EXECUTIVE SUMMARY

Numerical modelling techniques were used to examine the temperature and ice regime of the Site C reservoir. The water temperature characteristics, such as surface temperature and temperature profiles in the Site C reservoir were examined and the changes to water temperatures in the Peace River at the outlet of the Site C reservoir were predicted. The ice cover and thickness in the reservoir were also predicted. To achieve these predictions, a comprehensive three-dimensional numerical circulation-temperature model of the reservoir was used. The circulation model, H3D, has been used on several other lakes in British Columbia, notably Okanagan Lake and Mara Lake, and has been shown to accurately simulate observed temperature profiles and ice formation characteristics. Model accuracy is quantified in this report based on the modelling of a similar water body, Dinosaur Reservoir, just upstream of the Site C reservoir. Dinosaur Reservoir is bordered by the W.A.C. Bennett Dam and G.M. Shrum Generating Station at its upstream end, and by the Peace Canyon Dam at its downstream end. The Site C reservoir would begin at the outlet of the Peace Canyon Dam. Water temperature measurements in Dinosaur Reservoir and observed data on ice formation were used to calibrate and validate the model.

The primary inputs to the three-dimensional circulation model of Dinosaur Reservoir were the reservoir inflows, outflows, corresponding changes in reservoir water levels, wind stress at the surface, air temperature, humidity, and short-wave insolation. Meteorological conditions such as wind, insolation, back radiation, and latent and sensible heat fluxes were characterized based on available data. Some assumptions were made to account for incomplete wind and meteorological data throughout both reservoirs (Section 3 of this report). Winds in Dinosaur Reservoir were predicted from a meteorological station on top of the W.A.C. Bennett Dam and were assumed to follow the valley direction. Winds in the valley were statistically predicted from winds recorded at Fort St. John. Cloud cover, air temperature, and relative humidity in the valley were taken as identical to those observed in Fort St. John.

The model of Dinosaur Reservoir was calibrated using temperature measurements at multiple depths in the reservoir. As a validation of the model, the simulated water temperatures were compared with measurements taken at the Peace Canyon Dam tailrace, and ice predictions were compared with observations.

The model reproduced the observed temperatures at the outlet of Dinosaur Reservoir with a root-mean-square difference of 0.2°C during the two years for which W.A.C. Bennett Dam tailrace temperatures were available. Observed temperatures at three depths in Dinosaur Reservoir were also reproduced with root-mean-square differences of less than 0.9°C, indicating that the model is realistically simulating temperature stratification. The simulated
ice behaviour in Dinosaur Reservoir, characterized by sequences of short-term ice
formation and melting occurring several times per winter season, agreed well with satellite
and photographic ice observations. Further details on model calibration and validation can
be found in Section 6.

Simulation of the Site C reservoir predicted that a warmer mixed upper layer would form in
the summer than was the case in Dinosaur Reservoir, and a more extensive, thicker, and
more persistent ice cover would form in the winter. Stratified conditions are predicted
between the middle of May and October in a typical year. The simulated Site C tailrace
temperatures have a smaller daily range than those currently observed at a similar location
in the Peace River 6 km downstream. Compared to monthly average observed Peace River
water temperatures, simulated Site C tailrace temperatures are up to 1.5°C warmer during
the summer and fall and from 0.8°C warmer to 0.9°C colder in winter and spring. Simulated
Site C tailrace temperatures were more than 0.4°C colder compared to existing Peace
River temperatures from March through June.

Most of the differences in temperature at the outlet of the Site C reservoir can be described
as a time delay instead of as an absolute difference. Seasonally, simulated water
temperatures with the reservoir in place are one to two weeks late compared to the
presently observed Peace River temperatures. The lag is greatest during the colder months
(October through March).

The sensitivity of the model to variations in input data was tested for cases with faster wind
speed, altered outflow dynamics, and the presence of sediment. Changes due to these
three factors were generally less than 0.1°C, with the smallest changes seen in winter.
Since the predicted changes in outflow temperature due to the Project are greater than both
these sensitivities and the model accuracy, the model is deemed sufficiently accurate for its
intended purpose.

Temperatures in the Site C reservoir are predicted to increase due to climate change, with
the magnitude of temperature increase at the Site C reservoir outlet approximately 20% of
the air temperature increase in summer, and less than 5% in winter. Ice cover on the
reservoir would decrease in thickness and duration due to climate change.
ABBREVIATIONS AND ACRONYMS

H3D................................................................. Hydrodynamics in Three Dimensions
LiDAR................................. Light Detection and Ranging (an optical remote sensing technology)

GLOSSARY

Anemometer An instrument that measures wind speed and direction
Coriolis Effect An effect where moving objects or water are deflected due to the rotation of the Earth. In the Northern Hemisphere, the deflection is to the right.
Forebay In this report, that part of the reservoir just upstream of the intakes to the hydroelectric generating station.
Insolation Incoming solar radiation, or the amount of sunlight received at a particular location and time.
Module (subroutine) In numerical modelling, additional sections of computer code that can be added to account for specific physical processes outside of the ‘core’ functions of the model.
Tailrace That part of a hydroelectric facility that carries water away from the turbines at the downstream end.
Thalweg The line that connects the lowest points in a valley or river channel.
Thermocline In a water body, the interface between two layers of distinct temperature where there is a rapid temperature change over a limited depth.
Thermal Stratification In a water body, the formation or presence of vertical layers of distinct temperature, and therefore density.
Residence time The volume of water in a river reach or reservoir divided by the flow rate through the reach or reservoir. Residence time can be thought of as the time it takes a typical parcel of water to travel through the reach or reservoir.
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Appendix B ................................................................................................................................. H3D Technical Description
1 INTRODUCTION

This study forecasts the water temperature and ice regime of the Site C reservoir in response to flows and meteorological inputs. In particular, it examines the water temperature characteristics (surface temperature and temperature profiles in a multi-year simulation) and predicts ice formation (ice coverage and thickness) in the Site C reservoir under its expected maximum normal operating level, and the changes to water temperatures in the Peace River at the outlet of the Site C dam.

A comprehensive three-dimensional hydrodynamic and thermodynamic model of the reservoir was developed to conduct these temperature predictions. The time period simulated in the Site C reservoir model is from May 1995 through December 2011, covering 16.5 years of meteorological and hydrological variability. This particular period was selected to correspond to the period of the downstream ice study described in Volume 2 Appendix G Downstream Ice Regime Technical Data Report. In order to develop a reliable model of the Site C reservoir, a model of a similar water body, Dinosaur Reservoir, was first developed, calibrated to existing data, and validated against an independent dataset. The same calibration parameters were then applied to the Site C reservoir model. The time period simulated in the Dinosaur Reservoir model is from April 2008 through May 2012, based on the availability of input and calibration data.

Dinosaur Reservoir is bounded by the two existing dams along the Peace River— with the W.A.C Bennett Dam and G.M. Shrum Generating Station at the upstream end and the Peace Canyon Dam and generating station at the downstream end—and is just upstream of the Site C reservoir (Figure 1.1). The configurations of both reservoirs are described in Section 2.

Meteorological inputs for this three-dimensional circulation model are primarily wind speed at the surface of the reservoir, air temperature, cloud cover, and humidity. Meteorological inputs such as wind stress, insolation, back radiation, and latent and sensible heat fluxes were computed from the input meteorological data. Meteorological conditions in the Peace River valley were measured as described in Volume 2 Appendix K Microclimate Technical Data Report. Section 3 of this report outlines the meteorological data and assumptions used in the reservoir models.

Hydrological inputs for this three-dimensional circulation model are based on the measured outflow from W.A.C. Bennett Dam and Peace Canyon Dam, tributary inflows, and incoming water temperatures. The data collected and used in the model are presented in Section 4.

The hydrodynamic model (H3D) used to examine the variations of water temperature in the reservoir and ice formation at the surface is described in Section 5. Results for the long-
term simulation of water temperatures in the Dinosaur and Site C reservoirs are presented in Sections 6 and 7, respectively.

2 RESERVOIR DESCRIPTION

A general view of the study area with the reservoir locations is shown in Figure 1.1. Uplands along the Peace River, generally above a 700 m elevation, exhibit rolling topography. Benches lie at about 620 m and have mounds and hollows with an overall flat topography, much of which has been cleared and is cultivated or improved for pasture. The benches and uplands are dissected by the Peace River and its tributaries, with the valley bottom lying at about 450 m at Hudson’s Hope, and at about 410 m at the Site C dam site. The valley varies from up to 5 km wide where it is flat-bottomed with prominent terraces to about 1 km wide with V-shaped and canyon-like forms (Thurber 1977).

2.1 Dinosaur Reservoir

Dinosaur Reservoir is delimited at its upstream end by W.A.C. Bennett Dam, which retains Williston Reservoir. The intake structure takes in water from Williston Reservoir through ten separate penstocks located at two different depths, and releases it via two tailraces. The northern tailrace receives water from three deep and two shallower intake penstocks, while the southern tailrace receives water from five shallower penstocks. The temperature of the water within the tailraces differs whenever Williston Reservoir is stratified and depends on which turbine units are in operation. Peace Canyon Dam, completed in 1980, is at the downstream end of Dinosaur Reservoir, located 6 km southwest of Hudson’s Hope. The reservoir is about 23 km long, has a steep bottom bathymetry, and lies in a steep-sided valley. There are five main tributaries of Dinosaur Reservoir, the largest being Johnson Creek, all of which have negligible flow rates compared to the W.A.C. Bennett Dam outflow. The normal operating water level of Dinosaur Reservoir ranges between 500.00 m and 502.92 m (BC Hydro 2007). The corresponding water volume at a water level of 502.92 m is 234 million m³ (BC Hydro 2012, pers. comm.). The flow rate can vary up to the maximum water licence discharge of 1,982.18 m³/s and down to the minimum flow requirement of 283.17 m³/s (BC Hydro 2007). The residence time, defined as the reservoir volume divided by the flow rate, is approximately two days at the average post-regulation flow rate of 1,158 m³/s (BC Hydro 2012, pers. comm.). Dinosaur Reservoir is operated in hydraulic balance over the day in that inflow and outflow are approximately balanced, and there is little fluctuation in water level.

The reservoir bathymetry (Figure 2.1) was obtained from BC Hydro, who supplied digitized versions of drawings made in May 1984 from the Water Management Branch of the British Columbia Ministry of Environment. More recent bathymetric surveys of the W.A.C. Bennett
Dam tailrace area were also incorporated in the model, as well as a shoreline digitized by EBA from aerial images.

### 2.2 Site C Reservoir

The Site C dam and generating station would be located approximately 7 km southwest of Fort St. John, and 1 km downstream of the existing Moberly River confluence (Figure 2.2). The proposed reservoir would lie in a valley with sides consisting of terraces varying in elevation. The reservoir would never be completely shaded by the valley walls, an important factor when considering the effects of incident solar radiation on water temperature.

The main tributaries to the Site C reservoir would be the Halfway and Moberly rivers. Discharge from these tributaries is generally much smaller than the inflow from Peace Canyon Dam, except that flows from Halfway River during freshet can briefly be comparable to dam releases. Minor tributaries include Cache Creek, Farrell Creek, and Lynx Creek. These five tributaries were included in the model.

The Site C dam would form a long (83 km) and narrow (0.5 to 1.5 km) reservoir. The expected maximum normal operating water level is 461.8 m. The total water surface area would be about 9,330 hectares with a volume around 2,310 million m$^3$ as described in Section 4 of the Environmental Impact Statement. The bathymetry data for the H3D model was obtained from LiDAR and field surveys, with a fine (1 m) resolution in elevation. The long-term mean flow rate through the Site C dam is projected to be slightly higher than the Peace Canyon Dam outflow due to tributary inflows from the drainage area downstream of Peace Canyon Dam, and for the purposes of this study, the Peace Canyon Dam flows were assumed to be similar to historical values. The residence time, defined as the reservoir volume (2,310 million m$^3$) divided by the average flow rate (1,260 m$^3$/s), would be approximately 22 days.

For this study, it was assumed that the intake forebay channel would consist of six penstocks with entrances 24.9 m wide and 22.2 m high. The depth range covered by the penstock entrances would be 3.2 m to 25.8 m at the maximum normal operating level of 461.8 m (Figure 4.19 in Section 4 Project Description).

### 3 Meteorological Data and Assumptions

The hydrodynamic model uses wind, air temperature, humidity, and cloud cover to calculate incident shortwave radiation, longwave back radiation, latent and sensible heat fluxes, and the resulting net surface heat flux, which increases or reduces the water temperature at the surface. Incident short wave radiation is also transmitted down through the water column, attenuating as it propagates downward, providing thermal energy directly to water below the
surface. Vertical mixing transfers heat from the surface layer down through the water column, but mixing is limited by the stabilizing effects of stratification.

