbuscha Channel, which is in turn fed by a direct connection the Cheakamus River). The water level from Sue’s Channel is highly influential on water levels recorded at D24: on some occasions, surface water elevation was higher than the vent holes in the piezometers, flooding the pipes with surface water. On other occasions, surface water levels were below the vent holes but the groundwater upwelling was above those holes, meaning that upwelling groundwater drained out the holes and the logged water levels were underestimated on those occasions. Highly variable water levels in Sue’s Channel appeared to be more common in 2010, but in general the influence from Sue’s Channel puts some limitations on the accuracy of the data collected at D23/24 versus other logger locations.

• Beaver damming in BC Rail Channel in 2008 and 2009 was upstream of the logger pair in D52/53 and would have had little influence. However, in 2010 damming occurred shortly downstream of D52/53, causing surface water to frequently back up and flood the piezometers. The relative infrequency of site visits (every two months) means that it is not possible to say with certainty which high water levels recorded at D52/53 are accurate portrayals of groundwater elevation, and which are influenced by surface water flooding the piezometers.
3.0 DATA ANALYSIS METHODS

The process of data reduction and analysis included QA/QC checks and validation, assessment of trends or relationships between individual data types and river discharge, as well as comparison of spatial trends or relationships. In general, the analytical methods were developed to address the specific management questions. In some cases the scope of analysis was expanded to allow better description of the underlying physical process, in anticipation of information needs that may not have been specified explicitly in the Terms of Reference. The following points describe the general methods used:

- Raw data were compiled, reduced and QA/QC’d to provide continuous records of each measured parameter at each station.
- Hourly and daily mean values were calculated for temperature and water level.
- Plots of time series were constructed to visually explore trends and correlations. The exploratory work led to more detailed analysis where warranted.
- Trends and relationships between key parameters were assessed based on the management question guidance (e.g., side-channel water level or temperature vs. Cheakamus River discharge). The extent and type of statistical analysis done varied by parameter.
- Data derivatives, such as gradients or fluxes, were calculated using the numerical flow model and compared to previous estimates in 2003 (Jordan-Knox, 2003).
- Quantitative relationships were used to form an updated conceptual model of groundwater and surface water flow interactions between the Cheakamus River and NVOS side channels.

The following sections provide additional details on specific methods used. Additional details for more complex subtleties of the analytical methods are included in Appendix 4.

Pertinent results of the analyses described are presented in Section 4.0, with reference to more comprehensive results that are also included with the supplemental methods and results in Appendix 4.

It should be noted that with the exploratory nature of the monitoring program, the sequence of analytical methods to results as a process is not a linear step but rather an iterative one, wherein initial results inform subsequent methods to arrive at more comprehensive results and so on. The details provided below portray the general analytical approach used.

Each of the four management questions involved queries of several parameters as related to Cheakamus River flow. The type of data collected for each parameter varied and therefore where a single management question may have dealt with multiple parameters, conclusions were derived from multiple independent methods. Table 5 provides context for how the analytical methods described below relate back to the management questions of interest.
Table 5: Cross-reference of analytical methods section by management question

<table>
<thead>
<tr>
<th>Management Question</th>
<th>Analytical Methods Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. How do seasonal NVOS and TH floodplain shallow groundwater flow direction,</td>
<td>• Shallow groundwater flow direction conclusions derived from logger data (Section 3.3) and spatial analysis (Section 3.2).</td>
</tr>
<tr>
<td>temperature, DO, and pH vary in response to Cheakamus River mainstem flows ≤ 40m³/s?</td>
<td>• DO and pH conclusions were derived from bi-monthly manual sampling and the 2009 continuous monitoring trial (see Section 3.4).</td>
</tr>
<tr>
<td>2. To what extent does seasonal NVOS and TH side-channel hydrology depend on</td>
<td>• Side channel flow measurement data analysis – see Section 3.5.</td>
</tr>
<tr>
<td>groundwater flow interactions with Cheakamus River mainstem flows ≤ 40m³/s??</td>
<td></td>
</tr>
<tr>
<td>3. To what extent do key fish habitat variables related to flow (average depth,</td>
<td>• Analysis for addressing management question #1 and #2 provided requisite data for addressing question #3. See Sections 3.3, 3.4 and 3.5.</td>
</tr>
<tr>
<td>average velocity, discharge) and water quality (temperature, DO, and pH) in NVOS and</td>
<td></td>
</tr>
<tr>
<td>TH side channels depend on groundwater flow interactions with Cheakamus River</td>
<td></td>
</tr>
<tr>
<td>mainstem flows ≤ 40m³/s?</td>
<td></td>
</tr>
<tr>
<td>4. To what extent does salmonid production vary in NVOS and TH side channels in</td>
<td>• Indirect conclusions of effect on salmon production derived from conclusions about habitat characteristics.</td>
</tr>
<tr>
<td>relation to groundwater flow interactions with Cheakamus River mainstem flows ≤</td>
<td>• Exploration of direct links between groundwater levels and temperature vs. interim fisheries data (Section 3.6)</td>
</tr>
<tr>
<td>40m³/s, and to what extent has the implementation of the WUP affected salmonid</td>
<td></td>
</tr>
<tr>
<td>production in the NVOS and TH side-channel habitats compared to the pre-WUP state?</td>
<td></td>
</tr>
</tbody>
</table>

3.1 Data Quality Checks

All water-level data were graphed and examined in detail, and compared to manual water-level readings. Sudden data shifts associated with sensor repositioning were noted and the water-level record was adjusted as appropriate to fit manual measurements.

Anomalous short-duration events were observed in the record resulting from periodic sensor removal (data downloading) events and from sampling. Anomalous water levels and temperatures were filtered from the data record.
3.2 Spatial Data Processing

Using the external geo-spatial data described in Section 2.5.3, new data created to facilitate analysis included the following:

- A new digital elevation model was created of the floodplain, using all drivepoint elevations (Jordan-Knox (2003) and orthophoto (river channel and spawning channel banks, valley slopes). The river channel elevation profile was estimated as a longitudinal profile, fitted to intercept the water table map of the site. Floodplain elevation between spawning channels was estimated from interpolation between drivepoint elevations, adjusting for channel depression in the floodplain, and from field observations (used in numerical flow model and on maps of unsaturated thickness).
- Detailed digital map of spawning channels and Cheakamus River channel banks, which were digitized from the site orthophoto and verified with surveyed locations of monitoring points. In areas where tree cover obscured channels on the orthophoto, the channel banks were mapped based on site visit observations and photos.
- Digital water table maps at different times of the sampling period were created from water-level observations.
- Digital photographs of sampling locations, Cheakamus River channel, and other site details. Photograph locations were mapped.

These newly developed data are integrated into the maps included in this report and were fundamental for addressing the management questions by evaluating spatial characteristics of river-side channel connectivity. These data and related numerical groundwater flow model results (e.g., water table, contours, flow paths, fluxes) are also available in GIS format.

In this project, several maps of water levels ("water table") were created to aid interpretation of results:

- Mean water table (2008–2010 period of record), showing spawning channel network (and RBCH and TEND piezometers) at present time;
- Water table during high river discharge events (mean maximum water level calculated from three annual maximum values for years 2008, 2009, 2010);
- Water table during low river discharge (mean minimum water level calculated from three annual minimum values for years 2008, 2009, 2010); and
- Water table in 2000 during low river discharge (data from Jordan-Knox, 2003), showing spawning channel network at that time; the dataset has irregular monitoring events between July 2000 and September 2001, so the long-term mean level is not available (not representative of such short and irregular monitoring events). The low river discharge period on February 11, 2001 was selected because most monitoring points were measured on this date and the river was at a low flow of 12 m$^3$/s, which can be compared to the water table during low river discharge in the 2008–2010 period.

To complete the water table surface, and to connect the NVOS floodplain site with the BC Rail Channel on the north side of the river, the river water elevation had to be explicitly represented and combined with the water table surface. The river channel profile (see Appendix 4) was estimated from the digital elevation model and tied in with water elevation at the SGCH monitoring point. A limitation of this method is that it is not an exact profile downstream of SGCH, a reach of the river that was not surveyed. Using this river profile, the water level along the profile was adjusted by the observed variation of water level at SGCH relative to the minimum water
level at that location (the 2008–2010 minimum water table map and the February 11, 2001 low water table map use the same river profile water levels). The map of the water table is accurate only near the actual monitoring points.

The water table surface was interpolated in ArcGIS v10 (Geostatistical Analyst module). A Kriging interpolation method was used with an appropriate variogram estimate and values of surface fitting parameters to obtain a surface which is appropriate to this data type. The resulting shape and distribution of contour lines correspond with the hydrogeologic interpretation of the water-level data. The contour lines were adjusted manually to correct any interpolation problems and to match all data exactly. Contour lines were calculated at 0.25m elevation intervals.

A map of the difference between maximum and minimum water tables (based on three-year average annual statistics for the 2008–2010 period) was calculated by subtracting the two surfaces in ArcGIS (Spatial Analyst module).

Additional categorical maps were created where parameter values are represented by symbols and colours at each monitoring point location.

### 3.3 Water Level and Temperature Logger Data

The matched logger data for water temperature and level led to some similarity in how the data were processed and analyzed.

#### 3.3.1 Water Level Data Corrections

Raw and processed water-level data were compiled in an Excel spreadsheet. Prior to any analyses, raw water-level data were compensated for barometric effects using Equation 1. Note that Solinst barometric loggers convert atmospheric pressure directly to an equivalent water level (i.e., “barometric water level”), which simplifies compensation. All water levels were recorded in metres.

**Equation 1:**  
Compensated water level = Raw water level – barometric water level

Water-level data are recovered as water depth above pressure sensor. Compensated data were adjusted to elevation (metres above sea level) based on drivepoint survey information.

#### 3.3.2 Daily Mean Values

Mean daily water level and temperature values were calculated in Excel based on the arithmetic mean of hourly averages, which were calculated for 24 time periods from hour 00:00 to hour 23:00 for each day of record from 2008 to 2010. Missing values were ignored. If more than 50% of hourly data were missing for that day, the daily mean was not calculated and "no value" was reported.

#### 3.3.3 Inter-annual Water Level and Temperature Trends

The three-year linear trends in water level and water temperature were calculated using linear regression on daily average water level and water temperature, for locations with complete annual data records.
3.3.4 Seasonal Time Series

Time series plots of water level and temperature were done on hourly data in Excel spreadsheets. For efficiency, the hourly data were compressed to include only water-level points which changed by at least 3mm from the previous point. This method retains variability while decreasing the overall size of the data file.

3.3.5 Side Channel Water Level and Temperature vs. Cheakamus River Values

The time series regression was calculated using the R programming language and environment for statistical computing (The R Foundation for Statistical Computing, 2010). This includes calculation of cross-correlation function, determination of time lags between time series, descriptive statistics, and fitting a linear model between variables. The linear models were initially calculated using MS Excel 2007, as a first approximation, and the results were later compared to calculations from R language, showing that results were valid (and identical between the two software tools). Environment Canada (Hydrological Services) recommends the use of R for large time series analysis (Environment Canada, pers.comm.).

Any time series analysis usually involves several steps:

- Identifying and understanding the phenomenon represented by the sequence of measurements. In this case all variables are clearly understood (i.e., water level and water temperature).
- Trend identification and smoothing using a moving average, if necessary. The high-frequency noise component of water-level fluctuation is very important because events in data may be of short duration (e.g., high river discharge events).
- Analysis of seasonality can be done graphically or quantitatively. This involves comparing the nature of seasonal variation between different time series, computing autocorrelation correlograms and cross-correlation function correlograms (i.e., a plot of correlation coefficient at different time lags between time series pairs), seasonal means, annual means, range of variation, amplitude of variation, and phase shift (lag).
- Other analysis such as spectral analysis and plotting of periodograms.

The time series analysis methodology steps were:

1. Plot and compare time series graphs of hourly and mean daily data.
2. Plot scatterplots of pairs of variables (e.g., water temperature at D11 vs. SGCH), with the predictor variable SGCH plotted on horizontal axis.
3. Calculate differenced time series to remove auto-correlation (see Appendix 4).
4. Compute cross-correlation function (ccf) of each monitoring point temperature and water level time series and the Cheakamus River discharge and water temperature at SGCH. (In R programming language this is the ccf function).
5. From the ccf function, read the lag time between the two time series and the maximum R correlation coefficient at that lag time.
6. Remove the lag from the time series by shifting it on the time scale and display a new scatterplot. Re-compare time series graphs.
7. Investigate effects of other variables by showing third variable value (e.g., year or river discharge).

8. Determine any long-term trends in time series and compare to the expected predictor variables from Cheakamus River (SGCH). Remove anomalous known trends if it improves the linear relationship observed on scatterplots (e.g., at D23 and D45 a three-year linear trend in temperature was interpreted as anomalous and removed).

9. Compute linear regression using both the linear model and the generalized linear model.

10. Evaluate the regression statistics, the diagnostic plots of residuals (residual histogram, QQ (quantile-quantile probability distribution comparison) plot of residuals, residuals vs. predicted values, residual sequence or time, etc).

11. Display scatterplots of residuals with other variables which have a physical process basis considered to help explain any trends in linear regression residuals.

12. Lastly, other variables can be added to the model in multiple linear regression, or in step-wise linear regression if there is sufficient physical basis and a significant relationship. All modelled relationships using regression must have a strong physical process explanation that is supported by other onsite observations and hydrogeological principles.

13. The periodogram was also calculated using the fast Fourier transform function in R (see Appendix 4).

The linear regression and the statistics which evaluate the fit of the model indicated relationships between the variables, which must be explained by reasonable casual mechanisms to be valid. The \( R^2 \) (coefficient of determination) quantifies the linear model fit. The distribution of residuals indicates the quality of such model.

3.3.6 Conceptualization of Site Flow with Numerical Groundwater Flow Model

An updated, relatively simple, numerical flow model was constructed for the NVOS site as a tool for investigating the hydrogeological conceptual model and groundwater flow system. The model was implemented in FEFLOW (Wasy, 2010) and constructed at the scale of the NVOS site with high spatial resolution of all spawning channels. The model was calibrated to transient mean daily water level changes in all monitoring points used in 2008–2010, and to the observed range of spawning channel discharges. The model results provide an estimate of hydraulic conductivity for the shallow aquifer, groundwater flow paths, the fluxes of groundwater from river channel to spawning channels, and groundwater flux across the entire NVOS site, as well as providing insights into recharge and discharge dynamics. Further model description, results, and limitations are provided in Appendix 5.

3.4 Dissolved Oxygen and pH Analysis

Dissolved oxygen and pH data were collected according to nearly identical methods and timing (see Section 2.3.2).

Time series plots for both the discrete grab-sample data and the three-month continuous trial were generated for visualization and exploration of trends. Summary statistics of site-level DO were generated as a useful tool for reducing site-level variation in values.

The extent of statistical analysis differed based on potential to derive something meaningful from the data.
Grab-sample DO data were used in exploratory step-wise multiple linear regression, using mean groundwater DO at NVOS sites as the independent variable regressed against the following variables, along with log-transformed and quadratic forms, and interactions between each:

- Cheakamus River DO;
- Standard deviation of mean NVOS groundwater DO;
- Cheakamus River flow (same day);
- Cheakamus River flow (one-day lag);
- Cheakamus River flow (seven-day lag); and
- Daily air temperature (same day).

Analysis of pH data was less comprehensive since the high-level screening of the data demonstrated little to no sensitivity of this parameter by season or in relation to Cheakamus River flow.

### 3.5 Side Channel Surface Hydrology

Flow transect data were used to estimate discharge according to standard area-velocity calculations.

Discharge was plotted against staff gauge water level to develop rating curves. Rating curves were derived via linear regression in Excel. The best fit of logarithmic, linear, and power functions were chosen based on $R^2$ values, and comparison of regression coefficients for individual years was used to evaluate consistency of rating curves for the duration of the monitoring period.

Historical simulated hydrographs were created for channels in which a statistically valid fit was possible between Cheakamus River flow and the measured side-channel discharge. Historical Cheakamus River flow was subsequently used to predict historical side-channel flows via simple linear regression.

### 3.6 Groundwater Data and Fisheries Productivity

An overlap of only three years between groundwater parameters and fisheries productivity requires a largely exploratory assessment of potentially related parameters. To focus on the fisheries parameter that would provide the earliest indication of a link to groundwater parameters, analysis for direct correlation between groundwater data and fish production was conducted with a focus on egg-to-fry survival. Trends were evaluated through scatterplots and exploratory regression of egg-to-fry survival versus various winter (incubation period) flow and temperature metrics since continuous data are available for multiple years.
4.0 RESULTS

Results of data collection and analysis can be coarsely categorized as those pertaining to physical aquatic habitat quantity versus habitat quality. Habitat quantity refers to those metrics defining groundwater and surface water elevations in the NVOS area, as well as related physical habitat characteristics such as side-channel discharge. Habitat quality refers mainly to assessment of the water chemistry or temperature parameters monitored.

The results below are not presented by the sequential management questions that prompted this monitor, but rather by the categorical separation described above. These results are used to develop a conceptual model for the groundwater-surface water interactions (Section 5.1).

Discussion of conclusions for the management questions and related process-driven discussion (Section 5.2) is derived from the conceptual model and general results that precede it.

4.1 Water Levels and Groundwater Interactions

The water level in a given monitoring point depends on a complex interaction of surface water and groundwater and the type of hydraulic connection with the river. To characterize the interactions and provide results towards the management questions, water levels from all monitoring points were compared to each other and to the Cheakamus River water level and discharge variation. The connection between the river discharge and monitoring point water levels is described and quantified through time series cross-correlations and regression for the complete discharge record and for a filtered discharge record (<40m$^3$/s). An assessment of time lag between the river discharge events and the corresponding response in water levels at monitoring points is presented.

4.1.1 Description of Water Level Time Series

An initial understanding of how groundwater level at each site changes with time and in relation to other locations can be gained from a review of the time series graphical plots and summary statistics. At each monitoring point, the water-level time series has a variation of specific amplitude (variation about the mean value), range (minimum to maximum), and mean value. These summary statistics are presented in Table 6 and are shown graphically in Figure 6. Time series data for each of the three channels are overlaid with Cheakamus River water level to provide an initial illustration of synchronicity of water level trends (Figure 7 through Figure 9).

Regardless of river water level recorded in this study, the spawning channels are always wetted and flowing, generally with shallow depth (e.g., approximately 0.3m at average water levels). In this sort of channel system, the elevation of the channel bottom determines the mean drivepoint water level, whereas the specific channel hydraulics and water balance control how the water level varies around that mean value. This physical constraint of channel elevation is the key to understanding the flow system within the floodplain at NVOS site. Furthermore, just north and adjacent to the NVOS site, the Cheakamus River channel is at a higher elevation than the headwaters of spawning channels, which were excavated into existing cut-off side channels or excavated as new channels in the floodplain. Groundwater flow in this case will generally flow from the river channel to the spawning channels, and from higher elevation channels to adjacent lower elevation channels.
The water level variation is driven by hydrological events, where an event is usually a rapid change in river discharge and stage as a response to catchment wide precipitation, snowmelt, or change in water release from the Daisy Lake Dam. However, for most of the time of each year, the drivepoint water levels are near the minimum end of their respective range (see Figure 7 through Figure 9), and except during high river discharge events, the drivepoint water levels are approximately constant.

It is important to point out that the amplitude and range of variation of drivepoint water levels are in all instances (except for the TEND location) substantially less than the river water level change (as measured at SGCH). At SGCH, the river water level varies approximately 1.02m in an average year, between low flow and peak flow periods. At the spawning channel drivepoints, the typical variation of water level is between 0.17m and 0.55m (Figure 6), and the usual range is approximately 0.35m, which is about 30% of the river water level variation. Furthermore, in each spawning channel system, the range of variation generally increases downstream, so that the narrowest range is observed in channel headwater areas (groundwater inflow is the only water source), and the broadest range of water level variation is in downstream channel reaches (multiple water sources). In other words, the water level variation is cumulative, just as the channel flow is cumulative, while channel geometry remains almost constant.