The meteorological input data were obtained from nearby existing meteorological stations and meteorological stations installed specifically for the Project, as described in Volume 2 Appendix K Microclimate Technical Data Report. Wind generates currents, which modify vertical mixing and affect the rate of heat flux and therefore water temperature at the surface. Ice formation is also driven by heat fluxes between the atmosphere and water (or ice when already formed). When ice is present, the model uses this meteorological data, as well as computed water temperature and currents, to calculate the transmission of heat from the atmosphere to the water through the ice, the absorption of heat within the ice, and the ice temperature.

The closest regional Environment Canada meteorological station to the Project is Fort St. John Airport. The station records wind speed and direction, cloud amount and opacity, air temperature, and dew point temperature on an hourly basis. The Fort St. John station is located outside of the Peace River valley, on the plateau at an elevation of 694.90 m, approximately 12 km northeast of the Site C dam (Environment Canada 2011). There is also an anemometer on the W.A.C. Bennett Dam that is representative of wind conditions over Dinosaur Reservoir. The following subsections describe how the available meteorological data were used to represent meteorological conditions in the valley.

3.1 Winds

Hourly wind speed and direction from Fort St. John Airport are available from January 1, 1971, to present. Dinosaur Reservoir is, and the Site C reservoir would be, situated in the Peace River valley at least 140 m below the plateau, at their maximum normal water levels of 502 m and 461.8 m, respectively. A report by Thurber Consultants Ltd. (1977) suggests that winds in the valley are quite different from winds recorded on the plateau at Fort St. John. In particular, Thurber (1977) states that the wind direction is usually aligned with the valley, while the prevailing wind directions at Fort St. John are from the north, the southwest, and the east-southeast. A wind rose depicting the frequency and direction of winds at Fort St. John is shown in Figure 3.1.

Between 2009 and 2010, seven meteorological stations were installed in the valley, distributed along the length of the Site C reservoir (Figure 2.2; Volume 2 Appendix K Microclimate Technical Data Report). An important observation determined from the resulting wind time series in the valley is that while winds at Fort St. John have three dominant directions separated by about 120 degrees, winds in the valley have only two dominant directions separated by 180 degrees and aligned with the valley, confirming the observations of Thurber (1977). Even winds near the tributary valleys, such as at the Cache Creek meteorological station, are predominantly aligned with the main valley
direction and only under certain circumstances flow strongly from the tributary valleys. The meteorological station atop the W.A.C. Bennett Dam shows a similar pattern, with winds strongly aligned with the local valley direction.

Analysis of winds in the valley, as measured by the in-valley meteorological stations, indicates that the wind speed is usually much lower in the valley than on the plateau. Although the microclimate model accurately represented winds in the valley, the period of record for that model was only one to two years and therefore could not be used as inputs for this study (Volume 2 Appendix K Microclimate Technical Data Report). To provide 16.5 years of wind inputs, a method was developed to synthesize valley winds for the entire model run. To this end, EBA generated a statistical wind model to correlate winds in the Peace River valley with winds at Fort St. John, based on the in-valley meteorological stations and the valley direction. The details of the statistical prediction, including a discussion of prediction accuracy, are provided in a separate technical memo, Appendix A of this report.

In summary, winds in the valley are on average half the strength of winds on the plateau, and the valley provides an important steering effect. For the Dinosaur Reservoir valley, a simplified wind field was constructed with direction following the axis of the curvilinear grid and magnitude 50% of the wind speed at the W.A.C. Bennett Dam. The more complex statistical wind model for the Site C reservoir was an important step towards accurate predictions of water temperature and ice coverage because of the strong role that winds play in determining these two properties of the reservoir: winds generate currents at the surface of the reservoir, control the latent and sensible heat fluxes, modify vertical mixing in the water column and hence water temperature, and also affect ice formation.

Snapshots of the synthetic wind field in the two models are presented in Figure 3.2 (Dinosaur Reservoir model) and Figure 3.3 (Site C reservoir model). The statistical procedure for generating a synthetic wind field in the Peace River valley is more accurate for the stronger along-valley winds than for cross-valley and slope winds, as there is lower correlation at low wind speeds with Fort St. John. Slope winds are driven by horizontal air temperature differences and pressure gradients between the top and the bottom of the valley. However, these wind components are weak compared to the predominant along-valley winds, and water temperature is more sensitive to the stronger along-valley winds because exchanges of heat and momentum at the air-water interface are proportional to the wind speed and the square of the wind speed, respectively. Therefore, the statistical wind model captures the important winds for the purposes of hydrodynamic and temperature modelling.
3.2 Air Temperature

The top panel in Figure 3.4 shows hourly air temperature data observed at Fort St. John for the 1995–2012 period, with a four-day low pass filter applied for clarity of presentation. Hourly data for a single example year (2007) are shown in the lower panel.

3.3 Humidity

Humidity in the valley is calculated from hourly dew point air temperature recorded at Fort St. John. A review of model results indicated that humidity, and hence latent heat flux, has an important influence on simulated water temperatures in summer, but is less important in winter compared to the sensible heat flux.

3.4 Cloud Cover

Hourly cloud cover and cloud opacity data from Fort St. John are used in the model without modification. The top panel in Figure 3.5 shows cloud cover data for the 1995–2012 period, after a four-day low pass filter is applied for clarity of presentation. Hourly data for the year 2007 are shown in the lower panel.

4 HYDROLOGICAL DATA AND ASSUMPTIONS

For both Dinosaur and Site C reservoirs, the model is hydraulically forced by the reservoir’s inflows, outflows through the generating stations, and tributary inflows. Water temperature of tributary and reservoir inflows is an important input to the hydrodynamic model.

Evaporation and precipitation were estimated for the two reservoirs. According to Environment Canada’s 1971–2000 climate normal, precipitation at Fort St. John is 465.6 mm/year, and is assumed to be the same at the reservoir elevation for the purposes of this estimate. Evaporation from the reservoir surface of 223 mm/year was calculated using the same bulk fluxes routine that H3D uses for heat flux calculations. The net flux (precipitation minus evaporation) is estimated to be about 242 mm/year into each reservoir, or a yearly average of 0.71 m³/s for the Site C reservoir. Since inflows to the reservoir are typically on the order of 1,000 m³/s, the evaporation and precipitation mass fluxes can be excluded from the model, although the heat flux due to evaporation is represented in the model.

4.1 Tributary and Dam Flow Rates

Hourly W.A.C. Bennett Dam and Peace Canyon Dam outflows from 1984 through 2012 were available. The Dinosaur Reservoir model was only run for the period of time for which adequate calibration and validation temperature data are available (2008–2012). Figure 4.1
shows daily mean flows through the Peace Canyon Dam over the 2008–2012 period used in the Dinosaur Reservoir simulations.

The inflow from W.A.C. Bennett Dam is divided between two model cells representing the two tailraces, and distributed over the whole water depth and width of the model cells at these locations. The Peace Canyon Dam outlet is 39.0 m below the normal operating water level and is contained in a model cell 29 m wide and 16 m high. The corresponding model outlet area (396 m²) is larger than the actual design (four intake pipes of 9.75 m diameter and combined area of 299 m²). This slight simplification only changes the flow field in the cells immediately adjacent to the outflow, and does not affect computed temperatures.

Tributary flows into the Dinosaur Reservoir model were back-calculated based on W.A.C. Bennett Dam and Peace Canyon Dam outflows. Because estimated tributary flow (averaging approximately 11 m³/s) is negligible compared to the typical outflows from W.A.C. Bennett Dam (Figure 4.1), tributary inflows were added to the W.A.C. Bennett Dam outflow rather than accounting for them in the model at the exact tributary locations.

For the Site C reservoir model, the major inflow is the hourly Peace Canyon Dam outflow. Tributary inflows were estimated for the period from January 1995 through December 2011 (Volume 2 Appendix I Fluvial Geomorphology and Sediment Transport Technical Data Report). This longer time period, compared to the Dinosaur Reservoir simulation, allowed for an examination of a wide range of hydrological and meteorological conditions. Figure 4.2 shows the inflows to the reservoir for this time period. The Peace Canyon hourly data are displayed as a scatter plot to show the intra-daily variability in flow as dam releases increase and decrease to meet generating requirements. These hourly data were used in the reservoir model to accurately represent the hydrodynamic processes. The weekly averages of these flows are also shown.

The Halfway River discharges its waters into the Peace River about 46 km downstream of Peace Canyon Dam (Figure 2.2). This river and its valley are resolved by the model and the corresponding flow is added at the confluence of the Halfway River and the Site C reservoir (i.e., at the upstream extent of flooding of the Halfway embayment). The Moberly River discharges its waters less than 1 km upstream of the proposed location of the Site C dam and was added to the model at this location. Figure 4.2 also shows the daily flow rate for the five modelled tributaries between 1995 and 2011 at the reservoir confluence. At low flow, the tributary inflows are negligible. During freshet, the tributary inflows can account for a substantial fraction of the Peace River flow. Notably, the Halfway River flow was greater than the minimum licensed Peace Canyon Dam outflow of 283.2 m³/s in June in several years, and reached 2,790 m³/s in June 2001 during a particularly large freshet, exceeding the maximum licensed flow of the Peace Canyon Dam. Inflows from other tributaries along the reservoir (including Cache Creek, Farrell Creek and Lynx Creek) were estimated and added to the model (Volume 2 Appendix I Fluvial Geomorphology and Sediment Transport Technical Data Report).
Transport Technical Data Report). These three tributaries have much lower discharges than the Halfway and Moberly rivers.

The model assumes that the Site C reservoir would have a stable water level, within centimetres of the 461.8 m normal maximum operating level. The outflow at the Site C generating station is taken as the instantaneous sum of the Peace Canyon Dam outflow and tributary inflows. Consequently, simulated water level in the reservoir remains constant within a few tenths of a metre while flows through the reservoir vary in time. This assumption is not expected to influence the temperature and ice results as the proposed operating range is much smaller than the reservoir depth. The penstocks are represented in the model by two model cells, each of which is 74.7 m wide and 22 m high, which is similar in cross-sectional area to the design (Section 2.2).

In the modelling, both W.A.C. Bennett Dam and Peace Canyon Dam are operated in hydraulic balance over the day, in which outflows from Dinosaur Reservoir are always nearly identical to inflows. High flows from W.A.C. Bennett Dam generally occur in winter and lower flows in summer (May through September), while tributaries generally have a high flow rate during the May through September period and a lower flow rate the rest of the year.

One extreme flow event occurred during the simulated time period. The Williston Reservoir water level was lowered in the summer of 1996, resulting in a sustained period of high flows through both W.A.C. Bennett and Peace Canyon Dams. Flows were greater than 3,000 m$^3$/s for 50 days, and reached approximately 5,000 m$^3$/s for 20 days.

4.2 Water Level

In the modelling, water level in the Dinosaur Reservoir model adjusts itself according to the balance of inflows and outflows. The hydrology is fixed by the W.A.C. Bennett Dam and Peace Canyon Dam outflows, with the Peace Canyon Dam outflow modified by the estimated mean tributary flows.

For the Site C reservoir model, the water level is fixed at the expected maximum normal operating water level of 461.8 m by setting the outflow equal to the sum of all the inflows to the reservoir. These inflows include Peace Canyon Dam and the five major tributaries. Small variations in water level within the reservoir, on the order of 0.1 to 0.2 m, are due to natural water surface slopes, wind setup, and localized effects from tributary and dam inputs.
4.3 Water Temperature

4.3.1 W.A.C. Bennett Dam and Peace Canyon Dam Temperature Data

W.A.C. Bennett Dam outflow temperature data from October 2009 through April 2012 were provided by BC Hydro based on a flow-weighted average of thermostors in each tailrace channel. Temperature observations at W.A.C. Bennett Dam prior to 2009 relied on one thermistor and did not represent the combined output temperature during stratified conditions as each tailrace draws from different water depths.

Water temperatures have also been recorded hourly at the Peace Canyon tailrace, and data for the 2000–2012 period were available. These data were used to validate the Dinosaur Reservoir model results and as input to the Site C reservoir model. Observed W.A.C. Bennett Dam and Peace Canyon Dam outflow water temperatures for the period during which W.A.C. Bennett Dam temperature data are available (October 2009 through April 2012) are shown in Figure 4.3. The observed temperature differences between the inflowing and outflowing water is also plotted and represents the changes that the model must reproduce to be validated.

The temperature observed at the Peace Canyon Dam tailrace (outlet of Dinosaur Reservoir) is on average 0.14°C warmer than the temperature observed at W.A.C. Bennett Dam tailrace (inflow of Dinosaur Reservoir) over the 2009–2012 period (Figure 4.3). However, this difference consists of two seasonal characteristics. The difference is smaller and negative (0.05°C) during the winter months, reflecting cooling as the water passes through Dinosaur Reservoir during this season. The difference increases to an average of 0.4°C of warming between July and October. Both differences in temperature are due to the warming or cooling at the water surface of the Dinosaur Reservoir. W.A.C. Bennett Dam outflow temperatures in the summer undergo high frequency oscillations with a variable period of about one to four days, and amplitudes of up to 6°C, indicating switching between different intakes at W.A.C. Bennett Dam (Figure 4.3). The temperature fluctuations are partially filtered out by the time waters reach Peace Canyon Dam. For example, a two-day spike of cooler water from W.A.C. Bennett Dam in October 2009 appears as a smaller spike two to three days later at Peace Canyon Dam. However, in July through September, the variability of W.A.C. Bennett Dam temperatures is mostly smoothed out by processes within the Dinosaur Reservoir and the Peace Canyon Dam temperatures are relatively stable.

To provide 16.5 years of input data to the Site C reservoir model, Peace Canyon Dam output temperatures were required for the years 1995 through 2011. Observed water temperature data were available from 2001 to 2011. From 1995 to 2001, BC Hydro iteratively determined Peace Canyon outlet temperatures in the winter period based on the calibrated downstream ice model and observed ice front data (Volume 2 Appendix G Downstream Ice Regime Technical Data Report). Summer temperatures for 1997
through 1999 are unavailable. Averages of the Peace Canyon Dam observed summer
1 temperatures on each day of the year were used for these three summers, modified by a
2 biweekly temperature oscillation typical of the observed data. The observed and synthetic
3 Peace Canyon Dam temperatures are shown in Figure 4.4.

4.3.2 Tributary Temperatures
5 Tributary water temperatures were measured during 2006 and 2007 (Volume 2
6 Appendix E Water Quality Technical Data Report). These values were used to estimate
7 hourly tributary temperatures for the years 2000 through 2009 (Figure 4.5). The variations
8 in tributary water temperatures are closely related to the variations in air temperatures
9 recorded by Water Survey of Canada at their hydrometric stations on the Moberly and
10 Halfway rivers. The estimates were modified to account for winter tributary ice cover by
11 reducing the tributary temperatures to 0.1°C from mid-November to mid-March in each
12 year, based on winter temperature data collected in the Halfway River over the winter of
13 2011-2012 (Volume 2 Appendix I Fluvial Geomorphology and Sediment Transport
14 Technical Data Report). Tributary water temperatures for the years 1995 through 2000
15 and 2011 were estimated based on daily averages of the 2000–2009 temperature time
16 series.

4.3.3 Dinosaur Calibration Temperatures
18 Water temperature was continuously recorded from May through October 2008 at three
19 different sites within Dinosaur Reservoir: an upstream station (Dino 3) about 3 km from
20 W.A.C. Bennett Dam, a middle station (Dino 2), and a downstream station (Dino 1) near the
21 Peace Canyon Dam. These sites are shown on Figure 2.1. Each station recorded water
22 temperature at three different depths: 1 m below the surface, 5 m below the surface, and
23 3 m above the bottom of the reservoir. This last measurement corresponds to a depth
24 between 13 m and 15 m for Dino 3, between 20 m and 22 m for Dino 2, and between 33 m
25 and 35 m for Dino 1, depending on the water level in the reservoir. These temperature data
26 were used to calibrate the Dinosaur Reservoir model. Because W.A.C. Bennett Dam
27 temperature observations were incomplete in 2008, the model boundary was moved 3 km
28 downstream to the location of the upstream thermistors, and the temperature from these
29 thermistors was used as the model input.

4.4 Ice Formation
31 Three logging digital cameras observed ice conditions at locations in Dinosaur Reservoir in
32 the winters of 2010-2011 and 2011-2012. In addition, seven satellite images were
33 interpreted by C-CORE for ice model calibration (C-CORE 2012, pers. comm.). Most of the
34 satellite images were from RADARSAT 1 and 2 satellites, which can detect the differences
35 between smooth and rough surfaces. In calm conditions, the difference between a thin layer
of smooth ice and water is small, so the logging cameras were used to improve the
texture of the satellite data, as well as to qualitatively validate the model. The ice data
from the satellite images were used to validate the ice cover routines of the hydrodynamic
model. The ice module used in H3D has been validated in lakes in British Columbia, such
as Mara Lake (see Section 5.2).

5 METHODOLOGY

The spatial extent of the study area is limited to Dinosaur Reservoir and the Site C
reservoir, as described in Sections 3.1 and 3.2 and shown on Figures 2.1 and 2.2.

The temporal extent of the reservoir temperature and ice modelling is the years 2008
through 2011 for calibration and validation of the Dinosaur Reservoir model, and the years
1995 through 2011 for the model of the Site C reservoir.

5.1 The Hydrodynamic Model

5.1.1 Model Description

Circulation within the Dinosaur and Site C reservoirs was simulated using a proprietary
three-dimensional hydrodynamic model, H3D (Stronach et al. 1993). A comprehensive
technical discussion of H3D is provided in Appendix B. The following discussion provides
an overview of the model.

At each time step, H3D computes new values for the three components of velocity (u,v,w)
on a three-dimensional curvilinear grid (x,y,z), as well as scalar fields such as temperature,
dissolved solids, or sediment concentration. The spatial grid can be visualized as a number
of interconnecting computational cells, which collectively represent the body of water.
The curvilinear grid enables the model to follow more closely the varying orientation of the
sinuous Peace River valley, with the x-direction aligned with the along-valley direction.
Velocities are determined on the faces of the cells, and scalars such as temperature are
situated in the centre of the cells. The model operates in a time-stepping mode over the
period of simulation, dividing the multi-year simulation period into a number of small time
steps. During each time step, typically 20 to 40 seconds for the Site C reservoir model,
values of velocity, temperature, and any additional scalars are updated in each cell. The
vertical resolution was designed to resolve the thermocline over its entire annual cycle. The
model captures the important processes of the development of thermal stratification over
the course of the year, and the response, in terms of water level, enhanced currents and
vertical mixing, to wind-driven events. The model also resolves the complexities of flow in
the near-shore part of the reservoir. The increased vertical resolution near the
surface enables the model to consider the highly variable processes occurring close to the
1 water surface (i.e., temperature stratification, wind induced mixing, wind-induced velocity
2 shear, stream inflows).
3 Turbulence modelling is important in determining the correct distribution of velocity and
4 scalars (temperature, nutrients, sediments) that can be both passive or active, conservative
5 or non-conservative, and also subject to settling and re-suspension. The diffusion
6 coefficients for momentum and scalars at each computational cell depend on the level of
7 turbulence at that point. H3D uses a shear-dependent turbulence formulation in the
8 horizontal direction, and a shear- and stratification-dependent formulation in the
9 vertical direction.
10 H3D includes a penetrative convection mechanism: whenever a cell becomes denser than
11 the cell immediately below it, for instance through surface cooling at night, the two cells mix
12 instantaneously, thus removing the static instability. This leads to downward mixing of
13 scalars near the surface, which is important in the fall cooling period.
14 Atmospheric inputs are applied to each surface grid point in each time step. Data include
15 wind stress on the reservoir surface and radiant, convective, and latent heat fluxes through
16 the reservoir surface. Freshwater input to the reservoirs is dominated by flow from the
17 upstream generating facility, but the additional tributary inflows are also considered.

5.2 Ice Module

5.2.1 Description
20 Ice formation is driven by heat fluxes between the atmosphere and water, or through the ice
21 when already formed. H3D uses observed meteorological data, and computes and
22 balances the transmission of heat fluxes from the ice-air interface and the water-ice
23 interface through the ice, and the absorption of heat within the ice. The heat balance is then
24 used to compute ice properties such as the ice thickness and the fraction of each model cell
25 covered by ice, by determining whether ice is accumulating or melting. Wind also affects ice
26 formation in several ways: it produces currents that can inhibit ice formation; it affects
27 vertical mixing, and hence surface water temperature; and it affects the cooling rate
28 of surface waters. In addition, tributary flows and their respective temperatures affect the
29 formation of ice by modifying the surface currents and temperature stratification.
30 The ice module uses a number of parameters for heat fluxes, water, snow, and ice
31 properties. Standard values are taken, combined with results from Babine Lake, a deep
32 lake in British Columbia, where extensive field work has been conducted (Patterson and
33 Hamblin 1988). The thermal conductivity of ice is typically 2.30 W/(m°C). In these reservoir
34 models, a value of 1.15 W/(m°C) was selected to account for the insulating effect of snow
35 accumulation on top of the ice, which reduces the thermal conductivity. The sensitivity of
36 the simulated ice thickness to the reduction in thermal conductivity is a root-mean-square
difference of approximately 4 cm, which is small relative to Dinosaur Reservoir’s average ice thicknesses of 40 to 50 cm (discussed in Section 6.3).

Ice cover also results in a frictional boundary layer at the ice-water interface proportional to the ice thickness, but varying in roughness depending on whether ice is forming or melting. Parameters from Nezhikhovskiy (1964) are used to calculate a friction coefficient, which serves to decrease under-ice currents and, in most cases, reduce the rate of ice melting (Nezhikhovskiy 1964).

5.2.2 Validation: Simulation of Mara Lake Ice Cover

The available validation data for Dinosaur Reservoir included ice area observations but not measurements of ice thickness. The reliability of H3D in modelling ice thickness was demonstrated in a simulation of Mara Lake, north of Vernon, which is a part of the Shuswap Lake system in the Thompson Okanagan area of British Columbia (Hayco 2008). Data for quantitatively validating the ice module are not readily available, but the Mara Lake data, while not comprehensive, allowed a preliminary validation to be conducted. The nearest meteorological station is located in Vernon and provided hourly air temperature and wind data for the 2008–2009 period. The meteorological station located in Kamloops was used to obtain the cloud cover over the same period. The Shuswap River flow and the Mara Lake water level, obtained from the Water Survey of Canada, were used to estimate the flow through Sicamous Narrows and water level in Mara Lake. The model grid used for Mara Lake has a horizontal resolution of 100 m by 100 m. The vertical resolution varies from 0.5 m near the surface to 10 m for the deepest sections of the lake. The model was run from April 2008 to March 2009.

The simulated ice thickness versus time at locations corresponding to the observations near the northern shore of Mara Lake is plotted in Figure 5.1. The ice observations were not conducted at regular locations, and the variability of ice thickness on the same date is on the order of 0.1 m. The model matches observed ice thicknesses within the range of the observations on two of the dates. Alternatively, the predicted ice thicknesses match the observed values, if one shifts the simulated times by five days. This time shift could reflect differences between the prescribed meteorological conditions and the actual conditions prevailing at Mara Lake. The agreement between the model simulation and observations shown in Figure 5.1 shows that the model predicts appropriate ice thicknesses within approximately 0.1 m. Additional ice validation data will be presented for Dinosaur Reservoir in Section 6.3.
6 MODEL CALIBRATION AND VALIDATION: DINOSAUR RESERVOIR

To develop a model that would predict realistic conditions in the Site C reservoir, a model of Dinosaur Reservoir, a nearby water body, was developed, calibrated, and validated first. The model code and parameters developed for Dinosaur Reservoir were then used for the Site C reservoir.

6.1 Grid Details

Dinosaur Reservoir is represented in the numerical model by a high-resolution curvilinear grid (Figure 6.1). The dimensions of the grid cells varied with an average horizontal size of 121 m x 40 m, with the shorter horizontal dimension oriented across the reservoir axis. The reservoir is divided into 28 vertical layers with thicknesses varying from 0.5 m near the surface to 5 m for the deepest part of the reservoir. The horizontal and vertical resolutions of the grid differ in order to characterize the large aspect ratio of the reservoir, and to describe the variability of parameters such as stratification, wind mixing, and tributary inflow that are concentrated near the surface and require better vertical resolution. The average depth was 23.7 m and the water surface elevation was 502.1 m on the date of model initialization.

The outlet of Peace Canyon Dam, described in Section 2, is contained in three cells and three vertical layers. Model calibration was conducted from April to November 2008, the period during which in-reservoir thermistor data were available. For the validation run, the model was initialized at a temperature of 10°C on October 8, 2009, and run until April 1, 2012. The other model inputs are discussed in Sections 3 and 4.

6.2 Temperature

6.2.1 Results

Figure 6.2 and Figure 6.3 show representative surface temperature and ice thickness output from the Dinosaur Reservoir model. Figure 6.2 shows the maximum ice extent over the simulation period, which occurred on February 6, 2011, and Figure 6.3 is a snapshot of surface temperatures during a highly stratified day (August 11, 2011). The parameter represented in these figures is either the water surface temperature (by colours) or the ice surface temperature (grey shades) for parts of the reservoir covered with ice (results on ice formation are presented in Section 6.3). Both figures show that there is a relatively abrupt change in temperature as the reservoir widens just upstream of Johnson Creek. This location demarcates the start of ice formation.