As a minor exception from the general trend described above, it should be noted that the monitoring point at TEND is not part of the spawning channel system and is located uphill to the northeast of the BC Rail Channel. TEND is located near Tenderfoot Creek as well as a large pond through which the creek flows. The hatchery also pumps significant groundwater from the site to facilitate its operations. The large water level variation at TEND (1.18m in average year) is greater than of Cheakamus River stage variation and is not related to the river water level at all due to its uphill location. The only other point not located within spawning channels is RBCH, located in a small pond that is disconnected from flowing channels, but which is affected by shallow groundwater inflow and evaporation, and this point has slightly higher water level variation than any of the in-stream drivepoints at NVOS.

Visual inspections of the groundwater level time series overlaid with the Cheakamus River discharge (and water level), demonstrates the correlation between most of the drivepoints and river discharge. In each location at the NVOS site (except TEND), highs and lows in Cheakamus discharge are generally followed by a rapid rise and fall in drivepoint water level, although of much lower amplitude than the river water level rise (Figure 7 through Figure 9) (i.e., dampened). The water level recession generally follows the subsequent decline in river discharge, but the drivepoint water levels decline to pre-event levels over a longer period of time and vary between drivepoint locations. The statistical analysis of correlations of these time series is presented in Section 4.1.4 and the linear regression results in Section 4.1.5.
Table 6: Water level at monitoring points and river discharge summary statistics for period of record 2008–2010

<table>
<thead>
<tr>
<th>Channel Group</th>
<th>Station ID</th>
<th>Minimum (masl)</th>
<th>Maximum (masl)</th>
<th>Mean (masl)</th>
<th>Median (masl)</th>
<th>S.dev. (m)</th>
<th>Range of variation (max-min) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheakamus River</td>
<td>SGCH</td>
<td>54.21</td>
<td>55.22</td>
<td>54.43</td>
<td>54.36</td>
<td>0.20</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>D52</td>
<td>53.70</td>
<td>54.06</td>
<td>53.81</td>
<td>53.80</td>
<td>0.08</td>
<td>0.35</td>
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<tr>
<td></td>
<td>SGBCR</td>
<td>53.44</td>
<td>53.77</td>
<td>53.48</td>
<td>53.47</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>D55</td>
<td>52.37</td>
<td>52.91</td>
<td>52.45</td>
<td>52.43</td>
<td>0.07</td>
<td>0.54</td>
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<td>BC Rail Channel</td>
<td>D55</td>
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<td>52.43</td>
<td>0.07</td>
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<td></td>
<td>SGKIS</td>
<td>51.88</td>
<td>52.17</td>
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<td>51.90</td>
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<td>0.30</td>
</tr>
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<td></td>
<td>D50</td>
<td>52.08</td>
<td>52.33</td>
<td>52.11</td>
<td>52.10</td>
<td>0.04</td>
<td>0.26</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>D45</td>
<td>51.63</td>
<td>52.06</td>
<td>51.71</td>
<td>51.69</td>
<td>0.07</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
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<td>52.20</td>
<td>52.37</td>
<td>52.26</td>
<td>52.25</td>
<td>0.04</td>
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<tr>
<td></td>
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<td>51.73</td>
<td>52.08</td>
<td>51.80</td>
<td>51.79</td>
<td>0.05</td>
<td>0.35</td>
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<td>0.05</td>
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<tr>
<td>Paradise Channel</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D23</td>
<td>51.75</td>
<td>52.06</td>
<td>51.82</td>
<td>51.82</td>
<td>0.05</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>RBCH</td>
<td>51.88</td>
<td>52.43</td>
<td>52.01</td>
<td>52.00</td>
<td>0.07</td>
<td>0.55</td>
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<tr>
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<td>54.70</td>
<td>55.87</td>
<td>55.13</td>
<td>55.12</td>
<td>0.27</td>
<td>1.18</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coho Connector</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TEND</td>
<td>54.70</td>
<td>55.87</td>
<td>55.13</td>
<td>55.12</td>
<td>0.27</td>
<td>1.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>m³/s</th>
<th>m³/s</th>
<th>m³/s</th>
<th>m³/s</th>
<th>m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheakamus River</td>
<td>Brackendale</td>
<td>14.4</td>
<td>194.0</td>
<td>35.7</td>
<td>24.1</td>
</tr>
</tbody>
</table>

4.1.2 Spatial Variation in Water Levels

Analysis of spatial variation in water levels aids in understanding flow pathways over small geographic areas, as well as comparison of how any spatial patterns may have changed since the work done by Jordan-Knox in 2001/02.

The spatial variation of drivepoint water levels can be interpreted as the water table surface [as elevation in metres above mean sea level (masl)]. Figure 10 represents the average water table surface for the 2008–2010 monitoring period. In this case the water table represents the top of the saturated zone in an unconfined aquifer. There may be confining conditions present in floodplain areas away from channels due to the presence of a silty layer (Jordan-Knox, 2003), but the data were interpolated from in-stream monitoring points where unconfined aquifer conditions are present.

Groundwater gradients and flow directions can be inferred from the water table map. The groundwater gradient follows the river profile and general slope of the valley floor, from higher elevation to the north of the NVOS site, sloping downward towards the south. The highest water level away from the river is at TEND. At NVOS, the spawning channels follow old river channel depressions or are excavated into the floodplain sediments, and consequently the water levels are lower than the river water level. The steepest gradient is from the Cheakamus River reach upstream of the Bailey Bridge towards Dave’s Pond, and from the Cheakamus River downstream of the bridge towards the channel headwater areas. A steeper gradient also exists in the southern
part of the NVOS site as groundwater from the floodplain discharges towards the river. The groundwater flow directions are perpendicular to the contour lines on this map (Figure 10).

Results from the numerical flow model provide an alternative water table map (Figure 11). In many respects, this may be the most representative water table map because it is process-based and is calibrated to all drivepoint water levels. This map is very similar to the water table map presented in Figure 10, although there is a difference in water level at some points because the model result represents one specific time period in 2009. The model results show hydraulic head or the potentiometric surface, which is identical to the free water table in unconfined conditions. The effect of spawning channel “drains” is clearly visible in the deflection of the groundwater contours.

Flow paths of shallow groundwater derived from the numerical model are perpendicular to groundwater contours (see figures in Appendix 5). The model confirms that groundwater flow occurs from areas with higher water elevations toward areas with lower water elevations (usually the spawning channels). The river acts as both the recharge and discharge area for groundwater. The model behaviour demonstrates that physical flow processes, which are represented in the numerical model (e.g., Darcy’s Law, aquifer hydraulic properties, hydraulic gradients, boundary conditions, etc.) reproduce the observed water levels and provide more insights into the groundwater flow paths. The numerical groundwater model is thus a useful tool for helping understand the hydrogeologic system at this site.

Since the work completed in 2000–2001 by Jordan-Knox, groundwater levels appear to have risen. Consider the minimum water table map for the 2008–2010 period of record (Figure 12), which represents the annual minimum water level (averaged for three years 2008, 2009, 2010). Figure 13 compares this map to the previous water table created from 2001 water-level data by Jordan-Knox (2003). The map shown in Figure 13 is very similar to the mean water table map and the contour pattern is similar, but all water levels from the 2001 data are lower. This is not a surprising result given the changes onsite in the past decade. In 2001, the headwaters of Paradise Channel were draining a large portion of the site, and the groundwater gradients were steeper between the river and this channel. The construction of Gorbuscha Channel and piping large amounts of river water into that channel, and into Sue’s Channel, provided a large amount of recharge of groundwater to the floodplain and, as a result, the groundwater levels in the floodplain have risen. The water is spread out more evenly through a larger channel network at present time. In areas where the site has not changed since 2001, such as along BC Rail Channel, the old and new water levels are very similar.

4.1.3 Seasonal and Inter-annual Variation in Water Level

Both river discharge and stage have clear seasonality (Figure 14). The freshet period refers to the annual snowmelt event, which typically begins in March and peaks before July. The 2008 and 2009 river time series illustrate this typical freshet response. 2010 was anomalous because it had a very long peak flow period and the largest mean monthly flow occurred in August. There is usually a recession of flow (and river stage) from early summer to late autumn and a small secondary peak flow (and river stage) in November, corresponding to the late autumn rain period. The winter period has smaller mean monthly flow (and river stage) than other months of the year. An exception occurred in 2010, which had a significant peak in January due to a large rain-on-snow event.
At the channel drivepoints, some locations show the same monthly seasonal and inter-annual variation as river discharge (and stage) (e.g., D45, SGUP), although the amplitude of water level variation is much less than in the river (Figure 14). However, water levels at all of the other drivepoints do not have the same seasonal variation as the river. At D50, D11 and D55, the water-level record is too limited to allow comparison with river stage and discharge for seasonal variation (Figure 15). As previously described, TEND and D52 show the most difference with river discharge (and stage), though they are similar to each other, albeit with different amplitude of variation. TEND has very large water-level variation compared to other drivepoints. River stage during freshet does not appear to influence TEND, but there is a large peak in November–December that is interpreted to correspond to winter precipitation events, suggesting that TEND is recharged from precipitation rather than snowmelt or the river itself. For all three years of record, D52 also has a peak in November and no evidence of river freshet effect. D45 has a subdued freshet signature, and SGUP shows a freshet peak in 2010 only, a year in which the river had an anomalously large freshet discharge. At other drivepoints, the relationship with river discharge (and the dominant freshet seasonal event) is not as clear.

The data show a strong inter-annual variation of water levels (Figure 16). 2008 and 2009 show similar average river and drivepoint water levels. 2009 had, on average, lower river water level (and discharge) than 2008, but this trend is not clear in channel drivepoints. 2010 had higher river water level (and discharge) than the two preceding years by about 30%, the difference clearly observed at all drivepoints. Therefore, it can be concluded that that high river stage and discharge has more effect on channel water levels than years with lower river water levels and discharges. At TEND, the trend was reversed in 2010 (lower water level when the river had larger freshet), further supporting the conclusion that TEND is not connected to the river.

Review of water level data collected in 2000–2001 by Jordan-Knox (2003) shows that channel water levels are generally lower than the floodplain water levels (Figure 17). In addition, water-level variation is much greater in floodplain piezometers located away from spawning channels (the R-series piezometers from Jordan-Knox) as compared with channel water-level elevation. There is some scatter in the data, and a few anomalous measurements where water level has greater water level variation than the river, but this may be due to inaccurate survey elevations. The piezometers farthest from the floodplain-river margin showed either no response or only minimal response, while the piezometers closest to the river channel show the greatest increase in water levels with increased river stage. Some piezometers show delayed water-level responses.

This behaviour is consistent with a hydraulic-head response to pressure changes caused by changes in river water level (i.e., a change in gradient). Hydrogeologically, some areas may indicate the presence of confined aquifer conditions. The surficial silty gravelly sand layer on top of parts of the floodplain likely acts as a confining layer. Confined aquifers show a rapid and large response to pressure variations caused by river stage changes. In areas close to the channels, the channels act as drains and limit the water-level variation, as any excess water inflow caused by the river water-level rise results in only a small inflow of groundwater to the channel, which is drained away rapidly and, consequently, water level does not rise as much. The numerical flow model produced similar results.
4.1.4 Cross-correlation and Lag Time between Water Level and Cheakamus River Discharge Time Series

The visible similarity in hourly water-level trends was evaluated thoroughly to quantify the strength of the correlation, and more importantly to use the correlation data to estimate the time lag for a river-flow event to be translated to a groundwater change. Results indicate an unconfined aquifer in which a pressure wave induced by a river-level change is propagated to groundwater changes in a short period (e.g., a few hours).

The correlation(s) of the water-level time series with river discharge is visibly evident in Figure 7 through Figure 9. To quantify these correlations using statistical methods, the initial approach was analysis using the cross-correlation function (ccf) (see methods Section 3.3.5). This analysis was done on original hourly data and on transformed hourly data.

For the full discharge record of original hourly data, the highest correlations are observed at D45 (0.869) and D11 (0.785), both of which are located only a short distance from the Gorbuscha Channel (Table 7), which seeps water into nearby channels. The lowest correlation is observed at TEND (0.235). Note that, as would be expected, water level at SGCH has nearly perfect correlation to river discharge (Table 7). It is noted that discharge is monitored at Brackendale as compared to water level at SGCH, near the Bailey Bridge, so there is some difference in water level between these locations and, probably, slightly different stage-discharge curves. The limitation of this analysis is that channel water levels do not have a linear relationship with river discharge, particularly at low flows. The cross-correlation results on un-transformed time series data (Table 7) are strongly influenced by the high water-level “outliers” and by a large autocorrelation of the time series at long periods of low and stable water levels.

To reduce the influence of outliers on the results, the cross-correlation calculation was repeated using a transformed dataset, where data were log-transformed and offset with a 120hr lag. This transformation created appropriately linear data for regression analysis. The main purpose of offsetting time series is to remove auto-correlation, which can be particularly problematic with very narrow data recording intervals such as the water level time series used in this study. The use of 120hrs as a particular value for offsetting the time series is a result of trial and error. Any offset transformation will remove auto-correlation from time series, but if the offset time is too small, correlation analysis is dominated by noise and does not "see" hydrogeologic events. Conversely if the offset is too large, then more and more data are excluded from analysis (the amount of excluded data will equal the lag amount because one series is offset). The use of 120hrs represented a value that was not too long but long enough to include most hydrogeologic events (water level change events) which are shorter than seasonal variation.

After applying data transformation, the drivepoint water levels vary nearly linearly with river discharge (Table 7). The linear correlation coefficient (r) for the full discharge record is generally higher than for the original dataset. The highest correlation coefficients are observed for D45 (0.892) and D11 (0.835), and were above 0.7 at most locations except at TEND, SGBCR, D23 and SGKIS. These correlation results are considered the most representative of the three datasets examined.
Table 7: Linear correlation coefficient (r) between water level in monitoring stations and discharge in Cheakamus River, using original and transformed datasets.

<table>
<thead>
<tr>
<th>Channel Group</th>
<th>Station ID</th>
<th>Cross-correlation&lt;sup&gt;1&lt;/sup&gt; using original hourly drivepoint water level and Cheakamus River discharge</th>
<th>Cross-correlation of transformed water level data set and log discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time delay of river water level change to station water level change (hrs)</td>
<td>max r</td>
</tr>
<tr>
<td>Cheakamus River</td>
<td>SGCH</td>
<td>0</td>
<td>0.974</td>
</tr>
<tr>
<td></td>
<td>D52</td>
<td>1</td>
<td>0.471</td>
</tr>
<tr>
<td></td>
<td>SGBCR</td>
<td>0</td>
<td>0.675</td>
</tr>
<tr>
<td></td>
<td>D55</td>
<td>1</td>
<td>0.536</td>
</tr>
<tr>
<td>BC Rail Channel</td>
<td>D50</td>
<td>1</td>
<td>0.635</td>
</tr>
<tr>
<td></td>
<td>SGKIS</td>
<td>1</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>D45</td>
<td>1</td>
<td>0.869</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td>D50</td>
<td>1</td>
<td>0.635</td>
</tr>
<tr>
<td></td>
<td>SGKIS</td>
<td>1</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>D45</td>
<td>1</td>
<td>0.869</td>
</tr>
<tr>
<td>Paradise Channel</td>
<td>D11</td>
<td>2</td>
<td>0.785</td>
</tr>
<tr>
<td></td>
<td>SGUP</td>
<td>1</td>
<td>0.476</td>
</tr>
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<td></td>
<td>D23</td>
<td>0</td>
<td>0.481</td>
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<td>Coho Connector</td>
<td>RBCH</td>
<td>6</td>
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<td>TEND</td>
<td>TEND</td>
<td>18</td>
<td>0.234</td>
</tr>
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</table>

<sup>1</sup>Cross correlation function (ccf) using R statistical package; this is separate from regression model.

Perhaps the most informative outcome of the cross-correlation analysis of water levels among sites is that it provides the estimated time delay between a water-level change in the river and a subsequent change at a correlated side-channel drivepoint (Table 7). At most locations, the lag times between the time series were between 0 and 1 hour. With increasing distance from a side channel, the lag times increase: 6 hours at RBCH, and 18 to 21 hours at TEND. In the transformed dataset, the lag times were slightly more variable and longer, typically 1 to 3 hours, with the longest lag times at TEND (21 hours), RBCH (6 hours), and D52 (4 hours).

The important implication of the lag time estimates for water levels is that the pressure wave caused by changing river stage propagates through the aquifer to impart an effect on the groundwater level, and this process occurs over a relatively short period of a few hours. This result is indicative of an unconfined aquifer response. Because this effect is caused by a pressure wave, the lag time is not indicative of actual travel time of groundwater movement from a discharging river to recharging side channels.
4.1.5 Linear Regression Model of Water Level and River Discharge

Previous sections describe the variation of water level at monitoring points at NVOS and river discharge and showed differences in mean and range of variation, the seasonality of time series, and the existing correlation between time series. To provide statistically significant predictive models, linear regression was used after log-transforming and offsetting the original datasets as described in Section 4.1.4. In the resulting time series, the water level at a drivepoint (H) and the discharge (Q) have a linear relationship that can be analyzed using the following linear regression model (Equation 2).

**Equation 2:** \[ H = \text{coefficient} \times \log Q + \text{intercept}, \]

where:
- \( H \) = transformed water level record, where \( h(t) = h(t) - h(t-\text{offset}) \)
- \( Q \) = differenced river discharge time series, where \( q(t) = q(t) - q(t - \text{offset}) \)

In the Equation 2 notes, \( t \) is time in the time series record and the offset is 120 hours (described in Section 4.1.4, but see Appendix 4 for detailed rationale for the use of a 120-hour offset correction for time series analysis).

The linear regression analysis was done for both the full discharge record and for a subset of discharge \( \leq 40 \text{m}^3/\text{s} \). Results for both datasets are presented in Table 8, summarized graphically in Figure 18. Appendix 4 contains the statistical analysis details, bivariate graphs, graphs of residuals of regression, compared to original dataset and the transformed (differenced) dataset.

### Table 8: Linear regression model results for NVOS area water levels

<table>
<thead>
<tr>
<th>Channel Group</th>
<th>Station ID</th>
<th>Linear model of water level (H)(^1) and river discharge (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( H = \text{coefficient} \times \log Q + \text{intercept} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Full Discharge Record</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Discharge ( \leq 40 \text{m}^3/\text{s} )</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R^2 )</td>
</tr>
<tr>
<td>Cheakamus River</td>
<td>SGCH</td>
<td>0.926</td>
</tr>
<tr>
<td>BC Rail Channel</td>
<td>D52</td>
<td>0.576</td>
</tr>
<tr>
<td></td>
<td>SGBKCR</td>
<td>0.358</td>
</tr>
<tr>
<td></td>
<td>D55</td>
<td>0.437</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td>D50</td>
<td>0.556</td>
</tr>
<tr>
<td></td>
<td>SGKIS</td>
<td>0.404</td>
</tr>
<tr>
<td></td>
<td>D45</td>
<td>0.781</td>
</tr>
<tr>
<td>Paradise Channel</td>
<td>D11</td>
<td>0.683</td>
</tr>
<tr>
<td></td>
<td>D23</td>
<td>0.338</td>
</tr>
<tr>
<td></td>
<td>SGUP</td>
<td>0.346</td>
</tr>
<tr>
<td>Coho Connector</td>
<td>RBCH</td>
<td>0.467</td>
</tr>
<tr>
<td>TEND</td>
<td>TEND</td>
<td>0.262</td>
</tr>
</tbody>
</table>

\(^1\) Transformed time series by offsetting with lag of 120hrs: \( x(t) = x(t) - x(t-120hr) \); see Appendix 4.
For the full discharge record, the highest $R^2$ values from linear regression (strongest linear relationship between $H$ and $Q$) are observed at D45 (0.781), D11 (0.683) and D52 (0.576). The smallest $R^2$ is observed at TEND (0.262) (Figure 18).

For low-flow events where the river discharge is $\leq 40\text{m}^3/\text{s}$, the strongest linear relationship is at the same points but the $R^2$ values are smaller: D45 (0.753), D11 (0.553), D52 (0.492) (Figure 18). The smallest $R^2$ is again at TEND (0.119. Although the $R^2$ values are smaller with the $\leq 40\text{m}^3/\text{s}$ data, the relationships remain statistically valid. Side-channel and floodplain groundwater elevations therefore remain well correlated to low river flows, but within a rather narrow range. The difference in predicted groundwater level for river flows of $40\text{m}^3/\text{s}$ versus $20\text{m}^3/\text{s}$ in the regression models above is typically 0.02 to 0.03m.