Figure 6.4 and Figure 6.5 show vertical cross-sections of the water temperature and ice thickness along the thalweg, or deepest part of Dinosaur Reservoir, for the same
winter and summer days as the surface temperatures in Figure 6.2 and Figure 6.3. In
winter (Figure 6.4), there is weak “reverse” stratification in the reservoir, with temperatures
around 0.2°C at the surface and 1°C near the bottom. In summer (Figure 6.5), the reservoir
can be divided into two regions with different temperature regimes: the upstream region,
where temperature is vertically uniform, and the downstream region, where thermal
stratification develops.

To help explain these two distinct thermal regions, a plot of the cross-sectionally averaged
velocity along the axis of the reservoir is shown in Figure 6.6, as well as the cross-sectional
area. This figure shows the small cross-sectional areas and large velocities characterizing
the narrow, more river-like section of the reservoir running from the W.A.C. Bennett Dam
tailrace to Johnson Creek (about 9 km long) transitioning abruptly into a wide, more lake-
like section of the reservoir, with large cross-sectional areas and smaller along-channel
velocities. Strong mixing occurs in the upstream part of the reservoir, and consequently this
part of the reservoir shows little stratification. The downstream part of the reservoir between
Johnson Creek and Peace Canyon Dam is wider, resulting in lower velocities and weaker
vertical mixing.

The ability of the reservoir to develop vertical temperature structure also depends on the
horizontal flow of water. A strong thermocline cannot develop if surface water is drawn out
of the dam before sufficient heating can take place. The outlet to Dinosaur Reservoir is near
the bottom, so under lower flow conditions and winds that blow upstream, the warm surface
waters can be effectively protected from withdrawal, while ‘through flow’ from W.A.C.
Bennett Dam sinks and exits through the Peace Canyon Dam intakes. This is illustrated in
Figure 6.5 by following the ‘through flow’, represented by the near-homogeneous
temperatures below the 10°C contour, downstream from W.A.C. Bennett Dam, below the
front where stratification has developed near Johnson Creek, and out the Peace Canyon
Dam intake.

6.2.2 Model Calibration to Observed Temperatures within Dinosaur Reservoir

Two sources of calibration and validation data were available for the Dinosaur Reservoir
model: the 2008 thermistor data (Volume 2 Appendix E Water Quality Technical Data
Report) and the 2009–2012 period during which both W.A.C. Bennett Dam and Peace
Canyon Dam temperature data were available. The 2008 thermistor data were used to
calibrate the Dinosaur Reservoir model, and the 2009–2012 Peace Canyon temperature
data are presented as an independent validation. Commonly adjusted model parameters
include horizontal and vertical mixing coefficients, water clarity in the form of Secchi depth,
and coefficients modifying sensible and latent heat fluxes. During calibration, a range of
values for each coefficient was tested and model performance evaluated for each change.
Final model calibration parameters and further technical information are presented in
Appendix B. Some physical parameters, such as Secchi depth, were chosen based on the limited water quality data available.

The statistical methods used to measure model performance are root-mean-square error and a comprehensive ‘model skill’ equation (Equation 6.1). Root-mean-square error is presented in the same units as the original data and represents the magnitude of all errors over the entire predicted time period. Model skill is a measure of the agreement between predicted and observed data, with a skill of 100% representing a perfect match (Wilmott et al. 1981). It differs from the statistical correlation statistic r or $r^2$ in that a prediction that was perfect in magnitude but inverted in sign would still have a perfect $r^2$, whereas the skill would be negligible.

$$skill = 100 \times \left(1 - \frac{\sum |X_{Model} - X_{Data}|^2}{\sum (|X_{Model} - X_{Data}| + |X_{Data} - X_{Data}|)^2}\right)$$

Equation 6.1 Model Skill

Water temperatures recorded along Dinosaur Reservoir from May through October 2008 (Volume 2 Appendix E Water Quality Baseline Conditions in the Peace River) were used to calibrate the temperature model prior to its application to the Site C reservoir, specifically with respect to the simulation of stratification. Within the reservoir, temperature was continuously recorded from May through October at three different sites, as described in Section 4.3.3. Figure 6.7 shows the observed temperature time series at the three thermistor locations. The upstream thermistor represents the input temperature for model calibration. The bottom panel also shows the observed Peace Canyon Dam tailrace temperature. There is an increase in observed surface water temperature at the middle and downstream thermistors in absolute terms and relative to bottom temperature, reaching 7°C higher than the bottom water temperature on July 5, 2008. This increase in temperature is associated with moderate up-reservoir winds, which help to prevent the surface waters from being drawn out through the deep Peace Canyon Dam intake, and extend the warm surface waters upstream towards Johnson Creek. This stratification was quickly destroyed by a change in winds on July 6, 2008, resulting in the warmer water mixing with deeper water and exiting out the dam. The volume of warm water is smaller than the cooler water at depth, so the temperature increase measured at the Peace Canyon Dam is only 1.5°C by July 7, 2008.

The model provides a three-dimensional temperature field in Dinosaur Reservoir, allowing comparisons at the same depths and locations as the observations. For calibration purposes, the model was run using the Dino 3 (upstream) temperatures as the temperature of the W.A.C. Bennett Dam inflow since tailrace temperature were not available. Figure 6.8 compares time-series of simulated and observed temperatures at the downstream
thermistor site (Dino 1). The model reproduced both summer and winter temperatures, although the diurnal variability of the simulated surface waters is not as high as observed. The model matched the maximum surface water temperatures in early July and the associated stratification. The model also closely followed the fall cooling trend. The model performance is accurate with root-mean-square differences of 0.88°C for surface waters (1 m and 5 m depth), and 0.26°C for bottom waters (Table 6.1). Most of the temperature differences are in the form of small differences in timing of events such as the July 6 destratification, rather than large persistent offsets. Similar results were achieved at the Dino 2 station, although since Dino 2 is closer to the upstream boundary, it is not as useful for calibration.

### Table 6.1  Model Performance – 2008 Thermistors

<table>
<thead>
<tr>
<th>Location</th>
<th>Root-mean-square Difference (°C)</th>
<th>Model Skill</th>
<th>Maximum Difference (°C)</th>
<th>Minimum Difference (°C)</th>
<th>Mean Difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dino 1 Surface</td>
<td>0.88</td>
<td>97.56</td>
<td>5.35</td>
<td>-2.80</td>
<td>0.12</td>
</tr>
<tr>
<td>Dino 1 Bottom</td>
<td>0.26</td>
<td>99.79</td>
<td>1.71</td>
<td>-0.74</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The root-mean-square differences between simulated and observed values should be compared to the natural temporal variability in temperature, which is up to 1.5°C within one day at the surface thermistor. Model skill is high compared to the maximum possible value of 100%. Model simulations predict up to 10°C of temperature stratification can develop in summer in the downstream part of the reservoir, with maximum summer temperatures reaching 18 to 20°C at the surface and 9 to 11°C at the bottom of the reservoir during the most stratified days. The thermocline depth lies between 2 m and 10 m below the surface, and its location and strength vary with meteorological and hydrological inputs. These periods of high stratification are associated with the same up-reservoir winds that produced the observed July peak in surface temperatures in the 2008 data (Figure 6.7). The differences between the model predictions and observations are small compared with the observed degree of temperature stratification in Dinosaur Reservoir, and compared with natural temporal variability which shows that the model accuracy is adequate for predicting reservoir processes.

### 6.2.3  Model Validation with Observed Peace Canyon Tailrace Temperatures

The Dinosaur Reservoir model uses the W.A.C. Bennett Dam tailrace temperature as an input and computes the temperature throughout the reservoir up to the Peace Canyon Dam forebay. The period of record for accurate W.A.C. Bennett Dam temperature data is from...
October 2009 through April 2012. This period was used to validate the Dinosaur Reservoir model, using the parameter settings achieved during the calibration to 2008 thermistor data.

**Figure 6.9** presents time series of observed Peace Canyon Dam tailrace temperatures and the simulated Peace Canyon Dam intake temperatures for the period from October 2009 through November 2010. The model performance statistics for this run are shown in **Table 6.2.** The agreement is accurate, with a root-mean-square difference of 0.2°C, instantaneous differences ranging from 1.88°C to -1.24°C, and an average difference of -0.01°C. The skill in predicting Peace Canyon Dam tailrace temperatures is better than the thermistor calibration (**Table 6.1**), which is expected since the dam outflow temperature is an average of temperatures at many depths, while the thermistor comparison must match the exact vertical structure of the reservoir. The seasonal variation is reproduced correctly as well as secondary temperature oscillations with periods of approximately one to two days.

**Table 6.2 Model Performance – 2009-2010 Peace Canyon Dam Tailrace**

<table>
<thead>
<tr>
<th>Location</th>
<th>Root-mean-square Difference (°C)</th>
<th>Model Skill</th>
<th>Maximum Difference (°C)</th>
<th>Minimum Difference (°C)</th>
<th>Mean Difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peace Canyon Dam Tailrace</td>
<td>0.20</td>
<td>99.94</td>
<td>1.88</td>
<td>-1.24</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

The root-mean-square differences between simulated and observed tailrace temperatures are small compared with the variability in the observed data, and approach the accuracy of typical thermistor observations; therefore the model is deemed accurate for predicting reservoir outflow temperatures. This observation justifies both the model itself, and the methodology to assemble the input data for the model.

### 6.3 Ice Formation

The Dinosaur Reservoir model predicted ice cover and thickness for three winters, and the results were compared with satellite observations for the winters of 2010-2011 and 2011-2012. The upstream part of the reservoir from W.A.C. Bennett Dam to Johnson Creek, which is about one third of the reservoir area, is narrower and the resulting high velocities, along with the warmer water leaving the Williston Reservoir, tend to prevent ice from forming in this upstream reach. The downstream part of the reservoir, between Johnson Creek and Peace Canyon Dam, covers about two-thirds of the total reservoir area. The model predicts that this downstream area starts freezing when the air temperature is below -20°C, as described below.

**Figure 6.10** plots time series of the air temperature used in the model, the percentage of the reservoir covered by ice (area covered by ice divided by total area of the reservoir), and the mean ice thickness over the ice-covered part of reservoir (volume of ice divided by the
ice-covered area of the reservoir) for the winter of 2010–2011. The percentage of the reservoir covered by ice peaked at 77% in February, and the average ice thickness reached 0.50 m. The ice coverage based on satellite image observations, as described in Section 6.3, is shown as red squares. The sharp oscillations of the ice coverage in February and March show how quickly the simulated ice forms and melts from one day to the next, as the meteorological conditions vary. There is typically an inverse correlation between ice cover and average ice thickness. In general, sheltered areas, such as the Johnson Creek confluence and the area north of the anti-vortex dam (the promontory just upstream of Peace Canyon Dam that is visible on Figure 2.1), are frozen between early December and the end of May. When only the sheltered areas are frozen, the ice coverage (red lines, Figure 6.10) is small and the mean thickness of ice (blue lines) is high. The rest of the reservoir has an ice coverage that closely depends on the air temperature. Ice forms readily when the temperature is below -20°C, but quickly melts as the temperature increases. When a larger part of the reservoir freezes, the average thickness of ice typically decreases due to the large expanse of thin ice included in the average. Agreement with the three observed ice areas is good, with differences of 8.7%, 2.5%, and 1.2% of the reservoir area.

Figure 6.11 shows the same plot for the winter of 2011–2012. This winter was warmer than the winter of 2010-2011, with only two long periods with air temperatures below -20°C. Ice covered up to 38% of the reservoir in February and March, and the maximum average ice thickness was 0.35 m. Two satellite photos were interpreted in 2012, and while the model underestimated the ice area in January, the prediction in March was within 2% of the satellite image observation. The differences between the simulation and the observations could be due to dynamic processes such as movement of ice by wind or currents, formation of pressure ridges, or the accumulation of snow which are not simulated by the model. Figures 6.12, 6.13, and 6.14 show the simulated ice coverage and thickness as an overlay on the three satellite images from the winter of 2010–2011. The satellite-derived ice areas are shown as red cross-hatched areas, while the model-predicted ice thicknesses are in blue and green. The dates of each image coincide with the observed data points in Figure 6.10. The area upstream of Johnson Creek is excluded because it is not covered by the satellite image and forms no ice.