It is interesting to note that D45 has a strong linear relation with river discharge at both high and low flows. Across all monitoring points, and unlike the result of simple cross-correlations, the linear regression $R^2$ value is very similar for both the full discharge record and low-flow discharge record (except at TEND). Appendix 4 includes graphs of typical low-flow discharge events graphed and compared for each monitoring point (water level and differenced water level compared to discharge). These graphs show the nature of this linear relationship, with most monitoring points responding to both low and high river discharge events. The relationship of water level to river discharge is thought to be based on the physical process of hydraulic gradient change and pressure wave propagation as a response to river stage change, the stage being related to discharge via the stage-discharge curve; this topic is elaborated upon in Section 4.2.

It is possible to use the regression model to forecast channel water levels based on river elevation. However, the linear functions fitted through the regression model have the following limitations and requirements:

- Results apply only to the present channel system configuration and river/channel hydraulic connection.
- Any changes in channel geometry or channel roughness, or addition of new inflow sources or channels, may change the hydraulic gradients between the river and channels, affect channel water balances, and, consequently, water-level response to river discharge.
- As long as the Cheakamus River remains within its channel (no flooding), the linear relationships should remain valid. The river water level must be above the Gorbuscha intake pipe to maintain water flow into this pipe and to maintain the present channel hydrologic system. The exact elevation of the intake pipe at the bottom of the river bed should be verified if there is a desire to use the regression model to forecast channel water levels at extremely low river discharges.

### 4.2 Surface Water Depth and Discharge

As shown in the water level analysis in the preceding section, surface water depth in the side channels is related to changes in Cheakamus River discharge. However, the actual magnitude of water-level fluctuations is minor for the moderate range of Cheakamus flows that are relevant to management of the Daisy Lake dam. The continuous water-level data collected at the three side-channel staff gauges shows water depths ranging by approximately 0.25m, compared to a range of more than 1m over the same time period at the Cheakamus River staff gauge. Based on 18 field measurements distributed evenly over three years for Upper Kisutch and BC Rail Channel, and 12 measurements over two years at Upper Paradise, staff gauge water level
readings were limited to a narrower range of variation compared to the range from the automated loggers (Figure 19 through Figure 21).

4.2.1 BC Rail Rating Curve

Flow measurements at BC Rail Channel depict a significant shift in the stage-discharge relationship when comparing data points from 2008 and 2009 to data from 2010 (Figure 19). This was consistent with field observations, which noted a slug of large gravel migrating down the channel. In March 2010, the point where the staff gauge met bottom substrate was noticeably higher than in the previous two years. It is likely that this gradual bedload movement is in part attributable to the high number of spawning chum in November and December 2009, perhaps coupled with occasionally inflated channel velocities from breaches of the beaver dam. Regardless, the slopes fitted to the rating curves for 2008 and 2009 data were not significantly different, and so two rating curves are shown in Figure 19: one for 2008/09 and one for 2010. Both rating curves depict the expected statistically significant relationship between stage and discharge, but neither curve demonstrates as strong a correlation as the Upper Kisutch results (Section 4.2.1).

BC Rail Channel is fairly uniform from the headwaters at the outlet of Dave’s Pond to the downstream confluence with the Cheakamus River. Unlike Upper Kisutch Channel, there is no constriction point where reliably high velocities were available for taking flow measurements. The confidence in the flow estimates is still reasonably good given the low magnitude, but some instances where visible flow did not register a sufficient velocity on the Swoffer is likely part of the reason for the weaker statistical regression fit compared to Kisutch Channel.

4.2.2 Upper Kisutch Rating Curve

Eighteen flow measurements were taken at the Upper Kisutch Staff Gauge (SGKC) between March 2008 and February 2011. When plotted against the commensurate staff gauge readings, the fitted rating curve was fairly strong ($R^2 = 0.7258$) with no evidence of a shift in rating curve over the three years (Figure 21). The fit is particularly good given that the measured flows occurred within a narrow range of observed stages.

The flow measurement transect for Upper Kisutch was located shortly downstream of the staff gauge in a stable, narrow constriction of the channel, allowing for relatively higher confidence in these flow measurements over the other two channels, as flow at all verticals was always greater than the Swoffer velocity detection limit of 0.03m/s.

4.2.3 Upper Paradise Rating Curve

From the study outset, difficulty was encountered with obtaining contrast in discharge estimates at Upper Paradise Channel sufficient for generation of even a preliminary rating curve. The relationship between stage and discharge was not statistically significant based on the first 12 measurements (Figure 21). Although the Upper Paradise staff gauge is far enough upstream that backwatering effects of the downstream confluence with Sue’s Channel are not expected, water velocities in Upper Paradise were almost always at or below the detection limit of the Swoffer flow meter (0.01m/s) across most cross-section verticals. On numerous occasions, it was noted during discharge measurements that flow was visible (albeit minor), yet the flow meter did not register any velocity. Given the paucity of any other useful data from parallel monitors in Upper Paradise, and the very short length of the channel that is groundwater-fed, measurements...
were halted in 2010. Future development of discharge measurements in Upper Paradise would require use of a Doppler-type acoustic flow meter.

4.2.4 Side Channel Hydrograph Predictions

The close correlation between Cheakamus River water level (as measured at SGCH) and water level at the side-channel staff gauges, and the related Cheakamus flow estimates derived from the WSC rating curve, means that it is possible to fit a relationship between Cheakamus River flow to the measured discharge estimates. Doing so allows use of Cheakamus River flow data to predict what the flows in BC Rail Channel and Upper Kisutch would be, given current connectivity.

The fitted relationships between Cheakamus River discharge and side-channel discharge for Upper Kisutch generated a good statistical fit (Figure 22). A logarithmic relationship provided the best fit to the data (p<0.001, R²=0.66).

The fitted relationship was used to simulate hydrographs and mean annual discharge for Kisutch side channel in the WUP years 2008 through 2010. For comparison, pre-WUP years were also calculated, including daily flows and mean annual discharge time series (Figure 23 and Figure 24). Note that the simulated pre-WUP flow data represent flow conditions predicted to be present on current conditions, using the historical flows. Actual river/side-channel linkages were certainly different prior to the substantial reconstruction that commenced in the 1990s, leading to inter-channel seepage and greater surface water contributions in the side channels. In other words, the simulated hydrographs do not represent what side channel flow conditions were like in past years, but do provide some useful context for what current side channel conditions would look like now if the Cheakamus River were to be regulated under historical management regimes.

BC Rail Channel did not have as good a fit as Kisutch Channel when the same methods were applied. Although statistically significant (p=0.0418), the R² value of only 0.23 does not provide sufficient accuracy in prediction to warrant the simulated hydrographs as explored for Upper Kisutch. It would have been advantageous to develop a better fit here, as doing so would render the shifting rating curve within the channel moot, since channel discharge could be estimated from Cheakamus River regardless of what staff gauge reading was taken in the channel. The poorer fit for BC Rail Channel comes from adding at least two additional sources of variability compared to Kisutch Channel data (variable influences from Dave’s Pond and the frequent beaver activity).

4.2.5 Wetted Side Channel Width

For all three side channels, results suggest that changes in discharge are driven mostly by changes in velocity rather than stage. Despite reasonably good contrast in discharge measurements at Upper Kisutch and BC Rail Channel, the wetted top width at each monitoring cross-section changes very little. Each of the channels is generally confined by steep banks, and increasing the stage consequently has little effect on wetted surface width within the range of flows observed (Figure 25).

In BC Rail Channel, where the ratio between maximum and minimum observed discharge is 18:1, the maximum to minimum ratio for stage is only 1.4:1. Conversely, the maximum to minimum ratio for average velocity in the BC Rail Channel is approximately 35:1, supporting the assertion that contrast in flow is driven by velocity rather than water elevation. A similar relationship is apparent in Kisutch Channel, whereas in larger, less attenuated rivers the stage change range is
influenced to a greater degree by changes in discharge (Table 9). The low water velocities in Upper Paradise precluded inclusion of those data for analysis as the results were not accurate. Although maximum discharge on a given day has always been at BC Rail Channel, the maximum average velocity during a flow transect was observed at Kisutch Channel, where flow transects are taken at a narrowing of the channel relative to the generally wide, flat transects in the other two channels.

Table 9: Summary of contrast observed in stage, velocity, and discharge in side channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Stage</th>
<th>Average velocity</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max (m)</td>
<td>Min (m)</td>
<td>Max/Min ratio</td>
</tr>
<tr>
<td>BC Rail Channel</td>
<td>0.362</td>
<td>0.276</td>
<td>1.31</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td>0.285</td>
<td>0.205</td>
<td>1.41</td>
</tr>
<tr>
<td>Cheakamus River*a</td>
<td>1.728</td>
<td>0.835</td>
<td>2.07</td>
</tr>
<tr>
<td>Squamish River*a</td>
<td>4.370</td>
<td>1.712</td>
<td>2.54</td>
</tr>
</tbody>
</table>

*a Computed using WSC daily flow values over the same sub-set of dates. Velocity data are not available for these rivers.

The physical quantity of side-channel habitat for juvenile salmonids (and returning spawners) is defined in simple terms by the depth and wetted area of the channel. Based on these results, both of those parameters are insensitive to low-level fluctuations in Cheakamus River discharge. To provide some context of the velocity component of discharge, the average channel velocities were compared to published Habitat Suitability Index (HSI) curves for spawning and rearing chum salmon (Hale et al, 1985). HSI models are developed based on observed fish abundances, which are used to derive HSI scores from 0 to 1. The scores can be roughly equated to the “preference” for fish to choose habitat with certain characteristics. Hale et al. (1985) predict that habitat suitability for spawning and incubation is achieved at average channel velocities from 0.12 to 0.43m/s, and that scores exceeding an HSI of 0.8 are predicted for velocity between 0.046 and 0.64m/s. A comparison of these values against the velocities calculated from BC Rail Channel and Upper Kisutch Channel shows that the 0.8 threshold is frequently not met. To better evaluate the ambient Cheakamus flow conditions during which the low-velocity flow measurements were taken, velocity is summarized against Cheakamus River flow for both channels in Table 10. Same-day values of average daily flow for Cheakamus River are used for this comparison as it was previously shown that the hydraulic reaction time for river flow to side-channel flow is within an hourly (as opposed to daily or weekly) time range. It is clear that average velocity below the 0.8 HSI threshold exists during Cheakamus River flows well over 40m³/s. The results for Upper Kisutch channel are not representative of the entire channel, as flow transects were taken at a constriction point shortly before the channel passes underneath Gorbuscha Channel. While this location was optimal for ensuring velocity across the entire channel above the Swoffer detection limit, it does require caution in generalizing channel conditions based on these velocity data.

The linear correlation between mainstem flow and side-channel velocity is very weak (R² = 0.021 and 0.017 for BC Rail and Upper Kisutch Channels, respectively), meaning that average velocity in the side channels cannot be predicted from mainstem flow, based on the data obtained in this
study. When river flow is constrained to less than 40 m$^3$/s, the regression correlation becomes even poorer ($R^2 = 0.0038$ and 0.0005 for BC Rail and Upper Kisutch Channels, respectively). These data also demonstrate the source of measurement error in the side-channel discharge estimates: whereas stage is recorded with high precision, velocity (particularly low velocities) are subject to measurement uncertainty that propagates through to discharge estimates. Some verticals within BC Rail Channel occasionally recorded flow of 0.0 m/s even though some flow was visible (but less than the detection limit), resulting in average velocity and consequently discharge along the channel margins of BC Rail Channel that was at times underestimated.

Table 10: Relationship between Cheakamus River flow and average side-channel velocity

<table>
<thead>
<tr>
<th>Date</th>
<th>Avg. Velocity (BC Rail, m/s)</th>
<th>Avg. Velocity (Kisutch, m/s)</th>
<th>Cheakamus Flow (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-Mar-08</td>
<td>0.043</td>
<td>0.193</td>
<td>18.6</td>
</tr>
<tr>
<td>27-May-08</td>
<td>0.125</td>
<td>0.236</td>
<td>129</td>
</tr>
<tr>
<td>22-Jul-08</td>
<td>0.042</td>
<td>0.135</td>
<td>35.1</td>
</tr>
<tr>
<td>30-Sep-08</td>
<td>0.007</td>
<td>0.019</td>
<td>19.2</td>
</tr>
<tr>
<td>2-Dec-08</td>
<td>0.257</td>
<td>0.347</td>
<td>21</td>
</tr>
<tr>
<td>20-Jan-09</td>
<td>0.031</td>
<td>0.373</td>
<td>19.8</td>
</tr>
<tr>
<td>7-Apr-09</td>
<td>0.096</td>
<td>0.150</td>
<td>18.7</td>
</tr>
<tr>
<td>30-Apr-09</td>
<td>0.049</td>
<td>0.150</td>
<td>19.2</td>
</tr>
<tr>
<td>15-Jun-09</td>
<td>0.048</td>
<td>0.252</td>
<td>86.8</td>
</tr>
<tr>
<td>24-Aug-09</td>
<td>0.038</td>
<td>0.153</td>
<td>41.7</td>
</tr>
<tr>
<td>2-Dec-09</td>
<td>0.071</td>
<td>0.192</td>
<td>21.625</td>
</tr>
<tr>
<td>18-Jan-10</td>
<td>0.114</td>
<td>0.235</td>
<td>35.54</td>
</tr>
<tr>
<td>9-Apr-10</td>
<td>0.043</td>
<td>0.172</td>
<td>24.105</td>
</tr>
<tr>
<td>15-Jun-10</td>
<td>0.077</td>
<td>0.200</td>
<td>81.75</td>
</tr>
<tr>
<td>20-Aug-10</td>
<td>0.042</td>
<td>0.163</td>
<td>70.64</td>
</tr>
<tr>
<td>28-Oct-10</td>
<td>0.023</td>
<td>0.152</td>
<td>24.909</td>
</tr>
<tr>
<td>9-Dec-10</td>
<td>0.045</td>
<td>0.213</td>
<td>44.7</td>
</tr>
<tr>
<td>17-Feb-11</td>
<td>0.037</td>
<td>0.188</td>
<td>20.02</td>
</tr>
</tbody>
</table>

Ultimately, “suitability” of water velocity for chum (or other species) spawning and rearing will vary by site and local conditions. Habitat that is successfully used for spawning and provides good production must by definition be considered suitable, and the limitations on applying HSI scores developed as generalized values to any particular local ecosystem should be emphasized before interpreting any water velocity as unsuitable, or even sub-optimal.
4.3 Temperature

A cursory review of time series data for temperature trends of side-channel locations versus mainstem Cheakamus shows that trends are similar, but at some monitoring locations the lag time between peaks is fairly long and variable (see Figure 26 through Figure 29). Surface water temperature in the Cheakamus River shows a greater amplitude variation than side channel or groundwater temperature, and SGCH temperature (river water) also portrays a closer temporal correlation to air temperature than the groundwater-monitoring locations.

It is an intuitive link that there would be correlation between Cheakamus River water temperature and side-channel water temperature (be it side-channel surface water or shallow groundwater) since connectivity of the aquifer has been previously identified. Cheakamus River surface water undoubtedly contributes to the shallow groundwater seepage that supplies the NVOS side channels. However, it is fundamentally important to emphasize that the lag times in temperature trends between Cheakamus River and side channel (see Figure 26 through Figure 29) are longer than the very short lag time between a change in water level in the river (SGCH) and a related change in groundwater levels (e.g., results presented in Section 4.1). The temperature lag is a more appropriate means of “tracing” groundwater flow patterns, as it is essentially equates to following a “unit” of water of a given temperature through groundwater travel processes. The water-level response is conversely a hydraulic pressure connection in which the hour-scale lag between river level and groundwater level does not represent the actual travel time for river water to discharge as shallow groundwater and emerge as effluent side-channel water.

The extensive water temperature data summarized in the time series in Figure 26 through Figure 29 were used to develop comprehensive analytical results to generalize the surface water/groundwater interaction in the study area. These results from water temperature monitoring are highly informative in creating a conceptual model for comparison to the version developed by Jordan-Knox (2003) and in addressing the management questions.

The thorough analysis of the temperature data includes identification of relative contributions of deep groundwater, shallow groundwater, and surface water. Given the nature of the analysis, a review of the practical application of heat transfer is helpful context for this topic. A review of the process characteristics of heat transfer is included in Sections 4.3.1 and 4.3.2 and is followed by results of the groundwater mixing characteristics at each site (Section 4.3.3), regression model results (Section 4.3.4), and inter-annual variability trends in temperature (Section 4.3.5).

4.3.1 Factors Affecting Stream and Hyporheic Water Temperature

Water temperature change ($\Delta T_w$) is a function of the heat transfer in a discrete volume of material and may be described in terms of changes in heat per unit volume by Equation 3:

**Equation 3:**

$$\Delta T_w \propto \Delta \text{Heat} / \text{Volume}$$

Therefore, stream temperature changes as a function of two variables:

1. Heat transfer (conduction), which refers to processes that change heat in a defined water volume. Heat exchange is highly diurnal and seasonal.
2. Mass transfer (advection), which refers to transport of heat within a volume of flowing water. Mass transfer at the small scale inside a side channel involves advection, which is altered by dispersion; hyporheic exchange is largely an advection related process. At the channel reach scale, mass transfer is linked to channel water balance (i.e., inflows and outflows of surface water, groundwater inflow). The mixing of external flows of different temperatures with stream water changes the heat of water.

Quantifying energy exchanges is intensive in equipment and time, and results are site-specific even if the sites are similar in channel size, morphology, climate, and channel bed (e.g., Evans et al, 1998). However, the water temperature itself can be used as a tracer to infer the nature of stream-aquifer interactions at many sites, including the NVOS site.

Temperature is used as a natural tracer in groundwater studies in a wide array of applications (Anderson, 2005; Constantz et al, 2007). The rate at which water moves between streams and groundwater is governed by the head gradient across the streambed and the resistance to flow within the sediments of the streambed. Groundwater temperatures could be used to determine the direction and flux rate of groundwater, and to estimate the hydraulic conductivity of sediments that form the aquifer (Stallman, 1963). In general, the differential equations for heat transfer rates and change in water heat (change in temperature) are according to Equation 4, where the conductive heat depends on the thermal conductivity of sediments and the thermal gradient toward a stream bed, and the advective heat transfer depends on groundwater flux as described by Darcy’s Law, which states that the groundwater flux is proportional to gradient and the hydraulic conductivity of the streambed sediments.

**Equation 4:**

\[
\text{conductive heat} + \text{advective heat} = \text{water heat}
\]

Where advective heat transport is dominant, for example in perennial stream channels with coarse-grained sediments below the stream bed and no clay or silt layer lining the stream bed, as is the case in most of the NVOS side channels, the effect of heat conduction is most likely small compared to advection. Heat is transported with flowing groundwater following the flow paths at different spatial scales, which include lateral flow of shallow groundwater between the Cheakamus River channel bed and banks toward the spawning channels across levees, lateral flow between river-water-fed channels such as Gorbuscha Channel and other nearby channels (e.g., Paradise, Kisutch Channels), and longer flow paths which involve longer lateral and some vertical pathways, such as upwelling and downwelling groundwater inside and along spawning channels. In other words, advective heat transfer is probably dominant, wherein water picks up heat in its source and carries it to its discharge zone (it retains its thermal seasonal variation with some modification along the way due to conductive heat).

Stream temperature dynamics are complicated by many upstream and local conditions. As applied to the NVOS site and the Cheakamus River, these are:

- The upstream river catchment thermal balance (catchment scale processes controlling river temperature upstream of the NVOS site);
- Deep groundwater temperature and variation in flow pathways, thermal gradients and aquifer properties. Groundwater is one of the important heat-balance components within NVOS spawning channels;
- Climatic variables at NVOS (i.e., air temperature, solar radiation, precipitation, wind speed, etc.):
  - For slowly flowing channel sections, there is a relatively long period of time for atmospheric heat exchanges with stream water. These processes are dominated by solar...
radiation, longwave (thermal) radiation, streambed conduction, stream/air convection, evaporation, and precipitation (Oke, 1978). Air temperature may be a strong forcing factor for surface water temperature in some parts of the study area, particularly in large shallow standing water such as Dave’s Pond, which may also stratify its water temperature.