Ice tends to build from the shore, often leaving the middle part of the reservoir ice free because of the combined effect of less (shallower) water to cool near the shore and higher velocities in the centre of the channel. The middle of the reservoir only freezes a few days each year, when the air temperature approaches -30°C (Figure 6.10), with an ice thickness of a few centimetres. Some processes, such as the floating ice just downstream of Johnson Creek visible in the satellite image in Figure 6.12, cannot be reproduced by the model, but the areas of ice and open water are otherwise similar. It is not possible to determine ice
thicknesses from the satellite images, but the areas with persistent ice cover according to
the satellite images correspond well with the thicker ice in the model.

6.4 Conclusions
The Dinosaur Reservoir model reproduced observed water temperatures in all seasons.
The ice formation characteristics predicted by the model match well with satellite imagery
and photographs. Estimated valley-oriented wind velocities (50% of the winds at
W.A.C. Bennett Dam) are sufficient to reproduce temperature and ice trends in the
reservoir, and it is likely that the availability of site-specific meteorological data is the limiting
factor on model performance. Meteorological conditions near the Site C reservoir are better
characterized, which reduces the uncertainty of applying the model to the reservoir.

7 RESULTS: SITE C RESERVOIR

7.1 Grid Details
The Site C reservoir is represented in the numerical model by a high-resolution curvilinear
grid with cells of varying dimension, with a nominal horizontal size of 210 m by 90 m in
much of the reservoir (Figure 7.1). The grid has increased resolution (averaging 100 m by
100 m) near the confluences of the Halfway River, Cache Creek, and the Moberly River
(which is adjacent to the Site C dam site). The horizontal resolution of the numerical model
determines the smallest features that can be realistically resolved in the simulation. The
reservoir is divided into 26 vertical layers of thickness varying from 0.5 m near the surface
to 5 m for the deepest part of the reservoir and matching the layers in the Dinosaur
Reservoir model. The vertical resolution was designed to capture features such as the
thermocline. The reservoir depth varies from approximately 7 m near Peace Canyon Dam
to 52 m near Site C dam, with an average depth of 24 m at the maximum normal operating
level of 461.8 m. For this study, it was assumed that the intake forebay channel would
consist of six penstocks with entrances 24.9 m wide and 22.2 m high. At the maximum
normal operating level of 461.8 m, the penstock entrances would extend from a depth of
3.6 m to a depth of 25.8 m below the normal operating level (Figure 4.19 in Section 4
Project Description). The intake to the Site C generating station is contained in 2 cells
and 11 vertical layers in the model. The model was initialized at 3.0°C on April 30, 1995,
and run until November 2011—a total of 16.5 years. A long-term simulation allows an
examination of year-to-year variability in water temperature and ice cover, as well as
simulation of particularly cold winters in 1995 and 1996 and a large flow event in 1996. The
model inputs were discussed in Sections 3 and 4.
7.2 Temperature

7.2.1 Summary of Simulated Temperature Patterns in Site C Reservoir

Surface temperature maps summarize the changes in temperature along the length of the reservoir. Figure 7.2 and Figure 7.3 show representative views of surface temperature from the Site C reservoir model. Figure 7.2 shows a snapshot during a period with large ice extent, and Figure 7.3 is a snapshot of surface temperatures during a period with the highest temperature stratification. The temperature scales have been changed between these two figures to better represent the different temperature ranges in winter and summer. In Figure 7.2 “cool” colours (purple to blue) represent the temperature of open water, and grey shades represent ice thickness. The temperature patterns are similar to those for Dinosaur Reservoir: in winter, the warmest water is found either at the upstream end of the reservoir or in the deep waters at the downstream end of the reservoir, and ice forms over the downstream part of the reservoir. For the Site C reservoir model, the fraction of the reservoir covered by ice is considerably larger than for Dinosaur Reservoir due to the relatively slow-moving waters and longer residence times. In the summer, Figure 7.3, the water warms as it moves downstream through the reservoir, and averages 3.2°C warmer at the intake of the Site C generating station than at the tailrace of the Peace Canyon Dam in the month of June. Surface temperatures show a greater variation, and can be 8°C to 10°C warmer at the downstream end of Site C reservoir compared to the upstream end.

7.2.2 Summary of Simulated Temperature Cross-Sections in the Site C Reservoir

Cross-sectional plots of reservoir water temperature allow examination of stratification and changes in temperature and ice cover along the length and depth of the reservoir. Figure 7.4 and Figure 7.5 show vertical cross-sections of simulated temperatures along the deepest part of Site C reservoir (the thalweg) for the same days as Figure 7.2 and Figure 7.3, respectively. In winter (Figure 7.4), there is “reverse” stratification in the reservoir, with temperatures ranging from nearly 0°C under the ice to 2°C at the bottom. The reverse stratification arises because fresh water is densest at 4°C and the reservoir cools more at the surface than at the bottom, while simultaneously being protected from wind mixing energy by ice cover. In summer (Figure 7.5), the reservoir can be divided into two sections with different temperature regimes, similar to the temperature regimes in Dinosaur Reservoir but with a more diffuse transition. In the first 20 to 30 km of the Site C reservoir, velocities would be higher and the temperature would be vertically homogeneous. This part of the reservoir would be shallow (less than 20 m deep) and narrow (about 0.8 km wide), which would result in high velocities, between 0.2 m/s and 2.0 m/s, and sufficient shear stress to mix the water. At greater distances from the Peace Canyon Dam, the reservoir would become deeper (up to 52 m deep) and wider (up to 1.5 km). As a result, the velocities would be one or two orders of magnitude smaller.
Unlike Dinosaur Reservoir, water in the Site C reservoir would be withdrawn from the top half of the reservoir. The ‘through flow’ can be followed in Figure 7.5 above the 8°C contour in this snapshot as it separates from the bottom near the Halfway River, bypassing cooler deep water. Warm surface water would also be drawn out through the dam, but the length of the reservoir would be sufficient for vertical stratification to develop before this water is withdrawn. Additional discussion of density and transport patterns in the Site C reservoir can be found in the Reservoir Sediment Report, Appendix G of Volume 2 Appendix I Fluvial Geomorphology and Sediment Transport Technical Data Report.

Time series of surface and bottom reservoir temperatures at a representative location in the lower basin of the reservoir (Lower Basin Station in Figure 7.1) are shown in Figure 7.6. The temperature difference between the surface and the bottom is also shown. The reservoir develops 5 to 15 degrees of temperature stratification in most years. Stratified conditions typically start in the middle of May when temperatures exceed 4°C. Mixing occurs in the fall, typically in mid-October.¹

The duration of stratified conditions in the lower basin of the reservoir is typically 155 days, ranging from 129 days in 2002 to 171 days in 2005. Stratified conditions last much longer than in Dinosaur Reservoir, as the residence time of the water in the Site C reservoir is about 22 days, compared to the 2 to 3 day residence time in Dinosaur Reservoir. The depth of the thermocline that is generated depends on the meteorological conditions. Maximum surface temperatures reach between 16 and 21°C in the years modelled, while temperatures at the bottom of the reservoir gradually increase throughout the summer but reach only 9 to 11°C before mixing completely with surface waters during the fall overturn.

The Site C dam intake structure would span depths between 3.2 m and 25.8 m, but the model predicts that water would be withdrawn from a wider depth range. For example, denser waters from deeper in the reservoir can be drawn up into the forebay, illustrated by the temperature contours in Figure 7.4 sloping upwards towards the intake depth.

However, this withdrawal does not extend to the bottom of the reservoir until the fall overturn, and cool water remains in the lower basin of the reservoir until the surface waters cool and wind-induced mixing destroys stratification.

Modelling the high-discharge event in the spring and summer of 1996 (Figure 7.6) shows higher bottom temperatures and lower surface temperatures in the Site C reservoir than other years, and a shorter time period during which the reservoir is stratified. The residence

¹ This destruction of stratification is sometimes known as the fall overturn, and results from factors such as increased vertical mixing due to winds and reduced heating or strong cooling of surface waters. These two processes form a positive feedback loop whereby surface cooling reduces the density difference with respect to bottom waters, reducing the stability of the water column stratification, and allowing the next wind mixing event to penetrate to deeper waters.
time of the Site C reservoir is reduced to five days at the 5,000 m$^3$/s flow rates seen in this event (Figure 4.2).

### 7.2.3 Comparison between Simulated and Observed Water Temperature at the Outlet of the Site C Reservoir

The simulated water temperature at the outlet of the Site C reservoir was calculated by averaging the temperatures over the model cells containing the intakes to the generating station. The time series of simulated temperatures at the Site C intakes is shown in Figure 7.7 for the period between January 1995 and November 2011. The Peace Canyon Dam tailrace temperatures are also shown to illustrate the changes in temperature that would occur over the length of the reservoir. In summer, the simulated temperature at the Site C reservoir outlet is warmer earlier in the year than the waters at the outlet of Peace Canyon Dam. The maximum difference in temperature between the two extremities of the Site C reservoir reaches 6.2°C in June 2002. In winter, the temperature is colder earlier in the year at the Site C reservoir outlet than it is at Peace Canyon Dam, with a difference reaching -1.9°C in December 2001. These differences in water temperature are a result of the warming or cooling induced during the water’s residence time in the reservoir and the temperature effects of tributary inflows, as discussed previously. The smallest change in simulated temperatures between the Peace Canyon Dam and Site C tailraces occurred during the high flow event in 1996, because the water did not have as much time to warm as it travelled the length of the reservoir.

The water in the existing Peace River naturally changes in temperature between Peace Canyon Dam and the Site C dam location due to meteorological and hydrological fluxes. Determination of the differences between the expected (simulated) Site C reservoir tailrace temperature and temperature at the equivalent location on the Peace River under existing conditions is one of the primary objectives of this study and provides an understanding of predicted changes in river temperature due to the Project. Observations of the existing Peace River temperatures near the Site C dam site were available from the Water Survey of Canada hydrometric station #07FA004 (Peace Above Pine), which is 6.5 km downstream of the dam site. Figure 7.8 compares time series of simulated Site C tailrace temperatures with observed temperatures at Peace Above Pine. The monthly average simulated and observed water temperatures for each month are presented in Table 7.1.
Table 7.1 Simulated and Observed Average Monthly Temperatures at Site C Tailrace (October 2007 – October 2011)

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean Monthly Temperature (ºC)</th>
<th>Conditions with the Project: Simulated</th>
<th>Difference (Simulated – Observed)</th>
<th>Time Lag (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing Conditions: Observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>0.47</td>
<td>1.20</td>
<td>0.73</td>
<td>16</td>
</tr>
<tr>
<td>February</td>
<td>0.72</td>
<td>0.71</td>
<td>-0.01</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>1.37</td>
<td>0.97</td>
<td>-0.40</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>2.89</td>
<td>2.03</td>
<td>-0.86</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>5.89</td>
<td>5.18</td>
<td>-0.70</td>
<td>9</td>
</tr>
<tr>
<td>June</td>
<td>10.47</td>
<td>9.92</td>
<td>-0.56</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>12.58</td>
<td>12.85</td>
<td>0.27</td>
<td>8</td>
</tr>
<tr>
<td>August</td>
<td>12.75</td>
<td>13.86</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>11.40</td>
<td>12.70</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>9.04</td>
<td>10.48</td>
<td>1.50</td>
<td>16</td>
</tr>
<tr>
<td>November</td>
<td>5.71</td>
<td>6.69</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>2.25</td>
<td>3.04</td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>

A positive difference in Table 7.1 indicates that water leaving the Site C reservoir is warmer than the existing river at the Peace Above Pine station. The simulated mean monthly temperatures are higher from July to January, and lower between February and June. The largest changes are evident in April and October where mean temperatures are 0.86°C cooler in April and 1.50°C warmer in October compared to the existing Peace River.

The monthly averaged simulated and observed water temperatures at the Site C tailrace, as in Table 7.1, are plotted in Figure 7.9. The daily range for the observed and simulated temperatures (Table 7.2) is plotted as whiskers, or ‘error bars,’ and the difference between the simulated and observed mean monthly temperatures are plotted as bars along the bottom axis.

The changes in temperature due to the Project can be characterized as a time delay as well as an absolute difference. Instead of measuring the vertical distance (i.e., temperature) between the simulated and observed time series on Figure 7.8 and Figure 7.9, measurement of the horizontal distance between the curves represents time. Due to limited observations, the available data were categorized into four seasons (January through March, April through June, July through September, and October through December) corresponding to the ice-covered, warming, summer, and cooling temperature seasons (Table 7.1). Lags were calculated by time-shifting the curves until the difference between the two curves was minimized. These time lags are presented in the last column of Table
7.1. The time lags indicate that seasonal temperatures in the Peace River with the reservoir in place would be approximately one to two weeks behind existing conditions. The largest time lags occur during the colder months, when the bulk of the reservoir and the presence of ice cover keep the reservoir outflow colder than the existing river.