- Effective shade (near stream vegetation, type and condition, channel morphology) is the dominant control over the rate of stream heating from solar radiation (Boyd and Kasper, 2003). The NVOS spawning channels are all highly shaded and the direct solar radiation is limited during most of the year.
- Ground surface properties, ground temperature variation, factors affecting shallow groundwater recharge and recharged water temperature.

- Stream flow and thermal balance:
  - Hydrologic balance of stream reach including all natural flows and also artificial discharge augmentation and withdrawals. At the NVOS spawning channels, the hydrologic balance is dominated by artificial flow augmentation (e.g., Gorbuscha intake), hyporheic flows, and groundwater discharge.
  - The heat balance is most likely dominated by mass transfer, similar to a hydrologic balance.
  - Channel morphology and geometry, sedimentation, and other processes that affect stream flow. This includes debris in channels, beaver dam occurrence and artificial modification of channels.

4.3.2 Diurnal and Seasonal Temperature Variation Background

Groundwater temperatures generally are more stable than surface water temperatures, and the comparison of time-series measurements of sediment temperature and water temperature represents a valuable tool for identifying regions of diffuse groundwater inflow or outflow relative to surface waters (Silliman and Booth, 1993). Temperature profiles in the surficial zone potentially provide information about seasonal recharge/discharge events from precipitation and interchange with surface water (Anderson, 2005). The amplitude of temperature fluctuations decreases with depth; below approximately 1.5 metres, temperatures are not significantly influenced by diurnal fluctuations at the land surface. Seasonal variations in groundwater temperature are minimal below about 10 metres depth. So, the fact that seasonal variation is still observed in the deep groundwater-monitoring stations indicates that there is still some mixing with shallow groundwater or with river water.

Temperature measurements in gaining (upwelling groundwater) stream channel beds show very low diurnal temperature variation and the water temperature has only the longer frequency seasonal variation of groundwater temperature. In losing (downwelling groundwater) stream bed sections, the stream water is advected into the shallow aquifer and the temperature measurements in sediments below stream bed show much larger diurnal temperature variation. At the NVOS site, the sediments underlying the spawning channels are of high hydraulic conductivity and at shallow sediment depths where the groundwater drivepoints are installed, the temperature records are very sensitive to direction of groundwater flow.

4.3.3 Temperature as a Proxy for Determining Relative Groundwater Source Contributions

There were two general types of response in monitoring locations to temperature variation, depending on direction of hyporheic exchange between side-channel surface water and groundwater in the underlying aquifer: 1) groundwater heat dominated, and 2) mixed groundwater and surface water heat influences. By comparing the seasonal trends in extremes of the
temperature data, it is possible to provide some characterization of the relative contributions of these components at the micro-habitat level.

4.3.3.1 NVOS Sites Dominated by Groundwater Heat

Groundwater heat controls the temperature at five locations: D52, TEND, SGUP, D45, and D23. (Note that where paired loggers were in place, only one of the two was used for characterizing temperature relationships.) Temperatures at these locations have low seasonal amplitude variation (Figure 26 through Figure 29), which is typical of groundwater seasonal temperature variation, and there is little or no diurnal temperature variation, with some occasional multi-day scale events due to temporary hyporheic flow reversals during high river discharge events (e.g., at D45).

Mean winter water temperature is one of the best descriptive statistics for assessing the effects of groundwater input (Figure 30a). During winter, the mean water temperature is much higher in areas with deep groundwater upwelling because groundwater annual temperature is relatively stable and is not affected by cold winter temperatures at the discharge zone:

- D52, D23, SGUP, and TEND have the highest winter temperatures with relatively small inter-annual differences (D52 and TEND have the strongest deep groundwater temperature thermal control on observed data).
- SGBCR and D55 also largely showed groundwater thermal control during winter.

The mean summer temperature (Figure 30b) is also a useful statistic although not as much so as the winter water temperature. These groundwater heat-dominated sites have the lowest summer temperature:

- D23 shows a very low amplitude temperature variation during the whole year, has a slightly bi-modal seasonal distribution, has a similarly cold temperature during the summer as other groundwater discharge areas, but its winter temperature is 1°C colder than other groundwater discharge areas. It is possible that D23 has the deepest groundwater discharge due to some particular hydrostratigraphic unit properties in that area.

The difference between the mean summer and mean winter water temperature (Figure 31) shows the average range of temperature variation over the year, and clearly distinguishes the groundwater-controlled points from surface-water-controlled points. Again, the points showing the greatest influence from groundwater are D23, D52, TEND, D45:

- The seasonal temperature time series at these points has a long phase shift (of peak temperature) relative to river or air temperature, also very indicative of significant travel time (up to 82 days at D52) from a groundwater recharge source.
- D23 has a bimodal distribution and the lowest seasonal variation amplitude, which is not easily explained at this time.

No systematic spatial pattern exists for the monitoring sites dominated by groundwater versus those with greater influence from surface water mixing.
### 4.3.3.2 NVOS Sites Dominated by Mixed Groundwater and Surface Water Heat

Surface water and shallow groundwater connection to surface water appear to control the temperature at most drivepoints at these locations: RBCH, D11, D50, SGBCR, D55, and SGKIS (Figure 31). Each of these locations has a different amplitude of variation, different lag time to Cheakamus River water temperature, and a different amount of diurnal temperature variation:

- SGKIS, D45 and RBCH have a mixed thermal control, with some effects due to groundwater temperature and shallow groundwater flow that is affected by river temperature or air temperature (especially in case of RBCH).
- The coldest winter temperatures are at D50 and D11, which appear to be affected by shallow groundwater inflow from the river or a river-fed flowing channel and show similar temperatures to river temperature.
- D50, which is located in a small shallow and very slowly flowing headwater area of Kisutch Channel, is also affected by air temperature because mean winter water temperature there is actually colder than river temperature in 2009 and 2010. Cooling by air temperature is the only explanation to achieve water temperature colder than river temperature, which is usually the coldest flowing surface water body at this site.
- D11 and D50 have high amplitude of seasonal variation in temperature, similar to the Cheakamus River, but there is no diurnal temperature variation indicating both are recharged by lateral or shallow upwelling of groundwater which is directly recharged by the river (or by nearest flowing surface water channel).
- D11 is only separated from flowing Gorbuscha Channel by approximately 10m of floodplain deposits, which visibly seep water into Paradise Channel at the D11 location. The temperature lag time relative to the river is 15 days, which agrees with the short travel path and the expected groundwater flow velocity in this type of sediment.
- RBCH is located near a shallow water pond, which will have its own local water budget (evaporation and groundwater recharge probably dominating). The groundwater source is most likely shallow groundwater flow between Sue’s Channel and the Coho Connector Channel and Paradise Channel. The temperature variation is most likely due to energy exchanges between pond water and the atmosphere and solar radiation heating in summer. Winter temperatures are colder than average groundwater temperature.

With respect to annual range of temperature variation, points such as SGUP, SGBCR, D55, and SGKIS are groundwater-influenced points but with seasonal surface water (or air temperature) effects. The most seasonally variable water temperatures are at D50, D11 and RBCH, all of which are much more influenced by shallow groundwater flow that is affected by river water temperature and also probably by air temperature (especially at RBCH, and possibly at D50 as determined from looking at winter mean temperatures).

The Cheakamus River has a much higher seasonal temperature range than any of the drivepoints, and air temperature has the greatest range of seasonal temperature variation (refer to Figure 26 through Figure 29). The river temperature integrates inputs from the entire river catchment. A comprehensive model showing relative catchment-level contributions to river temperature is well beyond the scope of this report, but it is important to emphasize that Cheakamus flow itself is extremely unlikely to be a dominant variable for determining river temperature except at extremely low flows below what is observed in any of the past or present water use regimes.
4.3.4 Temperature Linear Regression Model

The linear regression and the statistics which evaluate the fit of the model indicated relationships between the variables, which must be explained by reasonable casual mechanisms to be valid. The mechanism of heat transfer is mostly through advection of groundwater or by flow of surface water and mixing with groundwater and downwelling at some monitoring points, resulting in a simple linear regression model using river temperature (at SGCH) as the primary independent variable. Adveotive heat flux will likely dominate because of the high permeability of aquifer materials and relatively rapid groundwater flow, and, to a lesser extent, by heat conduction (heat exchange between groundwaters flowing nearby but having different temperatures). At some locations, such as RBCH and in parts of Kisutch Channel (and also in Dave’s Pond), where water is mostly stagnant and slowly moving, atmospheric heat exchanges can also be integral in the heat budget.

The R² (coefficient of determination) values are listed in Table 11 and presented graphically in Figure 32. These statistics evaluate the regression model fit. At most of the monitoring points, the R² is considered to be high, indicating a strong linear relationship of drivepoint water temperature and river temperature – but again note that river temperature was not in turn statistically correlated to river discharge. The highest R² value is at D11 (R² = 0.957), a value so high that the two time series are essentially identical, despite small amplitude and mean temperature differences. The difference in amplitude is accounted for by the coefficient value (“the slope”) of the linear model, while the difference of the mean of the water temperature time series between D11 and SGCH is accounted for by the intercept coefficient (shift of mean magnitude of the temperature time series). The linear coefficient shows the difference in temperature amplitude variation between individual sites and the Cheakamus River, which has the largest water temperature amplitude of variation of all natural water bodies monitored at the NVOS site, and water temperature.

At six of the monitoring points the R² value between water temperature and Cheakamus River water temperature (at SGCH) is above 0.9, which means highly linear and significant relationship. At points which have suspected groundwater discharge zones, the seasonal variation of water temperature is visibly different on the time series graphs, and this also becomes apparent in the lower R² statistics, smaller coefficient, and greater intercept values in the linear model, indicating a weaker relationship with river water temperature.

The regression summary data (Table 11) also show the extent by which the time series at individual monitoring sites needed to be offset in order to achieve the best model fit. This offset, or lag time, can be construed as the travel time for groundwater, whether it travels over a very short distance from the Cheakamus River through the NVOS dykes or is longer-retention groundwater with more complex travel patterns. With the exception of the Upper Paradise staff gauge, there is a marked difference in the length of travel time for surface water loggers versus those in shallow groundwater drivepoints (note that D55, which was installed in June 2009, is merely a stilling well and is not embedded below the channel substrate).

The lag time for shallow groundwater (i.e., hyporheic zone water) varies considerably, but in all cases is several days, and in one case more than two months. Conversely, the surface water loggers (SGBCR, SGKIS and D55) demonstrate lag times of less than 12 hours. Notwithstanding the considerable variability among sites for the lag time, the days-to-weeks time for groundwater drivepoints is an important result for considering whether higher hydraulic head may be able to influence groundwater temperature by decreasing the travel time through a short distance of aquifer. Any influence of hydraulic head on the travel time to these monitoring points will not be
significant, and as a result the temperature-regulating processes of groundwater flowpaths remain unchanged.

Table 11: Linear regression results and temperature lag time for predicting drivepoint water temperature based on river water temperature

| Channel Group | Station ID | Cross-correlation with SGCH on hourly temperature | Cross-correlation with SGCH on mean daily temperature | Linear model of transformed data at monitoring drivepoint: 
T = coefficient * T<sub>SGCH</sub> + intercept |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lag (days)</td>
<td>max r</td>
<td>lag (days) +/- 0.5</td>
<td>max r</td>
</tr>
<tr>
<td>BC Rail Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D52</td>
<td>74.3</td>
<td>0.831</td>
<td>82</td>
<td>0.862</td>
</tr>
<tr>
<td>SGBCR</td>
<td>1</td>
<td>0.931</td>
<td>0</td>
<td>0.927</td>
</tr>
<tr>
<td>D55</td>
<td>0.0</td>
<td>0.947</td>
<td>0</td>
<td>0.953</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D50</td>
<td>8.8</td>
<td>0.915</td>
<td>9</td>
<td>0.932</td>
</tr>
<tr>
<td>SGKIS</td>
<td>0</td>
<td>0.966</td>
<td>0</td>
<td>0.966</td>
</tr>
<tr>
<td>D45</td>
<td>22.9</td>
<td>0.767</td>
<td>22</td>
<td>0.773</td>
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<td>Paradise Channel</td>
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</tr>
<tr>
<td>D11</td>
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<td>0.924</td>
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<td>0.947</td>
</tr>
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<td>2</td>
<td>0.479</td>
</tr>
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<td>SGUP</td>
<td>29.2</td>
<td>0.870</td>
<td>29</td>
<td>0.865</td>
</tr>
<tr>
<td>Coho Connector</td>
<td>RBCH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>0.934</td>
<td>5</td>
<td>0.943</td>
</tr>
<tr>
<td>TEND</td>
<td>TEND</td>
<td>N/A</td>
<td>61</td>
<td>0.884</td>
</tr>
</tbody>
</table>

For the surface water monitoring points, the shorter time lag (i.e., travel time) is likely an outcome of higher relative contribution of air temperature to the heat budget, as well as direct seepage of surface water through the NVOS dykes (which can be directly observed in several areas but would have no bearing on data collected in groundwater drivepoints).

4.3.5 Inter-annual Temperature Variation at NVOS

There are inter-annual trends in all temperature records at the NVOS site. Table 12 provides a summary of these trends. The controlling variables for side-channel surface water or shallow groundwater temperature are Cheakamus River temperature and local air temperature, and both have a slight increasing trend from 2008 to 2010, during the monitoring period. This trend may be non-linear but it can be approximated with a linear model with a linear (slope) coefficient of approximately 0.001°C/day, which corresponds to almost 1°C over the three-year monitoring period. The annual minimum temperature increases and seems to dominate this trend, while the annual maximum temperature does not increase. In other words, the winter temperatures were increasing from 2008 to 2010. The inter-annual trends were incorporated into the linear models
through regression of time series between the drivepoint water temperature and river water temperature (see previous section).

At most drivepoint locations, the same linear trend is observed as for river and air temperature. At D55, D50 and D11 there were not enough data to assess long-term trends. Two points were anomalous (D45 and D23) in that the trend was reversed. This is not interpreted as instrument drift because both sensors in the pairs (D45/D46 and D23/D24) showed the same trend. A comparison of the three years (see Appendix 4 for graphical illustration) shows that there is no consistent temperature shift over the whole year, but that the wavelength of the seasonal variation appears to be changing (summer and winter season length and phase of peak and minimum temperature may be shifting).

In the Cheakamus River (SGCH) the year 2009 has colder winter and warmer summer temperatures. However, this inter-annual variation is not always seen at groundwater drivepoints. TEND has the same consistent inter-annual variation as the river and air temperature. Other points do not. TEND is the only drivepoint that is not affected by shallow groundwater exchange with the Cheakamus River because it is located above the floodplain and away from the river and is most likely recharged by precipitation and water from nearby surface water, both water sources mostly likely controlled by seasonal air temperature variation.

Table 12: Inter-annual variation summary table for water temperature

<table>
<thead>
<tr>
<th>Channel Group</th>
<th>Station ID</th>
<th>Linear trend coefficient (°C/day)</th>
<th>Annual Mean</th>
<th>Annual Maximum</th>
<th>Annual Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheakamus River</td>
<td>SGCH</td>
<td>0.0011</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td></td>
<td>D52</td>
<td>0.0009</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td></td>
<td>SGBCR</td>
<td>0.0005</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td></td>
<td>D55</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
</tr>
<tr>
<td>BC Rail Channel</td>
<td>D50</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
</tr>
<tr>
<td>Kisutch Channel</td>
<td>SGKIS</td>
<td>0.0015</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td></td>
<td>D45</td>
<td>-0.0008</td>
<td>decrease</td>
<td>decrease</td>
<td>#N/A</td>
</tr>
<tr>
<td></td>
<td>D46</td>
<td>-0.0004</td>
<td>decrease</td>
<td>decrease</td>
<td>#N/A</td>
</tr>
<tr>
<td>Paradise Channel</td>
<td>D11</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
<td>#N/A</td>
</tr>
<tr>
<td></td>
<td>SGUP</td>
<td>0.0013</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td></td>
<td>D23</td>
<td>-0.0009</td>
<td>decrease</td>
<td>decrease</td>
<td>decrease</td>
</tr>
<tr>
<td></td>
<td>D24</td>
<td>-0.0014</td>
<td>decrease</td>
<td>decrease</td>
<td>decrease</td>
</tr>
<tr>
<td>Coho Connector</td>
<td>RBCH</td>
<td>0.0014</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td>TEND</td>
<td>TEND</td>
<td>0.0006</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
<tr>
<td>Weather station air temperature</td>
<td>Squamish</td>
<td>0.0020</td>
<td>increase</td>
<td>increase</td>
<td>increase</td>
</tr>
</tbody>
</table>
4.3.5.1 Summary

The extensive temperature data collected in the NVOS area between 2008 and 2011 revealed a number of informative results that help to refine previous conceptual models of the groundwater-surface water linkages. For instance:

- The linear regression model shows that river temperature (and to a lesser extent air temperature) coupled with an appropriate time lag can be used to predict water temperature at a fine spatial scale.
- The temperature of side-channel surface water or groundwater can be used as a tracer for estimating travel time of short-residence groundwater.
- Considerable variability in time lag among sites with little spatial separation demonstrates the complexity of underlying sediments and consequently groundwater mixing paths.
- The lag time, which can be equated to travel time of water from river to monitoring location, varies from days to weeks (and in some cases months) for shallow groundwater drivepoints. Higher river flows may have some effect on reducing the travel time but it would be inconsequential (e.g., effect would be minutes or hours measured against days or weeks).
- In addition to using regression model to formulate predictive relationships for groundwater temperature from river temperature, temperature magnitude and variability at the site level can be used to infer the relative contributions of deep groundwater control versus shallow groundwater mixing.
- A small but statistically significant increasing trend in river temperature, air temperature, and groundwater temperature was noted for the years 2008 to 2010. The causal factor(s) driving this trend are not related to Cheakamus River flow.

In general, the results demonstrate that shallow groundwater supplying the NVOS side channels is correlated to factors other than river discharge – most notably Cheakamus River water temperature and air temperature. Cheakamus River temperature at SGCH is in turn also correlated to air temperature (Figure 33), and likely a number of other catchment-scale influences that are beyond the scope of this report. However, river discharge between 15m$^3$/s and 40m$^3$/s does not have a statistically or biologically meaningful effect on the temperature of the Cheakamus River.

4.3.6 Dissolved Oxygen

The overall study methods for data collection were described in Section 2.3.2. Sixteen field samples for DO were obtained from 11 locations, approximately every other month between January 2008 and January 2011. Of the 11 locations, five were obtained from in-stream nested pairs of drivepoints (e.g., in these locations, two hyporheic water samples were obtained from the paired deep-shallow piezometers); four were obtained from surface water stations; and two were obtained from floodplain groundwater wells (see Figure 3). Additionally, over a three-month period starting in October 2009, DO was logged every 15 minutes at three locations (two of which had one logger in the hyporheic zone and one in side-channel surface water; see Figure 5). Oxygen probe malfunctions on some visits resulted in only partial coverage of the 16 samples during some visits, and the unreliability of the 2008 data led to their being dropped from analysis.
4.3.6.1 Field Sample Results

In all cases, DO in Cheakamus River was higher than any of the side-channel surface water or hyporheic water sampled. This is an expected result; atmospheric exposure and relatively turbulent flow of river water will keep it well aerated versus water which has been subject to microbial oxygen consumption through groundwater pathways. Also common to all three side channels is a generally parallel trend in DO over time at all locations.

Two-year time series for each of these locations were plotted, with the results of Cheakamus River DO overlaid on each plot (Figure 34 through Figure 36). For all three side channels monitored, the relative relationships amongst samples within the same channel were quite consistent. For instance, in BC Rail Channel, the paired loggers at D52/53 were similar in DO but consistently higher than D54, and all three of these hyporheic water samples were lower in DO than BC Rail surface water (Figure 34). To generalize, given inherent variability in DO, the magnitude of separation for DO values between sites is fairly consistent and cases where lines cross in Figure 34 through Figure 36 are infrequent; crossing lines indicate a switch in the relative DO relationship between sites within a channel. In most cases where lines do cross it can be attributed to the normal range of variation for the DO sensor and/or minor variation for sites with roughly similar DO concentrations.