The average of the daily temperature ranges (maximum to minimum) for both the Peace Above Pine station and the simulated Site C tailrace temperatures are summarized in Table 7.2. The model results suggest that the Site C tailrace temperatures would have a smaller daily range compared to the existing river.

### Table 7.2 Simulated and Observed Average Daily Temperature Range at Site C Tailrace (October 2007 – October 2011)

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean Daily Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing Conditions: Observed</td>
</tr>
<tr>
<td>January</td>
<td>0.11</td>
</tr>
<tr>
<td>February</td>
<td>0.20</td>
</tr>
<tr>
<td>March</td>
<td>0.48</td>
</tr>
<tr>
<td>April</td>
<td>0.84</td>
</tr>
<tr>
<td>May</td>
<td>0.88</td>
</tr>
<tr>
<td>June</td>
<td>1.29</td>
</tr>
<tr>
<td>July</td>
<td>1.11</td>
</tr>
<tr>
<td>August</td>
<td>0.93</td>
</tr>
<tr>
<td>September</td>
<td>0.61</td>
</tr>
<tr>
<td>October</td>
<td>0.40</td>
</tr>
<tr>
<td>November</td>
<td>0.24</td>
</tr>
<tr>
<td>December</td>
<td>0.18</td>
</tr>
</tbody>
</table>

7.3 Ice Formation

The modelling results suggest that, in the Site C reservoir, ice would form quickly in response to meteorological changes but would not melt as suddenly as in Dinosaur Reservoir. The ice would start forming first near the Site C dam, where the reservoir is deeper and wider with lower velocities, and would propagate upstream towards the Peace Canyon Dam. Ice would also start forming in tributary arms of the reservoir at the beginning of the winter in November or December. In the winter of 2007-2008, a representative winter based on air temperatures, the first major onset of ice covered two-thirds of the reservoir in 11 days, before partially melting again. The ice would form faster on the north side of the reservoir than on the south side. It was confirmed, by means of a model simulation without the Coriolis force, that this preferential formation is due to Coriolis deflection of the water.
flowing through the reservoir, resulting in slightly higher velocities along the south shore
that reduce ice formation. The frictional drag of ice reinforces this pattern, further reducing
the velocities on the north shore of the reservoir. The last area of ice formation would be the
centre of the reservoir, which would also be the first place to melt. The ice formation
processes in the reservoir differ from those in a flowing river. The ice formed on the
reservoir is thermal ice, which forms in solid sheets on the surface. The spatial pattern of
ice formation predicted in the Site C reservoir is similar to the pattern of ice formation on a
flowing river in that the ice tends to form at the downstream end first, with ice coverage
progressing upstream through the winter.

Figure 7.10 shows a time series of the air temperature, the percentage of the reservoir
covered by ice (area covered by ice divided by the total area of the reservoir) and the mean
ice thickness over the ice-covered part of the reservoir (volume of ice divided by the ice-
covered area of the reservoir) as predicted by the model for the years 1996–2011. An
example of nearly full ice coverage was shown in Figure 7.2, illustrating 95% coverage on
January 14, 2005. During most of the cold periods shown in the model, the reservoir
freezes between the dam and just upstream of the Halfway River, and during the coldest
days, ice reaches farther upstream to Lynx Creek. Cycles of formation and melting occur a
couple of times during most winters, depending on the temperature and wind conditions,
but the ice cover is more stable than in Dinosaur Reservoir. A typical amount of ice melt in
one event is 20% of the reservoir area. The first 20 km of the reservoir from Peace Canyon
Dam (which includes Hudson’s Hope) is only occasionally covered by ice. This part of the
reservoir close to Peace Canyon Dam has higher velocities, which reduces ice formation,
and the temperature of the outflow from Peace Canyon Dam is always above zero. Higher
velocities near Lynx Creek and downstream of Farrell Creek also inhibit ice formation,
whereas a widening of the reservoir between these two tributaries allows thin ice cover to
form. The maximum coverage over the simulation period occurred in mid-January 1996,
reaching 98% coverage after nearly a week with air temperatures below -40°C.

Figure 7.11 shows the results for the winter of 2007–2008 and the short-term fluctuations in
ice properties. There are fewer sharp oscillations in the ice coverage than in Dinosaur
Reservoir, showing that the ice is not melting and re-forming as frequently and the greater
ice thicknesses are less easily melted by periods of warm air temperature. It takes a few
days for the ice to form initially. Subsequent partial melt and ice re-formation cycles occur a
couple of times every winter, but there is a tendency for ice coverage to reach its maximum
value in February. In general, an ice cover forms on the tributary arms of the reservoir from
early November to the middle of May, and sub-zero temperatures are sufficient to freeze
areas with slow-moving water. When there is an ice cover on the tributary arms of the
reservoir, but not the majority of the reservoir, the ice coverage (red lines) is below 5% and
the mean thickness of ice in the tributaries (blue lines) is about 0.1 m. As the rest of the
reservoir freezes, depending on the air temperature and wind conditions, average
thicknesses climb steadily. Ice cover up to and including Halfway River corresponds to an
ice cover of 65%.

Simulated ice cover maps for the first day of each winter month for the winter of 2007-2008,
indicated as boxes on Figure 7.11, are shown in Figures 7.12 through 7.16. Small pockets
of ice form in October, and the area covered starts increasing in early November. When the
air temperatures drop and remain below -15°C, in early December, ice cover increases
from 12% (Figure 7.11) to 60% of the reservoir surface in the span of eight days. The ice
cover subsequently dropped to 26% by mid-December. The ice coverage reached 71% on
January 1, 83% on February 1, and decreased to 67% and 42% on March 1 and April 1,
respectively (Figures 7.12 to 7.16). The ice thickness steadily increased until mid-February
to an average of 0.53 m, after which both cover and thickness started dropping. The
average thickness of ice decreases with the coverage when the air temperatures are
warmer for an extended period of time (Figures 7.10, 7.11).

7.4 Discussion of Model Sensitivity

The model parameters used in this study were adjusted, where appropriate, based on the
calibration and validation datasets to best fit the observations. The correspondence
between simulated and observed temperatures in Dinosaur Reservoir, discussed in
Sections 6.2.2 and 6.2.3, provides confidence in the reliability of the model and gives
numerical estimates of uncertainty. Values for flows through Peace Canyon Dam and
W.A.C. Bennett Dam as well as from the major tributaries are well known, and there is little
uncertainty in these parameters. Estimates or assumptions were made regarding other
input data, for example, estimates of winds over the reservoirs and using yearly average
tributary temperatures when data were unavailable. The sensitivity of the simulated outlet
temperatures were tested in scenarios with increased wind speeds, alternate intake
hydraulics near the dam, and using an implementation of H3D with suspended sediment
included. The sensitivity of the reservoir ice cover to some of the changes is also presented
in this section.

A possible source of uncertainty is the in-valley wind speeds. As described in Volume 2
Appendix K Microclimate Technical Data Report, winds in the post-reservoir valley may
be slightly faster than existing conditions due to the decreased friction of the reservoir
surface compared to the existing land cover. A Site C reservoir temperature and ice model
scenario was run with wind speeds increased by 10%. The resultant simulated Site C
reservoir outlet temperatures increased by approximately 0.1°C from August to October,
decreased by a similar amount in June, November, and December, and were less than
0.1°C colder from January through April as compared with the standard scenario. The
changes result from increased heat fluxes both into and out of the reservoir, and alterations
in the vertical distribution of heat and the timing of stratification and destratification. The
increase in wind speed had transient changes on the reservoir ice cover with no long-term
trend. The 0.1°C sensitivity to a 10% increase wind speed is small compared to the predicted temperature changes due to the Project (Table 7.1).

Another possible source of uncertainty in the model is the velocity distribution of water as it is drawn into the intakes of the Site C generating station. It was assumed in H3D that water enters the intakes at uniform velocity with respect to depth. The results of BC Hydro’s computational fluid dynamics modelling, which examined the hydraulics of the headpond, intakes, and dam tailrace, indicate that velocities were higher near the bottom of the intakes and lower near the top. As the water temperature changes over this vertical distance, the calculation of output temperature could be altered compared to the straight average used in this study. A post-processing of model results that weighted temperatures according to the velocities from the computational fluid dynamics modelling resulted in outlet temperatures that were less than 0.1°C warmer in winter, and up to 0.4°C cooler in summer, reflecting the larger proportion of deep water that is drawn into the Site C generating station. In winter, temperatures of the deep water are warmer than the shallow and mid-depth water, so withdrawing a greater proportion of deep-water results in a somewhat warmer predicted outflow temperature. In summer, bottom temperatures are cooler than in the rest of the water column, so withdrawing a greater proportion of deep water results in a cooler outflow temperature. The 0.1°C to 0.4°C sensitivity to the velocity distribution at the outlet is small compared to the predicted outflow temperature changes due to the Project in the appropriate seasons and, more importantly, tends to reduce the predicted changes, so the model results as presented in Table 7.1 are deemed conservative. This sensitivity test did not change the reservoir ice regime.

**Volume 2 Appendix K Microclimate Technical Data Report** describes predictions of spatially and temporally varying temperature and humidity conditions in the Peace River Valley under post-reservoir conditions. The predictions are based on the period of October 2004 through September 2005 and indicate a small increase in average annual air temperature, the magnitude of the monthly difference being from 0.6°C colder to 1.2°C warmer. (Table 5.1.1 of Volume 2 Appendix K Microclimate Technical Data Report). As part of the assessment of the climate change effects, the Site C reservoir model was re-run with air temperatures that were 1°C and 4°C warmer, values that approximate and exceed the predicted changes due to the presence of the reservoir. Changes in outlet water temperatures were found to be at most 20% of the increases in air temperature. Consequently, changes in water temperature due to microclimate associated with the presence of the reservoir would be at most 0.2°C. The sensitivity of the reservoir to air temperature increases is discussed with respect to climate change below in Section 7.5.

The temperature and ice model for this study was adapted in another study to simulate the transport and deposition of sand, silt, and clay in the reservoir (Appendix G of Volume 2 Appendix I Fluvial Geomorphology and Sediment Transport Technical Data Report.). Suspended sediment in sufficient quantities can change the density of water and therefore...
the behaviour of the reservoir in terms of stratification and temperature distribution. When
the sediment model was run for the decade 2000–2009, and compared to the temperature-
only model, the outflow temperatures were generally within 0.1°C. Temperatures during the
spring freshet were cooler in the sediment model, while temperatures during the fall were
approximately 0.1°C warmer. This seasonal pattern is likely due to the trapping of relatively
warm, yet sediment-laden water during the spring freshet in the lower basin area, and the
mixing of this warmer water up and out the dam in the fall. The sediment model had no
systemic difference in ice cover, but a small (0% to 5%) decrease in ice thickness.

These sensitivity tests help understand the variability in temperature and ice predictions
under alternative assumptions regarding model inputs or dam hydraulics. The responses to
changes in inputs in terms of outlet temperatures are small compared to the predicted
changes due to the Project (Table 7.1) and none of the sensitivity tests change the
conclusions of this report in terms of the general thermal and ice regime within and the
reservoir.

7.5 Discussion of Climate Change

As described in Volume 2 Appendix T Climate Change Summary Report, air
temperatures in the Peace region have increased approximately 1.2°C over the past
century, and are projected to increase 1.9°C to 2.5°C by 2050 and 2.5°C to 3.9°C by 2080.
The increase in mean air temperatures has been, and is expected to be, mostly due to
warmer temperatures in winter. A slight increase in tributary flow and earlier freshets are
expected in the Peace region.

The sensitivity of water temperatures in the Site C reservoir to climate change was tested
with a series of model runs with air temperatures increased by a constant ranging from 1°C
to 4°C. These constant increases are simpler than the time-varying climate change
scenarios but span the range of temperature increases in 2050 and 2080 time frame. The
response of the Site C reservoir to climate change would also depend upon the response of
Williston Reservoir to a warming climate, but in the absence of quantitative predictions in
Williston, the Site C reservoir model was tested without changing the temperature of the
inflowing water. An additional sensitivity test with warmer inflowing water confirmed that this
approach is the most conservative as the warming in the inflowing water would reduce the
temperature difference between water and air in the Site C reservoir and result in smaller
water temperature changes attributable to the Project.

The climate change sensitivity modelling indicated that the increase in outflow temperature
from the Site C reservoir averaged 20% of the air temperature increase for the months of
March through October. Winter water temperature increases were less than 5% of the air
temperature increase. For example, for a 4°C increase in air temperatures, outflowing water
is expected to be about 0.8°C warmer in the summer and fall, and less than 0.2°C warmer
in winter. The smaller changes in winter are due to higher inflows compared to the summer, and therefore the decreased residence time in the reservoir, as well as the insulating effect of ice cover, once formed. The air temperatures, even considering 4°C of warming, are still well below zero during most of the winter.