Results from the two floodplain groundwater wells portray anoxic conditions, particularly in TEND (Figure 37). This is not a surprising result, as the travel time for groundwater movement to these stations was shown in the temperature tracer analysis to be quite long. TEND is the only station that can be accurately characterized as deep groundwater, not hyporheic water, and would be subject to more extensive microbial DO consumption. Results at RBCH are lower than most of the other monitoring stations but do follow the similar seasonal pattern and trend-matching to mainstem river DO values.

4.3.6.1.1 Analytical Results

The time series plots from the discrete DO grab samples makes it quite clear that Cheakamus River DO is highly correlated to DO levels of the groundwater (hyporheic water) wells in the side channels. To reduce the data noise stemming from inter-site variability, an average value of all groundwater DO samples for each sample day was calculated (Table 13). This analysis excluded the surface water results and the results from the two floodplain wells, in TEND and RBCH. The usefulness of trying to predict DO in hyporheic water at a microhabitat level is questionable: it might be possible to draw some conclusions at the individual sites that were monitored, but given the inter-site variability, it would be inappropriate to extrapolate that to any particular habitat area that was not being specifically monitored. Given the resource management focus of the WUP, a more appropriate approach is to focus on the question of how Cheakamus River flow affects DO conditions in the NVOS channels as a whole. Therefore, use of the average DO from all of the groundwater wells in side channels eliminates some of the noise in the analysis and also focuses in on the system-level spatial aspect.
Table 13: Summary of discrete groundwater DO grab samples from side-channel sites

<table>
<thead>
<tr>
<th>Date</th>
<th>Cheakamus River DO (mg/L)</th>
<th>Average Groundwater DO (mg/L)</th>
<th>Groundwater DO σ</th>
<th>Cheakamus River Flow (m³/s, same day)</th>
<th>Cheakamus Flow (m³/s, 1 day lag)</th>
<th>Cheakamus River Flow (m³/s, 7 day lag)</th>
<th>Daily Air Temp (°C)a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 30/09</td>
<td>8.8</td>
<td>3.14</td>
<td>2.33</td>
<td>19.2</td>
<td>19.2</td>
<td>19.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Jun 15/09</td>
<td>6.75</td>
<td>2.91</td>
<td>0.21</td>
<td>86.8</td>
<td>91.7</td>
<td>77.6</td>
<td>17.2</td>
</tr>
<tr>
<td>Aug 24/09</td>
<td>9.55</td>
<td>3.89</td>
<td>2.1</td>
<td>41.7</td>
<td>40.9</td>
<td>41.3</td>
<td>15.7</td>
</tr>
<tr>
<td>Dec 8/09</td>
<td>8.75</td>
<td>3.59</td>
<td>1.88</td>
<td>17.9</td>
<td>18.8</td>
<td>18.7</td>
<td>-4.0</td>
</tr>
<tr>
<td>Jan 21/10</td>
<td>12.25</td>
<td>6.27</td>
<td>2.61</td>
<td>22.1</td>
<td>25.9</td>
<td>36.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Apr 21/10</td>
<td>12.96</td>
<td>5.4</td>
<td>2.8</td>
<td>24.0</td>
<td>28.3</td>
<td>24.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Jun 15/10</td>
<td>11.7</td>
<td>6.15</td>
<td>2.55</td>
<td>83.2</td>
<td>88.8</td>
<td>73.3</td>
<td>12.7</td>
</tr>
<tr>
<td>Aug 20/10</td>
<td>10.33</td>
<td>3.45</td>
<td>1.55</td>
<td>74.7</td>
<td>56.8</td>
<td>81.0</td>
<td>14.8</td>
</tr>
<tr>
<td>Dec 9/10</td>
<td>12.3</td>
<td>5.49</td>
<td>3.1</td>
<td>47.7</td>
<td>50.4</td>
<td>27.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Feb 17/10</td>
<td>12.95</td>
<td>4.88</td>
<td>3.03</td>
<td>99.9</td>
<td>98.2</td>
<td>106.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

a Obtained from Environment Canada air temperature data from Squamish, BC

The summary data of groundwater DO compared to Cheakamus River DO make the correlation that was apparent in the time series plots more obvious. Figure 38 plots the averaged groundwater DO values in time series, with Cheakamus River and RBCH DO values also included. All three lines follow very similar trends, and the magnitude of DO concentration decreases from Cheakamus River to in-channel groundwater to floodplain groundwater as represented by RBCH.

Given the well-established connection between Cheakamus River surface water and NVOS groundwater, it is reasonable to expect that the comparable results between Cheakamus DO and groundwater DO are causative, as opposed to just correlated. A simple linear regression of average NVOS DO as predicted by Cheakamus DO measured on the same day reveals a strong statistical relationship ($R^2=0.7631$; see Figure 40). The previous temperature-based assessment of groundwater travel time from the mainstem of the river to upwelling to side channels may suggest that these results are counter-intuitive: if the travel time is on the order of weeks to even months in some cases, it should not be expected that the DO in groundwater should be so well correlated to DO in the mainstem on the same day, but rather should be correlated to mainstem DO many days previous. However the broad sampling interval for these data (two months or more) will tend to centralize longer-duration processes. While DO measured in Cheakamus River on a given day may not be a good proxy for DO two months previous, it likely is a reasonable proxy for DO one or two weeks previous, if mainstem DO follows a typical seasonally driven pattern with lesser reliance on daily DO changes from fluctuating flow turbulence.

Demonstrating strong evidence for a causal relationship between DO in the Cheakamus mainstem and NVOS groundwater does not directly address the question of management interest for the WUP, which is whether or not Cheakamus River low flow (not DO) is influential on groundwater DO. The fact that groundwater DO is in all cases lower than mainstem DO is not surprising, but as a working hypothesis, it may be that the magnitude of the decrease from mainstem DO to groundwater DO changes as mainstem flow decreases. An alternative causal
mechanism may be that managed low flows in the Cheakamus River decrease the river's DO, though given the atmospheric processes that drive river DO, this would be highly implausible unless flows were reduced to extremely low values.

To expand the analysis to include other potentially influential variables for groundwater DO, stepwise multiple linear regression was carried out using each of the variables shown in Table 13, along with their log-transformed and quadratic-transformed values, and interaction terms between each of the variables.

Adding any untransformed or transformed version of Cheakamus flow (regardless of which time lag is used) and an interaction term between flow and mainstem DO and/or air temperature as potential predictors in a multiple linear regression did not yield any significant results other than just mainstem DO (e.g., Table 14). Removing the insignificant predictors (and their derivatives) from Table 13 and using only Cheakamus DO as an independent variable yields an improvement in the example shown in Table 14 (final model adjusted $R^2=0.689$; p-value = 0.0018; 8 d.f).

Table 14: Sample regression output for NVOS DO as related to Cheakamus River parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.3610</td>
<td>1.73</td>
<td>-0.208</td>
<td>0.83932</td>
</tr>
<tr>
<td>Cheakamus DO</td>
<td>0.443</td>
<td>0.139</td>
<td>3.173</td>
<td>0.0099</td>
</tr>
<tr>
<td>Cheakamus Flow (7 day lag)</td>
<td>-0.039</td>
<td>0.041</td>
<td>-0.963</td>
<td>0.3582</td>
</tr>
<tr>
<td>Air temperature</td>
<td>0.006</td>
<td>0.0086</td>
<td>0.711</td>
<td>0.49355</td>
</tr>
</tbody>
</table>

Residual Standard Error: 0.7586 on 6 degrees of freedom

Multiple R-squared: 0.7614 , adjusted R-squared: 0.642

F-statistic 6.381 on 3 and 6 degrees of freedom; p-value 0.02693

The results show that average DO in the side channels is well correlated to the DO in the Cheakamus River, but unrelated to the discharge, based on the flow ranges experienced by the bi-monthly sampling. River discharge could conceivably influence DO but only at extremely low values if aeration or temperature of river water became affected. Therefore, based on these data, one cannot say that the strength of the correlation between mainstem DO and groundwater DO is flow-dependent. This evidence supports the suggestion that the WUP flows are not affecting DO availability in the side channels. The main limitation on the use of these data is that there are relatively few data points (n=10; Table 13).
4.3.6.2 Continuous DO Monitoring

The continuous DO monitoring trial provided a different perspective by observing trends in a finer temporal scale than the bi-monthly program could provide.

Loggers were installed as pairs in surface water and hyporheic water in BC Rail Channel and Upper Kisutch Channel, and as a single deep groundwater station at TEND, from October 22 2009 to January 18 2010. The three-month time series showing DO values at all five loggers, as well as Cheakamus River water level (as a proxy for flow), is plotted in Figure 40.

A number of interesting trends emerge from the three-month time series. Firstly, the DO measured in the surface water of BC Rail Channel was by far the most variable, and also had the lowest DO values aside from the deep groundwater at TEND. The second most variable results were obtained at the other surface water logger, KDOS. Greater hour-by-hour variability in surface water DO versus groundwater or hyporheic water DO is not surprising, as surface water is more prone to atmospheric effects that may aerate water through physical stirring, increased water velocity, etc. Surface water is also subject to biological oxygen demand that may fluctuate on a daily or sub-daily time scale. The very large fluctuations in DO at the BC Rail surface water logger are likely attributable at least in part to similar fluctuations in biological oxygen demand. Repeated beaver damming in Dave’s Pond upstream from BCRDOS occurred throughout the monitoring period, with the fisheries crew from Instream breaching the dam multiple times per week for returning spawners (C. Melville, pers. comm.). Increasing retention time of already stagnant water in Dave’s Pond would have the effect of decreasing DO of water flowing downstream to BCRDOS, whereas every breach of the dam would lead to a short-term rush of more aerated water. Similarly, the high abundance of chum spawners observed in BC Rail Channel in 2009/10 (Troffe et al., 2010) would have alternating effects of aerating water through redd excavation, and depleting DO through microbial consumption of the salmon carcasses.

A second apparent trend in the three-month time series is a general and gradual increase in DO concentration occurs at the four loggers in Upper Kisutch / BC Rail Channel, though not at TEND. This may be a seasonal trend as lower water temperatures into the winter lead to higher oxygen solubility in cooler water.

Finally, for low and moderate flows the DO measured at the five loggers appears to behave independently of Cheakamus River water level. However, the same cannot be said for very high flow events where the water level exceeds 54.8 to 55.0masl. When storm flow peaks occur, a consistent pattern can be observed at most or all of the four in-stream loggers wherein DO concentration initially responds by decreasing by 0.5 to 1mg/L, and then rebounds to either pre-storm levels or in a smaller number of cases demonstrates a brief increase (e.g., the January 14, 2010 event). This visually apparent correlation between Cheakamus River flow (at least for high flows) and side-channel DO is contrary to the results that were shown for the bi-monthly sampling, when no correlation between side-channel DO and river flow was obtained. It also presents a relationship that may at first appear to run contrary to the conceptual model of travel time demonstrated by the temperature data, since the high-flow event response suggests that aerated river water may be “flushing” through groundwater very quickly.

To provide a more detailed perspective on the nature of the hyporheic water DO response to high flows, the graphical time series is shortened to six discrete events over the three-month period where one or more DO sensors portrayed the typical response trend to a high Cheakamus flow (Figure 41 through Figure 44). On October 31, 2009 a heavy rain-on-snow event led to peak flow
conditions across the South Coast, with the Cheakamus River at Brackendale peaking at 182 m$^3$/s (Figure 41). To varying degrees, four of the five DO loggers show a response within 6 to 18 hours of a small decrease in DO concentration. For TEND and Kisutch surface water and groundwater, the subsequent rebound in DO concentration results in higher values than existed before the storm event. A storm event of much smaller magnitude on November 9 resulted in Cheakamus River flow peaking at 72 m$^3$/s (Figure 42). There is no discernable effect on side-channel or groundwater DO except for a transient decrease by 0.75 mg/L at BC Rail groundwater (BCRD Ogre), approximately 24 hours after the storm event. This was the smallest flow for which a detectable decrease in DO occurred at any of the five DO loggers. Between November 14 and 17, three more rain-on-snow events in the alpine drainage led to Cheakamus River flows exceeding 110 m$^3$/s, and on each occasion the characteristic decrease in DO occurred at the Kisutch groundwater logger (Figure 43). The same pattern is only seen at the BC Rail groundwater logger on the November 14 event, and is not clearly present at either of the surface water loggers. The three-month monitoring trial was fortunate to capture a very large storm flow event on January 13–14, 2010, in which Cheakamus River flows peaked at nearly 350 m$^3$/s (Figure 44). This very large event led to a measurable decrease in DO concentration at all four of the in-stream loggers, and perhaps more importantly led to an overall increase in DO for the days that followed, compared to pre-storm concentrations. The time series does not extend past January 18, but the increase in DO appears to be transient over the three- to four-day period, with groundwater DO trending back to pre-storm levels.

The above results can be interpreted in terms of the groundwater travel time model developed from the water temperature data. Those data supported the hypothesis that while surface water from Cheakamus River no doubt contributes to the groundwater upwelling into NVOS, the actual travel time for any physical “packet” of water from the mainstem through to upwelling is on the order of days to weeks, depending on the side-channel location. As Cheakamus River flows increase, the physical head pressure increases the velocity of groundwater, but not by an amount that could decrease the overall travel time by multiple days. Therefore, even during very high flows like the 350 m$^3$/s experienced on January 14, it would not be expected that aerated river water would move through groundwater processes quickly enough to directly supply higher DO water to NVOS on the approximately four-hour time scale observed in Figure 44. Similarly, direct movement of aerated river water to NVOS channels during storm events would not explain the characteristic decrease in DO that first occurs.

To interpret the observed process, consider first that DO measured at any of the four in-stream loggers is a mixture of side-channel surface water (e.g., supplied from groundwater but flowing via surface for some distance upstream of the logger), or groundwater that is upwelling in the immediate vicinity of the logger. The relative proportion of these two components will differ for the paired loggers: dominant surface water component in the BCRDOS or KDOS loggers, and higher groundwater component in BCRDOG or KDOG, both of which were buried to chum redd depth of >0.3 m (see Figure 5). When short-term peak flows occur, the overall travel time of groundwater from river to NVOS does not significantly change, but the hydraulic pressure effect is nearly immediate. This pressure change will lead to an increase in pressure gradient, e.g., increase in groundwater upwelling velocity, for a duration matching the peak flow event. The magnitude of the change in groundwater velocity will be commensurate with the size of the peak flow event. With a short-term increase in groundwater upwelling, so too will come an increase in the relative proportion of the groundwater component for DO measured at the surface water loggers, and even more so for the two sub-surface loggers. This would explain why the initial response from peak flow events is to see a decrease in DO in NVOS. This also explains why it is only for the very large flow events that the surface water loggers also demonstrate a decrease in DO, as this effect would take a greater change in contributions from “new” groundwater relative to the side-channel surface water flow.
Subsequent increases in DO to levels greater than pre-storm events are apparently infrequent and require an extremely high storm event such as the one that occurred on January 14. Rather than direct contributions of aerated river water entering the side channels extremely quickly, this increase is likely driven by physical processes within side-channel surface water that becomes more aerated with the higher velocity and likely heavy precipitation as well. In other words, given sufficient hydraulic pressure from river storm flows, side-channel surface water accumulate atmospheric oxygen more readily, and the higher water levels in the side channels during particularly extreme flow events may also increase the depth of horizontal mixing gradients in the hyporheic zone, thereby increasing the relative proportion of surface water to groundwater. This will cause higher DO in the two monitoring locations KDOG and BCRDOG, in which the overall gradient is upwelling but some mixing of surface water through horizontal gradients is also present.

One shortcoming in the continuous DO data collected is that there was not a matching logger recording DO in the Cheakamus River. While it is a reasonable assumption that high storm flows in the river lead to some increase in DO in the river from greater flow turbulence, it would have been interesting to compare the magnitude of DO fluctuations observed in the side channels to what occurs in the river. However, the trends observed in the continuous data are consistent with the physical process model derived from the temperature data.

The results suggest that DO in the NVOS side channels is driven by DO in the Cheakamus River, but the actual flow in the river is for the most part inconsequential except for very high values. Very high values refer to flows large enough to effect short-term changes in the upwelling pressure of lower-DO groundwater. While the effect on DO of these events is fairly small in magnitude and possibly inconsequential for a >4month incubation period, the process may be more important as a flushing flow that aides in removing metabolic waste and replacing nutrients in interstitial gravel spaces. Very low flow events may also cause a change in side-channel DO, but not within the range of flows observed in this study. “Very low” values would need to be low enough to allow oxygen depletion to occur in the river through stagnating water.

4.3.7 pH

Monitoring for pH generally mirrored exactly monitoring for DO in location and methods. The only differences in datasets for pH versus DO arise from instrument error at various times, which may have rendered data for one parameter at a particular site or day invalid when the other parameter was recorded accurately.

4.3.7.1 Field Sample Results

The three-year time series resulting from bi-monthly pH measurements at locations in BC Rail Channel, Kisutch Channel, Upper Paradise, and the two floodplain groundwater wells are depicted in Figure 45 through Figure 48. Results demonstrate minimal and independent variability among sites, with pH valued typically between 6 and 8. The lack of any spatial pattern or trend in pH was also reported by Jordan-Knox (2003). It is also likely that some of the variability is in fact measurement error from different units of the WTW 320 pH device rather than actual pH fluctuations.

4.3.7.2 Continuous Monitoring Results

Results for pH collected at five loggers on 15-minute increments between October 22, 2009 and January 18, 2010 are plotted along with Cheakamus River water levels in Figure 49. The lack of any contrast in the data for the four in-stream paired loggers is indicative of a stable pH environment regardless of the very large range of fluctuations in Cheakamus River flow.
conditions. Less expected results were observed at the TEND monitoring well, where pH did in fact fluctuate between 8 and 9, and in two cases (December 24 2009 and January 14 2010) the upwards fluctuations coincided with high flow events. Detailed analysis was not taken out for interpreting the potential process link between Cheakamus River flow and groundwater pH in a location as distant as TEND, nor was exploratory analysis as to whether concurrent regional weather processes may be involved.

Both the grab-sampling data and the continuous-monitoring data demonstrated that pH in the NVOS groundwater and side-channel surface water remains within an acceptable range for aquatic life (as defined by BC Water Quality Guidelines) regardless of Cheakamus River discharge.

4.3.8 Dissolved Metals and Anions

Laboratory results for dissolved metals and anions are appended to this report (Appendix 3). Most analytes tested were below the detection limit, and similarity between samples was quite high.

When measured against the BC Water Quality Guidelines for Aquatic Life (www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html), results indicated that no values exceed guideline thresholds, except one high result for zinc. Station D50, at the upper end of Kisutch Channel, had a measured zinc concentration of 250μg/L, compared to the guideline value of 31μg/L. No other sampling locations showed an elevated zinc concentration even close to this value (the next highest was 5μg/L). Our initial assessment is that this is an artefact, be it by corrosion of the piezometer or some other process. Several retests for at least zinc would likely be required to assess this data anomaly.

The blank samples (distilled water) and the duplicate samples of surface water taken from Cheakamus River showed no problems with chemical data quality.

Four of the locations where samples were obtained coincided with sample locations used by Jordan-Knox (2003). Sites D11 (Upper Paradise groundwater), KCSG (Kisutch Channel surface water), UPSG (Upper Paradise surface water), and CHSG (Cheakamus River surface water) all demonstrate very similar values in 2010 samples compared to the 2000 data, with a few exceptions (Table 15). The chloride results in 2010 were elevated in every sample. While this may ultimately be moot as the values remained well below aquatic threshold guidelines, it should also be noted that even the “blank” sample reported chloride concentration of 1.15mg/L, and so the results are likely biased high. Aluminum (D11, UPSG, CHSG), copper (D11), iron (D11) and manganese (D11) were the only other analytes for which more than a nominal difference was found in at least one of the 2010 samples compared to a decade previous.