The climate change sensitivity modelling indicated that ice cover on the Site C reservoir would decrease in thickness and duration. The average ice thickness decreased by approximately 5% for every degree of air temperature increase. For example, under an air temperature increase of 4°C, the maximum ice thickness was 0.43 m in February 2007 compared with the 0.52 m from Section 7.3. The maximum ice cover percentage under the 4°C temperature increase changed by less than 1%, but the duration of ice cover at a particular coverage decreased. For example, the time during which at least 20% of the reservoir was ice covered decreased from 19 weeks to 16 weeks.

The water temperature and ice conditions of Williston, Dinosaur, and Site C reservoirs would be influenced by changes in climate. Surface waters would warm with air temperatures, and ice coverage would decrease in thickness and duration. The Williston Reservoir would buffer the influence of warming air temperatures on water temperatures. Studies in the Great Lakes predict that surface water temperatures will increase along with air temperatures. However, bottom waters are predicted to warm less than surface waters (Great Lakes 2003). Assuming the same pattern in Williston Reservoir, and considering that most of the water at the W.A.C. Bennett Dam is drawn at depth, it is expected that waters entering the Site C reservoir would warm less than predicted future air temperatures. Other predicted results of climate change in the Great Lakes that may be applicable to Williston and Site C reservoirs include an increase in temperature stratification strength and duration.

8 CONCLUSIONS

A three-dimensional circulation model, H3D, was implemented for Dinosaur Reservoir and the Site C reservoir. The model computes a time-varying, three-dimensional velocity and temperature field, and also simulates time-varying and spatially-varying ice coverage on the reservoir. The model of Dinosaur Reservoir was calibrated and validated against water temperature measurements and predicted outflow water temperatures within 0.2°C. The model accurately represented the ice cover observations in Dinosaur Reservoir. The model results for the Site C reservoir indicated that it would behave more like a lake, while Dinosaur Reservoir behaves more like a river. The average residence time of the water in the Site C reservoir was about 22 days, as opposed to 2 to 3 days for Dinosaur Reservoir. In the first 20 km of the Site C reservoir, the bathymetry and flow rate induced a vertically homogeneous temperature. At greater distances downstream, the surface
warming in summer resulted in a stable thermocline. In winter, ice formed over extended
periods and was thicker than the ice observed in Dinosaur Reservoir. Ice started forming in
the tributary valleys and near the Site C dam location and gradually built upstream,
covering between 80% and 90% of the reservoir for up to two months in most winters.
Simulated temperatures at the Site C outlet were compared with existing Peace River
temperatures at a similar location. Simulated temperatures were warmer between July and
January, between 0.3°C (July) and 1.5°C (October). The monthly average simulated outlet
temperatures were between 0.4°C and 0.9°C cooler from March through June, and in all
months had a smaller daily range than the existing river. Temperature change can also be
considered as a one- to two-week time lag compared to the existing Peace River, with the
largest time lag occurring during the colder months.
The sensitivity of the model to variations in input data was tested for cases with faster wind
speed, altered outflow dynamics, and the presence of sediment. Changes due to these
three factors were generally less than 0.1°C with the smallest changes seen in winter.
Temperatures in the Site C reservoir are predicted to increase due to climate change, with
the magnitude of temperature increase at the Site C outlet approximately 20% of the air
temperature increase in summer, and less than 5% in winter. Ice cover on the reservoir
would decrease in thickness and duration due to climate change.

9 LIMITATIONS OF REPORT
This Technical Data Report pertains to a specific site, a specific development, and a
specific scope of work. The Technical Data Report may include plans, drawings, profiles,
and other support documents that collectively constitute the Technical Data Report. The
Report and all supporting documents are intended for the use of BC Hydro.

BC Hydro has the right to reproduce, use and rely upon this Report for proper purposes in
planning, operating and maintaining the electrical generation, transmission and distribution
system in the Province of British Columbia, including, without limitation, the right to deliver
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EBA does not accept any responsibility for the accuracy of any of the data, analyses, or
other contents of the Technical Data Report when it is used or relied upon by any party
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development at the subject site, unless authorized in writing by EBA. Any unauthorized use
of the Technical Data Report is at the sole risk of the user.
10 CLOSURE

This report was prepared and reviewed by the undersigned

Sincerely,
EBA, A Tetra Tech Company

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JR/JRS
Figure 1.1 Reservoir Temperature and Ice Modelling Study Area

Map Notes:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Proposed reservoir area (461.8 m maximum normal elevation) from Digital Elevation Models (DEM) generated from LiDAR data acquired July/August, 2006.

Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification.
Figure 2.1
Dinosaur Reservoir Bathymetry

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Dinosaur Reservoir bathymetry for water level of 502.0 m.
5. Locations marked are locations of 2008 thermistor data loggers.

Legend
- Thermistors
  - Depth (m)
    - 0 - 5
    - 5 - 10
    - 10 - 15
    - 15 - 20
    - 20 - 25
    - 25 - 30
    - 30 - 35
    - 35 - 40
    - 40 - 45
    - 45 - 50
    - 50 - 55
    - 55 - 60
    - 60 - 65

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MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Site C Reservoir bathymetry for water level of 461.8 m.
5. Locations marked are locations of meteorological stations.

Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification.
NOTES:
2. Elevation 694.9 m.

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Figure 3.1
Wind Rose
Fort St. John
Meteorological Station
(1971 - 2010)
Figure 3.2
Dinosaur Reservoir
Estimated Wind Speed and Direction

Map Notes:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Snapshot of wind speed and direction used in the Dinosaur Reservoir model.
5. Length of arrow represents wind speed.
6. The observed wind at FSJ for the same date and time was 10.3 m/s (37 km/h) from 220 degrees.

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Figure 3.3
Site C Reservoir
Estimated Wind Speed and Direction

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Proposed reservoir area (461.8 m maximum normal elevation) from Digital Elevation Models (DEM) generated from LiDAR data acquired July/August, 2006.
5. Snapshot of wind speed and direction used in the Site C Reservoir model.
6. Length of arrow represents wind speed.
7. The observed wind at FSJ for the same date and time was 3.6 m/s (13 km/h) from 260 degrees.

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Figure 3.4
Air Temperature
Fort St. John
Meteorological Station
(1995 - 2012)

NOTES:
1. Top panel shows temperatures/cloud cover over the modelling period with 4-day low-pass filter for clarity of presentation.
2. Bottom panel is unfiltered hourly temperatures for the year 2007.

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NOTES:
1. Top panel shows temperatures/cloud cover over the modelling period with a 4-day low-pass filter for clarity of presentation.
2. Bottom panel is unfiltered hourly cloud cover for the year 2007.

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Figure 4.1
Time Series of W.A.C. Bennett Dam Inflows to Dinosaur Reservoir (2008 - 2012)

Legend
- Peace Canyon (PCN) Hourly
- Peace Canyon (PCN) Weekly

NOTES:
1. W.A.C. Bennett Dam (GMS) flows assumed equal to Peace Canyon (PCN) flows.
2. Source: BC Hydro.
Figure 4.2
Time Series of Peace Canyon Dam and Tributary Inflows to Site C Reservoir Model (1995 - 2011)

NOTES:
1. Peace Canyon (PCN) hourly flows shown as scatter plot.
2. Peace Canyon weekly flows are low-pass filtered for clarity.
5. Source: Knight Piesold Ltd., BC Hydro.

Legend
- Peace Canyon (PCN) Hourly
- Peace Canyon (PCN) Weekly
- Moberly River
- Halfway River
- Cache Creek
- Farrell Creek
- Lynx Creek
Figure 4.3
Observed Water Temperature
W.A.C. Bennett Dam and Peace Canyon Dam Tailraces
(2009 - 2012)

Legend
Hourly water temperatures between 2009 and 2012 for:
- W.A.C. Bennett Dam (GMS) Tailrace
- Peace Canyon (PCN) Tailrace
- Difference

NOTES:
1. Positive "T Difference" indicates Peace Canyon (PCN) temperatures are warmer than W.A.C. Bennett Dam (GMS) temperatures.

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Figure 4.4
Observed and Estimated Water Temperatures at Peace Canyon Dam Tailrace (1995 - 2011)

NOTES:
1. Temperatures for summer 1995 and 1996, and from April 2000 to the present are observations by BC Hydro at the Peace Canyon (PCN) Dam.
2. Winter temperatures from 1995 to 2000 are estimated by BC Hydro from downstream temperature and ice models.
3. Summer temperatures from 1997 to 1999 are estimated by EBA using averages of the observed data and a synthetic oscillation based on observed data.
NOTES:
1. Source: Predicted tributary water temperatures from Golder Associates.

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Figure 5.1
Observed and Simulated Ice Thickness in Mara Lake (2008 - 2009)

Legend

Observations
- ▲ Ice measurements 23 m from shore
- ▼ Ice measurements 30 m from shore
- ● Ice measurements 46 m from shore
- ○ Ice measurements 61 m from shore
- ▲ Ice measurements 91 m from shore
- ● Ice measurements 152 m from shore

Model Predictions
- 50 m from shore (1.7 m water depth)
- 150 m from shore (7.2 m water depth)
- 250 m from shore (13.3 m water depth)

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Figure 6.1: Dinosaur Reservoir Model Grid

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Dinosaur Reservoir curvilinear grid with location of the three temperature data loggers.
4. Vertical cross-sections presented in the report were taken along the red line shown in this figure, corresponding to the deepest part of the reservoir, or thalweg. The corresponding vertical section of the grid is shown.

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MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled water surface temperature or ice thickness for February 6, 2011, during maximum ice extent.

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Figure 6.3
Simulated Dinosaur Reservoir Water Surface Temperatures (August 11, 2011)

Legend

Water Temperature (°C)

- 8.0 - 10.0
- 10.0 - 12.0
- 12.0 - 14.0
- 14.0 - 16.0
- 16.0 - 18.0
- 18.0 - 20.0

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.

Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification.
NOTES:
1. Vertical cross-section of water temperature along the deepest part of the reservoir on February 6, 2011, during maximum ice extent.
2. Contour lines and labels show temperature at whole-degree intervals.
3. Peace Canyon (PCN) outflow depth as annotated.

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Figure 6.4
Simulated Dinosaur Reservoir
Water Temperature and Ice Thickness
(February 6, 2011)
Notes:
1. Vertical cross-section of water temperature along the deepest part of the reservoir on August 11, 2011, during high thermal stratification.
2. Contour lines and labels show temperature at whole-degree intervals.
3. Peace Canyon (PCN) outflow depth as annotated.

Figure 6.5
Simulated Dinosaur Reservoir Water Temperature
(August 11, 2011)
Figure 6.6
Simulated Dinosaur Reservoir
Mean Longitudinal Velocity and Cross-Sectional Area
(July 14, 2007 - Warmest Day)

Notes:
1. Vertically and cross-sectionally averaged velocities calculated at all distances from W.A.C. Bennett Dam (GMS) Station on July 14, 2007.

Legend
- Blue: Cross-sectional Average Velocity
- Green: Cross-sectional Area
Figure 6.7 Observed Water Temperature in Dinosaur Reservoir at Three Locations (2008)

Legend
- 3 m Above Bottom Thermistor
- 5 m Depth Thermistor
- 1 m Depth Thermistor
- Observed Peace Canyon (PCN) Tailrace Temperature

NOTES:
2. Black line in the top panel is synthetic W.A.C. Bennett Dam (GMS) temperature.
3. Magenta line in the bottom panel is observed Peace Canyon (PCN) temperature.
NOTES:
1. Hourly water temperatures measured in 2008 at three different depths at Dino 1 (Downstream) Site.
2. See Figure 2.1 for location of thermistor observations.
3. Model results are presented from depths corresponding to each thermistor.
Figure 6.9
Observed and Simulated Peace Canyon Dam Tailrace Water Temperatures (2009 - 2012)

NOTES:
1. Comparison between the observed and modelled water temperatures at the Peace Canyon (PCN) tailrace.
2. This model run used observed W.A.C. Bennett Dam (GMS) outflow temperatures as in Figure 4.3.
3. Positive "T Difference" indicates modelled temperatures are warmer than observed temperatures.

Legend
- Red: Observed Peace Canyon (PCN) Tailrace Temperature
- Blue: Modeled Peace Canyon (PCN) Tailrace Temperature
- Black: Difference

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Figure 6.10 Observed and Simulated Ice Cover and Thickness in Dinosaur Reservoir (2011)

NOTES:
1. Average ice cover as a percentage of the total reservoir area.
2. Average ice thickness over the ice-covered area only.
3. Observed ice cover percentage interpreted from C-CORE satellite imagery.
Figure 6.11
Observed and Simulated Ice Cover and Thickness in Dinosaur Reservoir (2012)

NOTES:
1. Average ice cover as a percentage of the total reservoir area.
2. Average ice thickness over the ice-covered area only.
3. Observed ice cover percentage interpreted from C-CORE satellite imagery.