Aluminum is the only metal for which a noteworthy decrease was noted at more than one location when comparing 2010 and 2000 data. The difference in aluminum as measured by a pooled-variance two sample t-test is not significant (p-value 0.328), but the statistical power of such a test is very low with such a sample size. Concentration of aluminum ions in water can be driven by acid-base chemistry and lower Al^{3+} can be indicative of reduced acidity, however none of the results suggest that there has been any meaningful change in local pH. This said, the dataset is too small to correlate with other factors with any reliability.
Table 15: Summary of dissolved metal and anion data collected in 2000 and 2010

| Parameter                      | Units     | D11       | KCSG       | UPSG       | CHSG       | D52       | D53       | BCRSG      | D50       | D51       | RBCH      |
|--------------------------------|-----------|-----------|------------|------------|------------|-----------|-----------|------------|-----------|-----------|-----------|-----------|
| **General**                    |           |           |            |            |            |           |           |            |           |           |           |           |
| Chloride (Cl)                  | mg/L      | 1.200     | 2.500      | 1.300      | 2.000      | 1.200     | 2.48      | 2.37       | 2.410     | 2.970     | 2.380     | 2.340     | 20.300    |
| Fluoride (F)                   | mg/L      | 0.030     | <0.05      | 0.040      | <0.05      | 0.030     | <0.05     | 0.040      | <0.05     | <0.05     | <0.05     | <0.05     | <0.05     |
| Sulphate (SO4)                 | mg/L      | 3.900     | 3.880      | 4.700      | 3.440      | 4.400     | 3.410     | 4.700      | 3.36      | 3.88      | 3.990     | 4.180     | 3.710     | 0.910     |
| Nitrogen, Nitrate as N         | mg/L      | 0.075     | 0.060      | 0.076      | 0.030      | 0.091     | 0.040     | 0.057      | 0.01      | 0.02      | 0.010     | 0.020     | 0.030     | 0.020     | <0.01     |
| Calc NO3-                      | mg/L      | 0.332     | NA         | 0.336      | NA         | 0.403     | NA        | 0.252      | NA        | NA        | NA        | NA        | NA        | NA        |
| Nitrogen, Nitrite as N         | mg/L      | NA        | <0.002     | NA         | <0.002     | NA        | <0.002    | <0.002     | <0.002    | <0.002    | <0.002    | <0.002    | <0.002    | <0.002    |
| **Metals**                     |           |           |            |            |            |           |           |            |           |           |           |           |
| Hardness, Total diss           | mg CaCO3/L| 17.800    | 19.000     | 22.800     | 19.000     | 17.800    | 19.000    | 18.500     | 21.000    | 21.000    | 19.000    | 19.000    | 18.000    | 28.000    |
| Aluminium (Al)                 | mg/L      | 0.010     | <0.005     | 0.020      | 0.017      | 0.045     | 0.009     | 0.210      | 0.05      | 0.023     | 0.026     | 0.009     | 0.013     | 0.017     | 0.014     |
| Barium (Ba)                    | mg/L      | 0.006     | 0.008      | 0.008      | 0.006      | 0.004     | 0.005     | 0.014      | 0.015     | 0.015     | 0.013     | 0.008     | 0.008     | 0.022     |
| Calcium (Ca)                   | mg/L      | 6.000     | 6.760      | 7.900      | 6.270      | 6.200     | 6.510     | 6.500      | 6.58      | 7.25      | 7.34      | 7.34      | 6.56      | 6.27      | 8.120     |
| Copper (Cu)                    | mg/L      | 0.002     | <0.0005    | 0.001      | 0.001      | 0.001     | 0.001     | 0.001      | 0.0006    | 0.0012    | 0.0018    | 0.0009    | 0.0011    | 0.001     | 0.002     |
| Iron (Fe)                      | mg/L      | 0.160     | 0.380      | 0.005      | <0.05      | NA        | <0.05     | 0.019      | <0.06     | <0.05     | <0.05     | <0.05     | <0.05     | <0.05     | <0.05     |
| Lead (Pb)                      | mg/L      | 0.000     | <0.00025   | NA         | 0.000      | NA        | <0.00025  | NA         | <0.00025  | <0.00025  | <0.00025  | <0.00025  | <0.00025  | <0.00025  |
| Magnesium (Mg)                 | mg/L      | 0.500     | 0.550      | 0.700      | 0.530      | 0.500     | 0.550     | 0.500      | 0.52      | 0.6       | 0.59      | 0.57      | 0.53      | 0.51      | 1.810     |
| Manganese (Mn)                 | mg/L      | 0.027     | 0.007      | 0.002      | <0.0005    | 0.001     | <0.0005   | NA         | 0.0015    | 0.0005    | 0.0008    | 0.0023    | 0.0009    | <0.0005   | 0.002     |
| Phosphorus (P)                 | mg/L      | NA        | <0.075     | NA         | <0.075     | NA        | <0.075    | NA         | <0.075    | <0.075    | <0.075    | <0.075    | <0.075    | <0.075    | <0.075    |
| Potassium (K)                  | mg/L      | 0.900     | 0.650      | 0.800      | 0.640      | 0.700     | 0.650     | 0.600      | 0.53      | 0.75      | 0.83      | 0.71      | 0.71      | 0.63      | 0.880     |
| Silicon (Si)                   | mg/L      | 2.900     | 3.900      | 4.640      | 4.000      | 3.100     | 3.900     | 3.170      | 3.6       | 5.6       | 4.8       | 3.9       | 3.6       | 7.400     |
| Silicon (SiO2)                 | mg/L      | 6.206     | NA         | 9.930      | 6.634      | NA        | 6.784     | NA         | NA        | NA        | NA        | NA        | NA        | NA        | NA        |
| Sodium (Na)                    | mg/L      | 1.600     | 2.160      | 1.800      | 2.260      | 1.400     | 2.160     | 1.600      | 2.37      | 2.61      | 2.73      | 2.85      | 2.29      | 2.05      | 9.210     |
| Strontium (Sr)                 | mg/L      | 0.043     | 0.041      | 0.053      | 0.042      | 0.045     | 0.040     | 0.049      | 0.041     | 0.045     | 0.047     | 0.043     | 0.04     | 0.039     | 0.052     |
| Sulfur (S)                     | mg/L      | 1.680     | <5         | 1.830      | <5         | 1.680     | <5        | 1.790      | <5        | <5        | <5        | <5        | <5        | <5        | <5        |
| Titanium (Ti)                  | mg/L      | NA        | <0.01      | 0.002      | <0.001     | NA        | <0.001    | <0.001     | <0.001    | <0.001    | <0.001    | <0.001    | <0.001    | <0.001    | <0.001    |
| Zinc (Zn)                      | mg/L      | 0.009     | <0.005     | 0.011      | <0.005     | 0.003     | <0.005    | <0.005     | <0.005    | <0.005    | <0.005    | <0.005    | 0.25      | 0.005     | <0.005    |
4.4 Fish Productivity

The preceding analysis of physical links between Daisy Lake releases (e.g., Cheakamus River flow) and groundwater and side channel parameters demonstrated that within the management-relevant flow range, water quality parameters were for practical purposes unrelated to the discharge in the river. That is, the current WUP flows in the river do not appear to have a relationship with upwelling groundwater temperature, pH, or dissolved oxygen. These parameters are generally understood to influence the survival of eggs in gravel. In the absence of a link between river flow and these parameters, investigations of habitat quality versus egg survival become somewhat peripheral to the management outcomes of the monitoring, but temperature data were included as a potential predictor nonetheless, given the abundance of data. Temperatures were not logged in groundwater for the full 2007 through 2011 period that covers the four years of incubation periods, but January temperature data are available for each egg-to-fry survival year. Mean, low, and high temperature metrics were therefore calculated using only January data.

River discharge was established previously to be strongly correlated to small-scale changes in groundwater elevation, and so water elevation data were initially included as an independent variable in exploratory regression. Average, high, and low flow groundwater metrics through the critical incubation period were calculated as mean, 90th, and 10th percentile water level values in a representative BC Rail channel site (D52), for the period from November 1 to March 15 of each incubation season. The variance of water level in this same period was also calculated. However, the four years of egg-to-fry survival data extended beyond the range of groundwater monitoring on both ends of the time series, meaning that use of logger data only overlaps fully with two of the four years of egg to fry survival. November and December 2007 and early 2011 water-level data at D52 were not captured. Conversely, time series data for Cheakamus River flow are available for the full mid-2007 through mid-2011 period and so river flow was also used as a proxy for groundwater elevation. Ultimately it is the managed river flow that is being investigated as a potentially influential master variable on egg survival, and so it may be a more powerful predictor if it captures other linkage pathways to side channel habitat other than groundwater elevation. The suite of predictors investigated for egg-to-fry survival in BC Rail Channel were therefore chosen as shown in Table 16. With such a small sample size, only small combinations of parameters were used to avoid over-parameterizing the model.

Table 16: Exploratory variables for linkages to BC Rail egg-to-fry survival

<table>
<thead>
<tr>
<th>Spawning Year</th>
<th>E2F&lt;sub&gt;BCR&lt;/sub&gt;</th>
<th># Spawners</th>
<th>Cheakamus River</th>
<th>BC Rail (D52)</th>
<th>BC Rail (Staff Gauge)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q&lt;sub&gt;mean&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Q&lt;sub&gt;90&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Q&lt;sub&gt;10&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2007</td>
<td>24.5</td>
<td>595</td>
<td>23.48</td>
<td>39.8</td>
<td>14.2</td>
</tr>
<tr>
<td>2008</td>
<td>17.6</td>
<td>1279</td>
<td>22.246</td>
<td>29.9</td>
<td>15.5</td>
</tr>
<tr>
<td>2009</td>
<td>7.3</td>
<td>3243</td>
<td>29.877</td>
<td>44.7</td>
<td>17.6</td>
</tr>
<tr>
<td>2010</td>
<td>4.5</td>
<td>367</td>
<td>25.358</td>
<td>43.9</td>
<td>15.2</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data calculated for November 1–March 15 of incubation year.
<sup>b</sup>Calculated from January 1–31 of incubation year.
<sup>c</sup>Calculated from November 1–December 31 of incubation year.
<sup>d</sup>Calculated from January 1–March 15 of incubation year.
A clear downward trend is evident in the egg-to-fry survival in BC Rail Channel for the four years monitored – decreasing from 24.5% for eggs deposited in November 2007 to just 4.5% for eggs deposited in November 2010. Over the first three years the trend correlates well with increased spawner abundance, which approximately doubled over the first three years. Such correlated trends are suggestive of density-dependent effects wherein competition for redd space, disturbance of existing redds, and higher metabolic demands of incubating eggs leads to a lower proportion of eggs surviving to juvenile fish. However, the most recent data from 2010 breaks the initial trend quite dramatically, with the lowest number of spawners also producing the lowest egg-to-fry survival rate.

Exploratory plots suggest no link to egg-to-fry survival for most of the potentially influential variables collected in the groundwater monitor. Mean Cheakamus River discharge, 90th percentile discharge and 10th percentile discharge (Figure 50) during the incubation period show fairly little contrast over the four years of egg-to-fry survival. A warming trend in temperature data is evident (Figure 51), but there is no statistically significant correlation between mean January temperature and egg-to-fry survival (p=0.499).

The variable that is statistically correlated to egg-to-fry survival over the four years is the fluctuations in groundwater level during incubation period, represented by the variance of mean daily water levels at D52 (p=0.029 in a simple linear regression; Figure 52). It is interesting to note of logger data from BC Rail groundwater (D52), BC Rail Surface water (SGCH), Kisutch Channel groundwater (D51) and Cheakamus River water, that only D52 does NOT follow closely the variance pattern of the river (Figure 53). For all four loggers, water levels fluctuate increasingly over winters staring in 2008 through 2009 (the winter of 2009/10 was particularly stormy), but whereas variance decreases in the other three loggers for winter starting in 2010, it continues to increase at D52. The increasing variance in winter daily water levels at D52 is likely attributable at least in part to the heavy influence of beaver activity in this channel. No clear explanation is evident as to why the surface water staff gauge in BC Rail would not show a similar trend. Excessive fluctuation in groundwater elevation may be indicative of generally unstable flow conditions in the channel stemming from local disturbance, and this may play a causal role in why egg survival in BC Rail channel appears to have been waning over the four years of monitoring.

To give some context to the isolated egg-to-fry survival data in BC Rail channel, the same metric was also estimated by Instream for the entire NVOS complex. These estimates pool together fish from channels that are exclusively groundwater fed and those that are supplemented with direct surface water off-take, but in comparison with the BC Rail Channel data, the four year time series of survival for the entire NVOS demonstrates a sharp increase for 2010 spawners (Figure 54). The NVOS egg-to-fry survival for all four years are consistent with a density-dependent effect: an inverse relationship between number of spawners and the proportion of successful eggs. The same general relationship exists for the first three years of BC Rail Channel data.
5.0 DISCUSSION

The results of the various parameters monitored were used to develop a refined conceptual model of the groundwater-surface water interaction process. The conceptual model provides considerable clarity in explaining some results that may appear to at first be inconsistent, and further provides a basis for providing answers to the management questions. The discussion below first integrates the results presented into a summary of this process model, and then interprets these results in the context of the management questions.

5.1 Conceptual Model

The three-year monitoring program provided means to update the conceptual understanding of groundwater-surface water flow patterns in the area, building upon previous work by Jordan-Knox (2003). The conceptual model described herein integrates the results presented thus far and summarizes the refinements to previous models.

5.1.1 Site History and Implications for Hydrogeology

In the past 100 years, the Cheakamus River channel has changed its position significantly. At one time it flowed across the existing NVOS site (Marmorek and Parnell, 2002). Figure 55 shows the history of recent changes in channel plan form of the Cheakamus River near the NVOS site. In 1947, prior to dyking, the river was a high energy mountain river with a braided planform. The Daisy Lake Dam was constructed in 1957, followed by construction of river dykes in the 1960s along the lower Cheakamus River to prevent flooding. The NVOS site was developed in the 1980s. In 1982, Upper Paradise Channel was constructed to restore floodplain off-channel salmonid spawning habitat and in 1994, the Kisutch Channel was constructed to improve coho (*O. kisutch*) rearing habitat (Jordan-Knox, 2003).

Prior to dyking, the natural river side channels (not in present form) in the NVOS floodplain were often dry except for high-water periods. After dyking, these natural channels became disconnected from the main Cheakamus River channel and dried due to local water table lowering (Jordan-Knox, 2003). Before the new spawning channels were constructed at NVOS, the natural gradient would be determined by river geometry and with some mounding of groundwater inputs from direct sources due to recharge and inflow from valley sides (from the west side at this site). The water table was probably close to ground surface, depressed by natural channels and topographic lows, which acted as natural drains.

Most of the spawning channels follow former natural channels which were improved for fish habitat. Variation in surficial geology characteristics and, hence, aquifer characteristics, may have a preferred orientation (anisotropy), related to the former meandering river channels. The resulting hyporheic exchanges of river water and groundwater within spawning channels are likely controlled sediment-type variation related to the historic depositional environment.

In this type of fluvial setting, a dominant groundwater mechanism will be that of a “flow-through-system” between meandering river channel sections, where shallow groundwater flow within a river meander is driven by river channel elevation differences. A deeper, longer, groundwater flow pathway into the floodplain is possible due to the river channel flowing around the site, but this pathway would likely be near the middle of the floodplain and it may mix with the shallow groundwater originating in the nearby river channel. In most side-channel headwaters areas, the shallow groundwater inflow should dominate because of the driving hydraulic gradient from the river channel.
The new spawning channels were excavated into this floodplain until water was intercepted and flowing. At that time, once channels were excavated, the flow system “within” the river meander floodplain changed because more and deeper groundwater drains were introduced. This would have led to a lowering of the water table to the new channel bed elevations and a steepening of hydraulic gradients between the river and the nearest channels, until a new equilibrium was attained; something that probably occurred very quickly. Groundwater discharges into these channels because they are excavated into the floodplain with channel beds at a lower elevation than the Cheakamus River on the northern side of the site. However, most of the groundwater flux could probably be considered a shallow river-aquifer interaction, with either lateral flow or shallow groundwater upwelling into spawning channels: surface water infiltrating along the river channel bed and discharging into lower elevation spawning channels due to the resultant hydraulic gradient.

5.1.2 Groundwater-Surface Water Interactions at NVOS

The hyporheic zone is the mixing zone of surface water with groundwater. The intermixing can occur at the surface of stream beds and other surface water bodies, and also within the shallow sediments, as surface water travels as shallow groundwater flow and mixes with deeper groundwater. As a result, different groundwater types can exit into a stream bed to mix with flowing surface water (Winter et al, 1998).

River and stream channel geometry is very important in establishing groundwater gradients. All natural rivers and streams that are connected to high permeability aquifers have complex sequences of interactions with groundwater, often termed as: gaining, losing, flow-through, and parallel-flow stream reaches or sections (Winter et al, 1998).

In general, the flow, transport, and exchange of groundwater, nutrients, and oxygen in the fluvial plain is controlled by the following factors (Woessner, 2000):

1. The distribution and magnitude of hydraulic conductivities within the channels and fluvial plain sediments (referred to as aquifer heterogeneity or variability in aquifer hydraulic properties, which depend on the distribution of types of sediments);
2. The geometry and position of the stream channel within the fluvial plain; over a long time period this is also a dynamic process, which is often modified by engineered controls such as dykes; and
3. The relation of river stage (water level) to the adjacent groundwater gradients; this is the time-dependent dynamic process of changing hydraulic gradients and shallow groundwater flow to and from a river channel into a nearby floodplain.

Groundwater flow in an unconfined aquifer occurs from areas of high elevation (high hydraulic head) to areas with lower elevations (lower hydraulic head). The geometry and elevations of surface channels and river channel essentially control most of the shallow groundwater gradients and flow system at the NVOS site. Sediment heterogeneity and hydraulic head distribution produce intricate exchange patterns of surface and groundwater.
There are various spatial scales of groundwater-surface water interaction:

1. River valley or regional scale (this concerns deep groundwater flow in valley aquifers, some of which upwell at NVOS site); this includes the entire Cheakamus River channel and the underlying sediments, morphology of bedrock valley walls, geology of site, etc.

2. Reach scale (flow between Cheakamus River channel sections across floodplain sediments and channels which lie inside a river channel meander; flow between spawning channels as shallow groundwater flow).

3. Channel scale (flow inside spawning channels, local upwelling and downwelling of groundwater, channel profile and geometry, riffle-pool sequences, side and back channel effects).

4. Channel feature scale (flow around logs, boulders in channel bed).

The shallow groundwater monitoring points for this study are local sample points in a large space, and each point is affected differently by the various scales of groundwater-surface water interactions. This sample is probably adequate for the size of this site, heterogeneity of sediments and complexity of surface channels, although the actual variability in space of surface-groundwater interactions is likely larger than observed (e.g., patterns of upwelling/downwelling, shallow groundwater pathways, aquifer heterogeneity under the floodplain). The interpretation of monitoring results from last three years must be related to the site hydrogeologic conceptual model, which describes the physical processes that occur at this site and explains the hydrogeologic and hydrologic observations and all data collected.

In broad terms, data collected in 2008 through 2010 portray a floodplain system which is hydraulically connected to mainstem Cheakamus flows above and below 40m$^3$/s. However, the degree of connectivity is spatially and temporally variable, indicating a complex hyporheic zone with variable substrate composition. It is important to distinguish between the hydraulic connectivity between the river and NVOS channels, and actual travel time of river water that contributes to groundwater upwelling in the channels. This distinction provides the basis for the very short-duration lag between river water levels and the long lag observed for correlation between river temperature and groundwater temperature.

5.1.3 Hydrostratigraphic Units

The existing conceptual model of the subsurface sediments, and their hydraulic properties, was developed by Jordan-Knox (2003). The NVOS site is located within an alluvial zone between the Cheakamus canyon and Cheekye Fan, and a bedrock ridge. The NVOS spawning channels are located within a coarse-grained (sand and gravel) alluvial and fluvial sediment valley infill, deposited into a granitic bedrock valley. A detailed Quaternary geologic history of the site is presented by Jordan-Knox (2003).

The original valley fill hydrostratigraphic units developed by Jordan-Knox (2003) were compiled from borehole logs, test pits, and geophysical surveys. The coarse-grained sediment package has a thickness of at least 40m and was grouped into five generalized units based on expected hydraulic properties:

1. Silty fine sand (thin surficial cover of floodplain at NVOS site).

2. Silty, sandy cobble-gravel with boulders (aquifer unit present under NVOS site) – aquifer unit below NVOS site.
3. Sandy, boulder-gravel (north of NVOS site and present deeper below NVOS site) – aquifer unit.
4. Gravelly diamict – Cheekye Fan deposits (few km south of NVOS site) – aquitard unit (lower permeability expected).
5. Granitic/granodioritic bedrock (valley walls) – aquitard unit (low permeability).

Unit 2, the silty-sandy-gravel, forms the main shallow aquifer under the NVOS site and has sufficient thickness to convey a large groundwater flux, connecting the river channel with spawning channels. There is uncertainty as to the aquifer geometry, and whether this permeable unit pinches out south of NVOS site at the Cheekye Fan.

Unit 3, the deeper (>20m) sandy, boulder-gravel unit likely represents a significant groundwater flow pathway through the valley sediments, likely recharged by the Cheakamus River, the Daisy Lake reservoir, and any other water bodies upstream in the valley, as well as from precipitation.

At the NVOS site, contributions from deeper groundwater flow (i.e., contributions from Unit 3) are probably present at least in some locations along the spawning channels, contributing to channel temperature and water chemistry regimes. The evidence of this localized deep groundwater upwelling is:

- Water chemistry of some discharging groundwater;
- Relatively deep upward gradients present at some locations; and
- The large lag time in temperature time series (a natural tracer).

Water chemistry was sampled in 2000 before the Gorbuscha intake was active, at a time when the spawning channels were mostly supplied by discharging groundwater. Results were typical of what would be expected of deeper groundwater, with cation exchange and complexation reactions taking place – this is the strongest evidence for deeper groundwater upwelling (D. Allen pers. comm. 2011).

5.1.4 Aquifer Properties, Groundwater Flux and Gradients

The most accurate large-scale hydraulic properties for the aquifers are likely those determined by use of numerical methods. Three-dimensional numerical models were completed by Jordan-Knox (2003), and recently in more detail by SRK (Appendix 5). Properties for the shallow aquifer (Unit 2) estimated from the more recent model were between $5 \times 10^{-5}$ m/s and $1 \times 10^{-4}$ m/s, which differs somewhat from the value determined by Jordan-Knox (2003) of $1 \times 10^{-5}$ m/s (Appendix 5). The specific yield or storage property used in the recent model was 0.20.

Groundwater flux rates were extracted across four vertical cross-sections transecting the NVOS site:

- Section A extends approximately 300m in the west-east direction, from near station SGCH, and along the north end of NVOS, and the NVOS floodplain (this is the flow of groundwater from the river toward the NVOS site).
- Section B extends approximately 300m north to south along the river and around the NVOS site (this river direction is parallel to groundwater gradients shown on water table maps).
• Section C extends approximately 350m between the river towards the south-east of the NVOS, downgradient of all channels and the floodplain.
• Section D extends approximately 650m across the middle of the NVOS site in a west-east direction.

Table 17 summarizes groundwater flux estimates.

**Table 17: Calculated average fluxes and horizontal hydraulic gradients between the river and NVOS site**

<table>
<thead>
<tr>
<th>Section</th>
<th>Model Layer</th>
<th>(Q) Flux</th>
<th>Cross-section geometry</th>
<th>(q) Flux / area</th>
<th>K, hydraulic conductivity</th>
<th>Horizontal gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³/d</td>
<td>m³/s</td>
<td>Thickness (m)</td>
<td>section length (m)</td>
<td>A, xsec area (m²)</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>55.5</td>
<td>0.0006</td>
<td>2</td>
<td>284</td>
<td>568</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>0.147</td>
<td>0.000002</td>
<td>2</td>
<td>316</td>
<td>632</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>46</td>
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<tr>
<td>A</td>
<td>3</td>
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<td>0.004</td>
<td>8</td>
<td>297</td>
<td>2376</td>
</tr>
<tr>
<td>D</td>
<td>all</td>
<td>10503</td>
<td>0.1</td>
<td>57</td>
<td>657</td>
<td>37449</td>
</tr>
</tbody>
</table>

The primary groundwater flux is from the Cheakamus River in the north towards the NVOS site in the south. The volumetric flux (volume/time) in the shallow aquifer is low at 314 m³/day (0.004 m³/s). Most of that water discharges into spawning channels with a small percentage flowing under channels and discharging back into the river south of the NVOS site.

Along the east side of NVOS, there is almost no flux from or to the river.

The total flux across the site through all aquifers (equivalent to a thickness of 57m) is approximately 10,500 m³/day (0.1 m³/s).

For comparison, Jordan-Knox (2003) estimated a unit horizontal flux of approximately 4x10⁻⁵ m/s, which is greater than the 2x10⁻⁶ m/s flux estimated in the current model. Differences can be attributed to the higher hydraulic conductivities used by Jordan-Knox.

It is interesting to note that, when compared to the Gorbuscha intake pipe inflow rate (visually estimated as approximately 0.3 m³/s), the groundwater flux rate in the shallow aquifer is lower. This corresponds with visual observations that suggest most of the flow in spawning channels is fed directly from this intake.

Upward gradients monitored in 2000 did not vary with river stage, suggesting that the system was at steady state. The change in hydraulic gradient, as the river stage varied, was not large enough to cause a significant change in groundwater gradients towards the spawning channels. However, the data collected in 2008–2010 show a relatively strong correlation of channel water levels to
river discharge and stage. A local groundwater flow system between the river channel and the floodplain channels can also produce such gradients.

5.1.5 Groundwater Recharge Sources

The groundwater recharge areas can be inferred from the interpreted groundwater flow system, from elevations of water bodies and channels, the river channel profile, the valley topography, and by interpretation of temperature and water level variability.

5.1.5.1 BC Rail Channel

In the northeast part of the study area, near the BC Rail Channel, groundwater is most likely recharged by surface water from Tenderfoot Creek and the small lake which feeds the lower creek channel, near the Tenderfoot Hatchery, as well as some component of recharge from precipitation. Recharge occurs because the elevation of the valley floor is higher at the pond and Tenderfoot Creek than at the BC Rail Channel and the Cheakamus River. Deeper groundwater is likely also recharged to the north of this site, up valley, from precipitation, valley slope runoff, and from upstream reaches of the Cheakamus River. The travel time of groundwater over the 250m from the closest uphill water body will be substantial. From temperature analysis, the lag time of seasonal temperature variation to seasonal air and river water temperature is approximately 82 days at D52, located at the headwater of BC Rail Channel. At TEND, the lag time of temperature is 61 days. This suggests that groundwater is recharged also upstream of TEND and travels an even longer distance before affecting TEND temperature. From this analysis, the groundwater recharge area for the BC Rail Channel is somewhere up valley from TEND.

5.1.5.2 Upper Paradise and Upper Kisutch Channels

The Cheakamus River is the source of groundwater recharge to the Upper Paradise and Upper Kisutch channels. Groundwater recharge probably occurs between the Far Points Habitat Channels and where the river turns south as it is deflected by bedrock valley walls east of the NVOS. There will also be a southeasterly flow component from the Far Point Habitat Channels and the Coho Connector Channel – both of which are river fed – which most likely lose some surface flow to groundwater recharge. This groundwater flow continues and discharges into some of the NVOS channels and eventually into the lower part of Cheakamus River south of the NVOS site. Additional recharge probably occurs from valley slope runoff and precipitation west of the site.

5.1.5.3 Central NVOS Site

Local recharge of groundwater arises from losses between spawning channels, precipitation and contributions from deep groundwater. Where deeper groundwater discharges into channels (possibly at D23 and D45 monitoring points), the recharge zone will be distant, most likely from the Cheakamus River upstream of the NVOS site. Travel time for deep groundwater might be as long as one year.

5.2 Management Questions

Implicit within the four management questions that prompted this study was the need for enhanced understanding of the hydrogeological processes driving groundwater-surface water interactions at low flows. The data collected on water levels, discharge, DO, temperature, and pH allowed for a new conceptual model. The previous study at this site (Jordan-Knox, 2003) was based on different channel characteristics; the addition of Gorbuscha Channel in particular clearly
impacted the groundwater-surface water interactions, and the present conceptual model therefore represents an update of previous work based on current characteristics. Parameter-specific results interpreted in the context of this conceptual model allow for a number of conclusions regarding the management questions.

5.2.1 Question #1

How do seasonal NVOS and TH floodplain shallow groundwater flow direction, temperature, dissolved oxygen, and pH vary in response to Cheakamus River mainstem flows ≤ 40 m³/s?

The statistical correlation between Cheakamus River flow and groundwater elevation in side channels persists for mainstem flows between 15 m³/s and 40 m³/s, but the actual magnitude of any change in groundwater flow direction is very minor. The revised conceptual model concludes that flows within the spawning channels are in approximate steady state and transient behaviour is only shown during high discharge events in the river or following substantial changes in the Gorbuscha Channel intake. To expand on the second point, the river channel to the north of NVOS site is at higher elevation than floodplain. The spawning channel groundwater fluxes will remain in approximate steady state until the river discharge drops such that the intake pipe (Gorbuscha) is no longer under water (cutting off surface flow component of spawning channels). The shallow groundwater flux will continue until the river discharge drops below the natural groundwater flux between river channel and the floodplain.

Temperature, DO, and pH of shallow groundwater is correlated in varying degrees to the values of those parameters in the Cheakamus River, and are subsequently influenced by geochemical and biological processes during groundwater transport pathways that run from days to weeks, or even months. As the Cheakamus River is source water for groundwater recharge, it is therefore important to identify whether river discharge <40 m³/s has an influence on these parameters. For instance, do lower river flows lead to altered water temperatures, pH, or DO prior to discharging from river to ground? Or can higher flows lead to decreased travel times of groundwater pathways to an extent that limits the chemical and biological regulation of parameters prior to upwelling into the side channels. Regarding flow releases affecting Cheakamus River temperature, pH, or DO, this is theoretically possible but would require extremely low flow releases below the current WUP. Flow aeration, air temperature, and other catchment-level factors determine the values of these parameters. Regarding the prospect of higher hydraulic head decreasing the travel time of shallow groundwater, the extent of change on travel time would be inconsequential when measuring changes of hours against a scale of days to months, and any effect on shallow groundwater DO, pH or temperature through this process would be extremely unlikely.

5.2.2 Question #2

To what extent does seasonal NVOS and TH side-channel hydrology depend on groundwater flow interactions with Cheakamus River mainstem flows ≤ 40 m³/s?

Discharge measurements in side channels confirmed that side-channel hydrology remains correlated to river discharge for mainstem flows below 40 m³/s, at least for Upper Kisutch and BC Rail Channel. However, the extent to which the correlation equates to a meaningful change in water velocity compared to moderate flows above 40 m³/s is limited, and the strength of any relationship between river discharge and side-channel discharge diminishes at low flows as water velocity became more difficult to accurately measure with the available instruments.
Due to the confined configuration of BC Rail Channel (and to a lesser extent Kisutch Channel), higher discharge results in greater change to average channel velocity than to channel depth or wetted width. Water velocity is an important factor in determining suitability of habitat for spawning, incubation, and rearing. Observed water velocities were compared to published “Habitat Suitability Index” (HSI) scores for chum (e.g., Hale et al. 1985). Average channel velocities were sub-optimal from the HSI ranking at flows both above and below 40m$^3$/s, although chum spawning was abundant regardless. For river flow less than 40m$^3$/s, no statistical relationship was observed between average channel velocity and Cheakamus River discharge – however, because the water level (which is measured much more precisely than velocity at low flows) remained well correlated to river discharge at <40m$^3$/s flows, it is likely that the diminished Cheakamus flow vs. side-channel velocity relationship is at least in part attributable to instrument limitations. Regardless, the decrease in average channel velocity to values less than 0.03m/s was observed at flows greater than 40m$^3$/s and within the range of previous water management patterns: average channel velocity varies within a low but narrow range and differences may not be accurately measurable for Cheakamus River flows between 15 and 40m$^3$/s without more sophisticated instrumentation.

5.2.3 Question #3

To what extent do key fish habitat variables related to flow (average depth, average velocity, discharge) and water quality (temperature, dissolved oxygen, and pH) in NVOS and TH side channels depend on groundwater flow interactions with Cheakamus River mainstem flows ≤ 40m$^3$/s?

As described briefly in addressing Question #2, the availability of wetted habitat is for all intents and purposes insensitive to flow changes below 40m$^3$/s. The wetted top width of the three side channels remains essentially unchanged as flow changes, and recorded water levels correlated to river discharge in a way that was significant from only a statistical perspective.

Surface water quality in the side channels is driven by source water quality (deep and shallow groundwater), which in turn is not affected by Cheakamus River discharges within the 15 to 40m$^3$/s range – refer back to the discussion above surrounding Question #1. Temperature, DO, and pH of river water or side-channel water do not vary with river discharge on a short time scale. In one sense, freshet is correlated with higher seasonal temperature and so in that way water temperature can be said to be weakly correlated with discharge, but it is air temperature which is causing both discharge increase and water temperature increase during spring season.

Specific to side-channel surface water, the biggest water temperature changes can be made by changing flow system in spawning channels. Surface water quality in the side channels differs from the groundwater sampled in that dyke seepage may influence the former but not the latter. Therefore, increasing river water piped into Gorbuscha and Sue’s Channels may be able to induce the temperature profile of the groundwater-fed channels to be closer (but not identical) to the river levels.

Similarly, the processes controlling DO and pH in spawning channels are linked to water sources of channels: river water through a very shallow groundwater travel pathway, and deep groundwater. Faster-flowing channels with large amount of river water piped in have higher DO than slower-flowing channels. DO has seasonal behaviour (related to temperature and flow turbulence) and transient behaviour (hydraulic head changes, pressure pulses from river stage fluctuation, the usual hyporheic exchanges of low DO shallow groundwater near channel sides.
and bottom and channel water). Groundwater has low DO and groundwater discharge to channels will not change unless some major system changes occur (river drops very low below intake pipe, channels are excavated differently).

The points above notwithstanding, changes to intake pipe delivery to Gorbuscha and Sue’s Channel is a separate issue than the management question of Daisy Lake dam releases. More to the point, the extent to which side-channel surface water can be influenced by seepage is likely limited as slower-moving groundwater upwelling will still dominate the water supply to these channels.

5.2.4 Question #4

To what extent does salmonid production vary in NVOS and TH side channels in relation to groundwater flow interactions with Cheakamus River mainstem flows ≤ 40 m$^3$/s, and to what extent has the implementation of the WUP affected salmonid production in the NVOS and TH side-channel habitats compared to the pre-WUP state?

The data collected through this study and parallel monitors provides no direct evidence of a causal relationship between groundwater parameters and fish production metrics. A caveat is that the duration of anadromous fish production time series generally must be quite long to identify significant trends, owing to the complexity of life history for these species. Egg to fry survival of chum is the most likely to yield results given that survival will be driven by a combination of hyporheic water quality, substrate, and related density dependent effects. Analytical work possible at this time did identify a statistically significant link between water level fluctuations (e.g., variance of mean daily water level) during incubation and the egg-to-fry survival, but the variability in water levels is for the most part independent of Daisy Lake dam releases on that short of a scale. Environmental variables like winter storm conditions and – particularly for BC Rail channel – local wildlife or similar disturbances, are more relevant for considering daily flow stability. However, it is not yet clear whether the statistical correlation between groundwater variance and egg-to-fry survival is causative or coincidental. It is not possible to definitely interpret the results given the shortness of the time series.

All four years of NVOS egg-to-fry survival and three of the four years of BC Rail Channel data are consistent with density-dependent effects dominating the inter-annual variability of egg survival. The data presented here are not conclusive in this regard, and moreover inter-annual dominance of density dependent effects does not mean that there is not an upper limit on survival at any given spawner density that is controlled by groundwater processes. Nonetheless the deviation in trends for egg-to-fry survival for NVOS versus BC Rail Channel in 2010 seems key given the available data at present, and gives some support to the idea that significant groundwater alterations to the entire area are not causing a generalized decline in incubation success. It would be informative for subsequent monitoring to develop egg-to-fry survival estimates annually for Kisutch Channel in isolation, to give a second channel that is exclusively groundwater-fed for comparison to BC Rail channel.

Other analyses were considered at the outset of this work and may be worth following up on at a later date. For instance, there is a potential influence of groundwater parameters on embryonic development time. In this case, outmigration timing is a proxy indicator of emergence from gravel, and the median spawner abundance data can provide the start date. There is a potential causation effect of groundwater parameters influencing development time; such linkages have been documented for nutrient availability or water temperature. Delayed development can
subsequently influence size at migration and survival to reproductive age. This analysis may prove informative in future, once modelling of median date of outmigration is completed. These data will eventually be available through parallel fisheries monitors and it would be relatively straightforward to compare, for instance, temperature metrics through the embryonic development period to the spawner-to-migration time period. It should once again be noted however that this analysis may be peripheral to direct management interest given the ultimate inability of dam releases to influence groundwater temperature or dissolved oxygen. However dam releases can be used to produce small-scale changes in water elevation, which may have some influence on habitat quality by changing the proportional mixing of surface and groundwater at redd depth, and so future analysis using groundwater elevation data as a predictor of embryonic development period is justified.

While direct answers to this question may not yet be possible, indirect answers are suggested by the general robustness of shallow groundwater and side-channel characteristics in response to Cheakamus River flow. The data collected and the resulting conceptual model developed give no reason to believe that the quantity or quality of habitat available in side channels has been meaningfully impacted by the WUP compared to pre-WUP state. However, this monitor did not include all possible aspects of the subterranean ecosystem that may be linked with both river discharge and salmonid production. Completion of the fisheries monitors over coming years should provide evidence as to whether or not trends in abundance or survival have been concurrent with WUP implementation.
6.0 CONCLUSIONS AND RECOMMENDATIONS

In evaluating the Cheakamus WUP, the current flows are characteristically lower than the previous in-stream flow order by an amount that will lead to a measurable decrease in the water level and consequently discharge in groundwater-fed side channels. However, based on this analysis the practical significance of the differences is not consequential for the habitat quality parameters measured. The average wetted width, depth, and velocity of the channels that define the physical habitat for fish vary within an extremely narrow range across the broader range of Cheakamus River flows experienced in 2008 through 2010 (and note that for much of summer 2010, river flows were near-natural during turbine maintenance). In theory, the gradient difference between Cheakamus River and the NVOS channels is such that any river flow at all would provide a water table that could maintain similar side-channel flow, though a river flow that low would have consequences on water quality. The physical habitat quantity in the side channels is therefore connected to the mainstem flows, but not in a way that the current WUP would create biologically meaningful reductions in habitat.

Habitat quality is a more complex question than habitat quantity. The groundwater-monitoring program used temperature, DO and pH, with some lesser reliance on more specific water chemistry, to define habitat quality. Results for pH and anion monitoring gave no evidence that Cheakamus River flows less than 40m³/s are influential on these parameters. Results from temperature and DO monitoring were more informative in understanding groundwater-surface water interaction processes, but similarly provided evidence to reject the null hypothesis that flows less than 40m³/s will lead to adverse effects on DO and temperature. These two parameters are tightly connected to their respective values in the Cheakamus River, but actual river DO and temperature is extremely unlikely to be significantly affected by managed low flows under 40m³/s. Even at flows of 15m³/s, the river is highly aerated through normal flow turbulence, and the short travel time for flow from Daisy Lake to NVOS is negligible for the atmospheric processes that drive surface water temperature.

While Cheakamus River flow within the relevant management range (e.g., 15 to 70m³/s) will have little to no effect on DO or temperature in upwelling groundwater or NVOS surface water, at very high flows the physical head pressure does in fact lead to a characteristic but transient decrease of hyporheic DO, and in the case of extremely high storm flows, the transient decrease is also followed by a transient increase in DO. The frequency of these flushing flows and the type of fisheries data collected are not enough to make conclusions about the importance of this infrequent process for biological productivity, but flushing flows are generally considered a formative and therefore necessary part of aquatic systems. While the “flushing flow” threshold may be beyond the flow range meant for consideration in this monitor, it should be resolved as to whether the WUP is artificially reducing the frequency of flushing flows, or if the natural storm events that cause spill over the Daisy Lake dam are sufficiently large to make the extent of flow diversion inconsequential. The conclusions about DO are also partially derived by extrapolating the physical processes from the temperature data. The three-month continuous monitoring trial was consistent with the process model for groundwater-surface water interactions, but to increase confidence in the spatial representativeness of the conclusions, monitoring would have benefited from paired data collection in the Cheakamus River and from expanded spatial and temporal coverage within NVOS hyporheic water.

The duration of potentially informative fisheries data for groundwater processes is quite short. Statistical conclusions about the lack of an effect between the current WUP and fish productivity are not yet possible, but with the conceptual model of physical processes provided, there should
be some confidence that the fish habitat parameters previously thought most likely to be affected by low flows are within the same range that they would be under older water-use patterns.

The three-year study program focused on the groundwater processes considered at the outset to be the most likely to be impacted by the WUP. Groundwater-surface water interactions are in reality much broader and more complex than the parameters monitored here, and some processes not specifically targeted in this study may have biologically relevant implications – for instance, microbial processes or nitrogen/phosphorous cycling.

Seventeen of the 18 data loggers used for this study remain in place, and as of July 2011 are still collecting data every 15 minutes in the same locations (though memory will likely be full by late summer 2011).

6.1 Possible Future Work or Methodological Refinements

If additional conclusions about groundwater-surface water interactions are sought, a more focused data collection program may be helpful. Recommendations that may refine the conclusions herein include:

- Temperature is used as a proxy for a chemical tracer. The results of the conceptual model, which in turn inform the conclusions, are based in large part on the temperature data. The extent of data mean confidence in temperature conclusions is high, but as a check on the assumptions of travel time at high or low flows, chemical tracers could be used.
- Monitor water temperature in more groundwater piezometers between channels and at water bodies not monitored yet, including Dave’s Pond; also monitor spawning channel water temperature of flowing water (e.g., as opposed to surface water in staff gauges, which are essentially stilling wells).
- Expand fisheries monitors to allow estimates of egg-to-fry survival in more than one strictly groundwater fed channel. Currently, only BC Rail channel provides such an estimate, whereas the NVOS estimate includes both ground- and surface-fed channels.
- Expand variables of consideration to include additional biological indicators other than fish production. Fish production is subject to such a broad array of influential factors. Invertebrate productivity or microbial activity may respond to subtle changes in groundwater flux not identifiable through the current monitoring mechanisms.
- Flushing flow size and importance was inferred only from DO data. It would be useful to confirm flow thresholds necessary to avoid impacts on interstitial gravel spacing and related low-level nutrient parameters beyond DO.
- Expand the spatial and temporal scope of continuous DO monitoring by collecting automated data hourly at selected locations (including Cheakamus River) for one year. This would also address the point above regarding flushing flows.
- Accuracy of discharge estimates in Upper Paradise and BC Rail Channel was constrained by instrument detection limits on water velocity. Hydroacoustic Dopper devices could be employed to get accurate velocity measurements in Upper Paradise and BC Rail channels if further certainty is sought regarding the sensitivity of this parameter to low-level fluctuations in river discharge.
- Water level and flow monitoring could be expanded to improve the water balance of site and physical process model. Monitor inflow from Gorbuscha Intake if possible at regular time intervals during representative high and low river flow periods.
- Survey the elevation of Gorbuscha Channel intake pipe and survey river channel banks, bottom, and water elevation profile along river from the bridge and around NVOS site if more detailed flow modelling or analysis of hydrology on site is needed.

Notwithstanding the recommendations above, the three-year monitoring program provides strong evidence that the current WUP maintains essentially the same physical habitat quantity and quality as would be experienced in NVOS side channels for pre-WUP flow regimes.
7.0 REFERENCES


USGS (2007) Heat as a tool for studying the movement of ground water near streams. USGS, Curcular 1260


SITE LOCATION
2170 Paradise Valley Road, Brackendale, BC
BC HYDRO

FIGURE 1
Stream discharge
Stream geometry
Gravel shape, size and packing
Sediment deposition (size and distribution)
Instream oxygen concentration
Stream water temperature
Stage of embryo development
Size of embryo
Spatial distribution of eggs within spawning gravels

Turbulent surface-subsurface exchange
Hydraulic gradient
Riverbed scour
Substrate permeability

Intragravel flow velocity
Oxygen supply to egg pocket
Ammonia accumulation in egg pocket

Oxygen demand of deposited material
Intra-gravel oxygen concentration
Intra-gravel water temperature
Rate of oxygen uptake by embryos

Temperature of upwelling groundwater
Intra-gravel oxygen concentration
Intra-gravel water temperature

Probability of embryo survival

CONCEPTUAL FLOWCHART OF GROUNDWATER PROCESS LINKS WITH CHUM SALMON LIFE HISTORY

Job No.: 035-27.03
Dwg.: 0352703 S02.1
2170 Paradise Valley Road, Brackendale, BC
BC HYDRO
FIGURE 2
FIGURE 3

SITE MAP AND SAMPLING LOCATIONS

2170 Paradise Valley Road, Brackendale, BC
BC HYDRO
PVC pipe

wire mesh screening over apertures

logger sensors

Creek bed

Upwards hydraulic gradient inferred from nearby drivepoints to supply groundwater flow past sensor.
WATER ELEVATION SUMMARY DATA AT MONITORING DRIVEPIONS (2008-2010)

FIGURE 6
WATER ELEVATION SUMMARY DATA AT MONITORING DRIVEPIONTS (2008-2010)
FIGURE 8

WATER LEVEL TIME SERIES – UPPER PARADISE CHANNEL

Discharge in Cheakamus River near Brackendale (083A043)

- SGCH
- D11
- SGUP
- D23

Date

Discharge of Cheakamus River (m³/s)

56.0
55.5
55.0
54.5
54.0
53.5
53.0
52.5
52.0
51.5
51.0

Water Level (m above)

Jan-2008
Apr-2008
Jul-2008
Oct-2008
Jan-2009
Apr-2009
Jul-2009
Oct-2009
Jan-2010
Apr-2010
Jul-2010
Oct-2010
Jan-2011

Job No.: 035-27.03
Dwg.: 0352703 8.1
JAN 2012

WATER LEVEL TIME SERIES – UPPER PARADISE CHANNEL

2170 Paradise Valley Road, Brackendale, BC
BC HYDRO

Interpretation: The graph shows the water level time series for the Upper Paradise Channel, with discharge measurements taken in the Cheakamus River near Brackendale. The data is represented by different lines for SGCH, D11, SGUP, and D23, indicating varied water levels and discharges over the specified period from January 2008 to January 2011.
WATER LEVEL TIME SERIES – UPPER KISUTCH CHANNEL

Discharge in Cheakamus River near Brackendale (08GA043)

SGCH
D50
SGKIS
D45

WATER LEVEL TIME SERIES – UPPER KISUTCH CHANNEL

2170 Paradise Valley Road, Brackendale, BC
BC HYDRO

FIGURE 9
FIGURE 10
WATER TABLE MAP OF NVOS SITE (AVERAGE 2008-2010)

This water table surface represents the mean water table calculated from the period of record 2008-2010.
Cheakamus River spawning channels 2008-2010 monitoring points
interpolation add-in points
water elevation (msl) 66m
0.25 m contours (dashed lines)
1.00 m contours (solid lines)

Job No.: 035-27.03
Dwg.: 0352703 10.1
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Engineers and Scientists
2170 Paradise Valley Road, Brackendale, BC
BC HYDRO

PGL | Pottinger Gaherty
ENVIRONMENTAL CONSULTANTS
FIGURE 11

WATER TABLE MAP (HYDRAULIC HEAD DISTRIBUTION) AND FLOW PATHS CALCULATED BY NUMERICAL FLOW MODEL

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Pottinger Gaherty
ENVIRONMENTAL CONSULTANTS
MINIMUM (AVERAGE ANNUAL) WATER TABLE MAP OF NVOS SITE (PERIOD OF RECORD 2008-2010)
FIGURE 13

WATER TABLE MAP OF NVOS SITE IN 2000/01 (DATA FROM JORDAN-KNOX, 2003)

This water table surface represents the typical low water level during the monitoring period in 2000-2001 (data from Jordan-Knox, 2003). Spawning channel network is shown as it was in 2001.

Monitoring points on Feb 11, 2001
Interpolated data (points)
Cheakamus River
Water elevation (m a.s.l.)

0.25 m contours (dashed lines)
1.00 m contours (solid lines)

JAN 2012

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BC HYDRO

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Environmental Consultants

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Job No.: 035-27.03
MONTHLY MEAN WATER LEVEL BY YEAR (2008-2010) AT MONITORING POINTS
SGCH, D23, D53, D45, RBCH, TEND

(from: \Van-svr0\projects\01_SITES\Cheakamus\Data\River Q and drivepoint WL joined table.xlsm)
MONTHLY MEAN WATER LEVEL BY YEAR AT MONITORING POINTS
SGKIS, SGBCR, SGUP, D11, D50, D55

(from: \Van-svr0\projects\01_SITES\Cheakamus\Data\River Q and drivepoint WL joined table.xlsm)
FIGURE 16

WATER LEVEL ANNUAL RANGE OF VARIATION (MAX-MIN) IN MONITORING POINTS COMPARED IN THREE YEARS (2008 TO 2010)
WATER LEVEL VARIATION AT MONITORING PIEZOMETERS AT VARIOUS LOCATIONS
$R^2$ FROM LINEAR REGRESSION FOR FULL Q RECORD AND Q<40M3/s RECORD, AND $R^2$ FROM TIME SERIES CROSS-CORRELATION COMPARED GRAPHICALLY FOR CHANNEL GROUPS
BC Rail Channel Rating Curves

2010:
Stage = 0.1745Q + 0.3273
R² = 0.1258

2008/2009:
Stage = 0.4898Q + 0.2691
R² = 0.9184

Discharge (m³/s)

Stage (m)

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Dwg.: 0352703 19.2
JAN 2012

BC RAIL STAGE VERSUS DISCHARGE RELATIONSHIP
Kisutch Channel Stage vs Discharge - all years

Discharge (m³/sec) vs Stage (m)

y = 0.8612x - 0.1416
R² = 0.7258
Upper Paradise Channel Stage vs Discharge
(no significant relationship; no flow measurements in 2010)
Cheakamus River vs Kisutch Channel Discharge Relationship

\[ y = 0.0322 \ln(x) - 0.0567 \]

\[ R^2 = 0.6592 \]
Simulated Kisutch Channel MAD by Year

Year

Simulated MAD (m3/s)

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08


KISUTCH CHANNEL SIMULATED MAD TIME SERIES

Job No.: 035-27.03

BC HYDRO

Pottinger Gaherty

BC HYDRO

FIGURE 24
FIGURE 25
BC RAIL AND UPPER KISUTCH CHANNELS: STAGE VS WETTED TOP WIDTH

[Graph showing the relationship between channel stage (water elevation, m) and wetted top width (m) for BC Rail Channel and Upper Kisutch.]
Squamish mean daily air T

SGCH (Cheakamus River)

D11

SGUP

D23

air temperature is at Squamish Auto (10476F0) weather station, Environment Canada
air temperature is at Squamish Auto (10476F0) weather station, Environment Canada
Temperature (°C)

Month-Year

Squamish mean daily air T

SGCH (Cheakamus River)

D50

SGKIS

D45

air temperature is at Squamish Auto (10476F0) weather station, Environment Canada
FIGURE 29
WATER TEMPERATURE TIME SERIES – FLOODPLAIN GROUNDWATER STATIONS

Squamish mean daily air T

SGCH (Cheakamus River)

RBCH

TEND

Month-Year

Temperature (°C)

Squamish mean daily air T

SGCH (river)

RBCH

TEND

air

Job No.: 035-27.03
Dwg.: 0352703 S29.2
JAN 2012

WATER TEMPERATURE TIME SERIES – FLOODPLAIN GROUNDWATER STATIONS
FIGURE 30

CLASSIFICATION OF MONITORING DRIVEPOINTS AT NVOS BY WATER THERMAL REGIME
BASED ON (A) MEAN WINTER WATER TEMPERATURE, AND (B) MEAN SUMMER WATER TEMPERATURE
CLASSIFICATION OF MONITORING DRIVEPOINTS AT NVOS BY WATER THERMAL REGIME
BASED ON DIFFERENCE BETWEEN SUMMER AND WINTER MEAN WINTER WATER TEMPERATURE
Figure 32

Linear correlation and lag time of hourly and daily temperature data at monitoring drivepoints compared with river temperature at SGCH.

- **R^2** correlation coefficient from linear regression model of drivepoint temperature and river temperature at SGCH.

- Long travel time for groundwater.

**Legend:**

- BCR Channel
- Kisutch Channel
- Paradise Channel
- Extended Channel

**Axes:**

- Y-axis: R^2
- X-axis: Lag from SGCH (days)

**Data Points:**

- DS2
- SGBCR
- DS5
- SGKIS
- DS1
- SGUP
- DS3
- RBCH
- TEND
SEASONAL AND INTER-ANNUAL VARIATION IN AIR TEMPERATURE, RIVER DISCHARGE, RIVER TEMPERATURE, AND SIDE CHANNEL TEMPERATURE
Grab samples of DO in BC Rail Channel: 2009 - 2011

BI-MONTHLY DISSOLVED OXYGEN TIME SERIES: BC RAIL CHANNEL
Grab samples of DO in BC Rail Channel: 2009 - 2011

Dissolved Oxygen (mg/L)

Date

BCRSG
CHSG
D52
D53
D54
D55

6-Feb-09 17-May-09 25-Aug-09 3-Dec-09 13-Mar-10 21-Jun-10 29-Sep-10 7-Jan-11 17-Apr-11

BI-MONTHLY DISSOLVED OXYGEN TIME SERIES: UPPER PARADISE
Grab samples of DO in Upper Kisutch Channel, 2009-2011

Date

Dissolved Oxygen (mg/L)

CHSG  KCSG  D50  D51  D45  D46

FIGURE 36

BI-MONTHLY DISSOLVED OXYGEN TIME SERIES: UPPER KISUTC
Grab samples of DO in Regional Groundwater Wells: 2009-2011

Date

18-Dec-08 28-Mar-09 6-Jul-09 14-Oct-09 22-Jan-10 2-May-10 10-Aug-10 18-Nov-10 26-Feb-11 6-Jun-11

Dissolved Oxygen (mg/L)

0 2 4 6 8 10 12 14

CHSG RBCH THW

BI-MONTHLY DISSOLVED OXYGEN TIME SERIES: FLOODPLAIN WELLS
Averaged Dissolved Oxygen Time Series (error bars are one standard deviation)

<table>
<thead>
<tr>
<th>Date</th>
<th>DO (mg/L)</th>
<th>Cheakamus SG</th>
<th>Avg Groundwater</th>
<th>RBCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar-09</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul-09</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-09</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar-10</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul-10</td>
<td>5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Aug-10</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb-11</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun-11</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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FIGURE 38
Cheakamus Mainstem DO vs. Mean NVOS Groundwater DO

$y = 0.2856x^{1.1623}$
$R^2 = 0.7631$

Cheakamus Mainstem DO (mg/L) vs. Mean NVOS Groundwater DO (mg/L)

Job No.: 035-27.03  Dwg.: 0352703 S39.2  JAN 2012

NVOS GROUNDWATER DO VS CHEAKAMUS RIVER DO

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BC HYDRO

SRK Consulting
2170 Paradise Valley Road, Brackendale, BC
BC HYDRO

FIGURE 39
CONTINUOUS DO MONITORING: NOVEMBER 7 – 12 2009
FIGURE 43
CONTINUOUS DO MONITORING: NOVEMBER 13 – DECEMBER 1 2009

Dwgs.: 0352703 S43.2
Job No.: 035-27.03
JAN 2012

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CONTINUOUS DO MONITORING: NOVEMBER 13 – DECEMBER 1 2009

Dissolved Oxygen (mg/L)

Flow (m³/s)

Tenderfoot
KC Ground
KC Surface
BCR Ground
BCR Surface
Cheakamus Q

Date

8-Nov
13-Nov
18-Nov
23-Nov
28-Nov
3-Dec
CONTINUOUS DO MONITORING: JANUARY 8 – 18 2010
Grab samples of pH in BC Rail Channel: 2008 - 2011

BI-MONTHLY pH TIME SERIES: BC RAIL CHANNEL
FIGURE 46

BI-MONTHLY pH TIME SERIES: UPPER KISUTCH CHANNEL

Grab samples of pH in Upper Kisutch Channel: 2008-2011

Date

pH

CHSG
KCSG
D50
D51
D45
D46

0 1 2 3 4 5 6 7 8 9
14-Nov-07 1-Jun-08 18-Dec-08 6-Jul-09 22-Jan-10 10-Aug-10 26-Feb-11

Bi-monthly pH time series of Upper Kisutch Channel is shown. The pH values range from 4 to 8 with each data point representing a sample date from 2007 to 2011. The figure includes five different sampling locations identified by CHSG, KCSG, D50, D51, and D45, each with distinct line colors and markers.
Grab samples of pH in Upper Paradise Channel, 2008-2011

BI-MONTHLY pH TIME SERIES: UPPER PARADISE CHANNEL
Grab samples of pH in regional groundwater wells: 2008 - 2011

Date
11/14/07  6/1/08  12/18/08  7/6/09  1/22/10  8/10/10  2/26/11  9/14/11

pH
0  1  2  3  4  5  6  7  8  9  10

CHSG
RBCH
THW
FIGURE 49
CONTINUOUS pH MONITORING TIME SERIES

KDOG-1 (Kisutch Channel groundwater)
KDOS-1 (Kisutch Channel surface water)
TFDO-1 (Tenderfoot Hatchery groundwater)
BCRDOS-1 (BC Rail Channel surface water)
BCRDOG-1 (BC Rail Channel groundwater)

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Dwg.: 0352703 S49.2
JAN 2012

CONTINUOUS pH MONITORING TIME SERIES
FIGURE 50
BC RAIL EGG TO FRY SURVIVAL PLOTTED WITH CHEAKAMUS RIVER FLOW, 2007 – 2010

Spawning Year

Egg to Fry Survival (%)

Cheakamus Mean Flow
Cheakamus 90th % Flow
Cheakamus 10th % Flow

Flow (m³/s)

2006 2007 2008 2009 2010 2011

BC RAIL EGG TO FRY SURVIVAL PLOTTED WITH CHEAKAMUS RIVER FLOW, 2007 – 2010
BC RAIL EGG TO FRY SURVIVAL PLOTTED WITH BC RAIL TEMPERATURE STATISTICS

**FIGURE 51**

**BC RAIL EGG TO FRY SURVIVAL PLOTTED WITH BC RAIL TEMPERATURE STATISTICS**

- **Egg to Fry Survival**
- **Mean January Temp (D52)**
- **90th Percentile January Temp (D52)**
- **10th Percentile January Temp (D52)**
FIGURE 52

BC RAIL EGG TO FRY SURVIVAL AND LOCAL WATER LEVEL FLUCTUATIONS DURING INCUBATION

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Pottinger Gaherty

PGL

FIGURE 52
FIGURE 53

WINTER WATER LEVEL FLUCTUATIONS AT VARIOUS SELECTED NVOS SITES

2006 2007 2008 2009 2010 2011

Year

0.01 0.02 0.03 0.04 0.05 0.06

Variance of Daily Water Level

- SGCH
- D52 (BC Rail)
- SGBCR
- D51 (Kisutch)

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Dwg.: 0352703 53.2
JAN 2012

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FIGURE 55

PAST AND PRESENT RIVER CONFIGURATION AT NVOS

2008-2010 monitoring points
Valley slopes
2003 spawning channels
spawning channels after 2003
gravel bars (present)
Cheakamus River (present)
Historical River Channel
1891
1919
1954

Cheakamus River bank lines were digitized from scanned paper map (Figure A7-C.2) in report:
Marmotrek and Parnell (2002)
"Cheakamus River Water Use Plan Consultative Committee." Report by ESSA Technologies for BC Hydro,

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FIGURE 55