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Figure 6.12
Simulated Dinosaur Reservoir Ice Cover Compared with Satellite Imagery
(March 8, 2011, 18:20 PST)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for model snapshot corresponding to satellite acquisition time.
5. Satellite images from RadarSat-1 and 2 provided by C-CORE.

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Figure 6.13
Simulated Dinosaur Reservoir Ice Cover Compared with Satellite Imagery
(March 11, 2011, 06:20 PST)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for model snapshot corresponding to satellite acquisition time.
5. Satellite images from RadarSat-1 and 2 provided by C-CORE.

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Figure 6.14
Simulated Dinosaur Reservoir Ice Cover Compared with Satellite Imagery
(March 14, 2011, 14:17 PST)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modeled ice thickness for model snapshot corresponding to satellite acquisition time.
5. Satellite images from RadarSat-1 and 2 provided by C-CORE.

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MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Site C Reservoir curvilinear grid.
4. Vertical cross-sections presented in the report were taken along the red line shown in this figure, corresponding to the deepest part of the reservoir, or thalweg. The corresponding vertical section of the grid is shown.

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Figure 7.2
Simulated Site C Reservoir Water Surface Temperatures and Ice Thickness (January 14, 2005)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled water surface temperature or ice thickness for January 14, 2005, during a period of "reverse" temperature stratification and 95% ice cover.

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Figure 7.3
Simulated Site C Reservoir Water Surface Temperatures (July 16, 2004)

Legend

- Water Temperature (°C)
  - 8.0 - 10.0
  - 10.0 - 12.0
  - 12.0 - 14.0
  - 14.0 - 16.0
  - 16.0 - 18.0
  - 18.0 - 20.0
  - 20.0 - 22.0

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled surface temperature of water for July 16, 2004, the day with the highest temperature stratification of the simulated period.

Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification.
NOTES:
1. Vertical cross-section of water temperature and ice thickness on January 14, 2005, during a period of "reverse" temperature stratification and 95% ice cover.
2. Contour lines and labels show temperature at whole-degree intervals.
3. Site C outflow depth as annotated.

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NOTES:
1. Vertical cross-section of water temperature along the Peace River channel on July 16, 2004, the day with the highest temperature stratification of the simulated period.
2. Contour lines and labels show temperature at whole-degree intervals.
3. Site C outflow depth as annotated.
NOTES:
1. Location of Lower Basin Station marked on Figure 7.1.
2. Temperature difference is taken between surface and bottom layers of the model representing 1 m and 40 m depth, respectively.
3. Cut off temperature peak on July 16, 2004 is 20.6°C, temperature difference on the same date is 15.5°C.

Legend
- Red: Surface Water Temperature
- Blue: Bottom Water Temperature
- Black: Difference
NOTES:
1. Water temperature averaged over the depths of the Site C dam intake.
2. Peace Above Pine is raw temperature data from Environment Canada station 07FA004.
3. Data has been smoothed with a 36-hour low pass filter for clarity of presentation.

Legend
- Observed Peace Canyon (PCN) Tailrace
- Simulated Site C Tailrace

Figure 7.7
Simulated Site C Tailrace and Observed Peace Canyon Dam Tailrace Water Temperature (1995 - 2011)

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NOTES:
1. Water temperature averaged over the depths of the Site C dam intake.
2. Peace Above Pine is raw temperature data from Environment Canada Station 07FA004.
3. Source data is identical to Figure 7.7 but zoomed to Peace Above Pine period of record.
4. Data has been smoothed with a 36-hour low pass filter for clarity of presentation.

Legend
- Observed Peace Above Pine
- Simulated Site C Tailrace
NOTES:
1. Monthly averages of data in Figure 7.8.
2. Whisker plots are the average daily temperature range during each month.
Figure 7.10
Time Series of Simulated Ice Cover and Thickness in Site C Reservoir (1995 - 2011)

NOTES:
1. Average ice cover as a fraction of the lake area.
2. Average ice thickness over the lake area covered by ice.
3. Air temperature at Fort St. John.

Legend
- Average Ice Thickness (m)
- Ice Cover (%)
- Air Temperature (°C)

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Figure 7.11
Simulated Site C Reservoir
Ice Cover and Thickness
(2007 - 2008)

NOTES:
1. Average ice cover as a fraction of the lake area.
2. Average ice thickness over the lake area covered by ice.
3. Air temperature at Fort St. John.

Legend
- Red: Average Ice Cover on Dates of Ice Cover Maps in Figures 7.12-7.16
- Blue: Average Ice Thickness on Dates of Ice Cover Maps in Figures 7.12-7.16

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MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for December 1, 2007 at midnight (maximum extent in modelled period).

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Figure 7.13
Simulated Site C Reservoir Ice Thickness (January 1, 2008)

Map Notes:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.

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Figure 7.14
Simulated Site C Reservoir
Ice Thickness
(February 1, 2008)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for February 1, 2008 at midnight (maximum extent in modelled period).

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Figure 7.15
Simulated Site C Reservoir Ice Thickness (March 1, 2008)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for March 1, 2008 at midnight (maximum extent in modelled period).

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Figure 7.16
Simulated Site C Reservoir Ice Thickness
(April 1, 2008)

MAP NOTES:
1. Datum: NAD83
2. Projection: UTM Zone 10N
3. Base Data: Province of B.C.
4. Modelled ice thickness for April 1, 2008 at midnight (maximum extent in modelled period).

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12 REFERENCES

1. Literature Cited


2. Internet Sites


3. Personal Communications


APPENDIX A

Wind Prediction Technical Memo – BC Hydro Site C Wind Assessment
APPENDIX A: H3D TECHNICAL DESCRIPTION

1.0 INTRODUCTION

H3D is an implementation of the numerical model developed by Backhaus (1983; 1985) which has had numerous applications to the European continental shelf, (Duwe et al., 1983; Backhaus and Meir Reimer, 1983), Arctic waters (Kampf and Backhaus, 1999; Backhaus and Kampf, 1999) and deep estuarine waters, (Stronach et al., 1993). Locally, H3D has been used to model the temperature structure of Okanagan Lake (Stronach et al., 2002), the transport of scalar contaminants in Okanagan Lake, (Wang and Stronach, 2005), sediment movement and scour / deposition in the Fraser River, circulation and wave propagation in Seymour and Capilano dams, and salinity movement in the lower Fraser River. H3D forms the basis of the model developed by Saucier and co-workers for the Gulf of St. Lawrence (Saucier et al., 2003), and has been applied to the Gulf of Mexico (Rego et al., 2010). H3D and its hydrocarbon transport and weathering module have been used in two recent environmental assessment applications currently before the appropriate regulatory agencies. H3D was used to do oil spill modelling for the environmental and engineering assessments for the proposed Gateway project involving oil shipment out of Kitimat. The modelling work forms part of the information package submitted to the National Energy Board which is currently under review. Similarly, H3D was used to assess the fate of accidental fuel spills arising from a proposed jet fuel terminal in the Fraser River. This modelling work is part of the information package submitted to the provincial Environmental Assessment Office.

2.0 THEORETICAL BASIS

H3D is a three-dimensional time-stepping numerical model which computes the three components of velocity (u,v,w) on a regular grid in three dimensions (x,y,z), as well as scalar fields such as temperature and contaminant concentrations. The model uses the Arakawa C-grid (Arakawa and Lamb, 1977) in space, and uses a two level semi-implicit scheme in the time domain. H3D bears many similarities to the well-known Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) in terms of the equations it solves, but differs in how the time-domain aspects are implemented. H3D uses a semi-implicit scheme, allowing relatively large time steps, and does not separately solve the internal and external models as POM does. It also uses a considerably simpler turbulence scheme in the vertical. These considerations combined allow H3D to execute complex problems relatively quickly.
The equations to be solved are:

**Mass Conservation:**

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$  \hspace{1cm} (A1)

At the end of each timestep equation, (A1) is used to diagnostically determine the vertical component of velocity \(w\) once the two horizontal components of velocity \(u\) and \(v\) have been calculated by the model.

**X-directed momentum:**

$$\frac{\partial u}{\partial t} + \frac{u \partial u}{\partial x} + \frac{v \partial u}{\partial y} + \frac{w \partial u}{\partial z} + g \frac{\partial \eta}{\partial x} + \frac{1}{\rho_v} \frac{\partial}{\partial z} \left( \rho_v \varphi g dz - fv - \frac{\partial}{\partial x} A_H \frac{\partial u}{\partial x} - \frac{\partial}{\partial y} A_H \frac{\partial u}{\partial y} - \frac{\partial}{\partial z} A_v \frac{\partial u}{\partial z} \right) = 0. \hspace{1cm} (A2)$$

**Y-directed momentum:**

$$\frac{\partial v}{\partial t} + \frac{u \partial v}{\partial x} + \frac{v \partial v}{\partial y} + \frac{w \partial v}{\partial z} + g \frac{\partial \eta}{\partial y} + \frac{1}{\rho_v} \frac{\partial}{\partial z} \left( \rho_v \varphi g dz + fu - \frac{\partial}{\partial x} A_H \frac{\partial v}{\partial x} - \frac{\partial}{\partial y} A_H \frac{\partial v}{\partial y} - \frac{\partial}{\partial z} A_v \frac{\partial v}{\partial z} \right) = 0. \hspace{1cm} (A3)$$

**Water surface elevation determined from the vertically-integrated continuity equation:**

$$\frac{\partial \eta}{\partial t} = - \frac{\partial}{\partial x} \left( \int_{-H}^{0} u dz \right) - \frac{\partial}{\partial y} \left( \int_{-H}^{0} v dz \right) \hspace{1cm} (A4)$$

The effect of wind forcing introduced by means of the surface wind-stress boundary condition:

$$\left( A_v \frac{\partial u}{\partial z}, A_v \frac{\partial v}{\partial z} \right)_{z=H} = \frac{\rho_v}{\rho} \mu D_a i \tilde{U}_{\text{wind}} \left| \tilde{U}_{\text{wind}} \right| \hspace{1cm} (A5)$$

The effect of bottom friction introduced by the bottom boundary condition:

$$\left( A_v \frac{\partial u}{\partial z}, A_v \frac{\partial v}{\partial z} \right)_{z=-H} = K_{\text{bottom}} \tilde{U}_{\text{bottom}} \left| \tilde{U}_{\text{bottom}} \right| \hspace{1cm} (A6)$$

The bottom friction coefficient is usually understood to apply to currents at an elevation of one metre above the bottom. The bottom-most vector in H3D will, in general, be at a different elevation, i.e., at the midpoint of the lowest computational cell. H3D uses the ‘law of the wall’ to estimate the flow velocity at one metre above the bottom from the modelled near-bottom velocity.

The evolution of scalars, such as salinity, temperature, or suspended sediment, is given by the scalar transport/diffusion equation:

$$\frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x} + v \frac{\partial S}{\partial y} + w \frac{\partial S}{\partial z} + N_H \frac{\partial S}{\partial x} - \frac{\partial}{\partial y} N_H \frac{\partial S}{\partial y} - \frac{\partial}{\partial z} N_H \frac{\partial S}{\partial z} + N_v \frac{\partial S}{\partial z} = Q. \hspace{1cm} (A7)$$
In the above equations:

\[ u(x,y,z,t) \]: component of velocity in the \( x \) direction;
\[ v(x,y,z,t) \]: component of velocity in the \( y \) direction;
\[ w(x,y,z,t) \]: component of velocity in the \( z \) direction;
\[ S(x,y,z,t) \]: scalar concentration;
\[ Q(x,y,z,t) \]: source term for each scalar species

\( f \): Coriolis parameter, determined by the earth’s rotation and the local latitude;
\[ A_H(\partial u / \partial x, \partial u / \partial y, \partial v / \partial x, \partial v / \partial y) \]: horizontal eddy viscosity;
\[ A_V(\partial u / \partial z, \partial v / \partial z, \partial \rho_{\text{water}} / \partial z) \]: vertical eddy viscosity;
\[ N_H(\partial u / \partial x, \partial u / \partial y, \partial v / \partial x, \partial v / \partial y) \]: horizontal eddy diffusivity;
\[ N_V(\partial u / \partial z, \partial v / \partial z, \partial \rho_{\text{water}} / \partial z) \]: vertical eddy diffusivity;
\[ C_{D,\text{air}} \]: drag coefficient at the air-water interface;
\[ C_{D,\text{bottom}} \]: drag coefficient at the water/sea bottom interface;
\[ \rho_a \]: density of air;
\[ \rho_w(x,y,z,t) \]: density of water;
\[ \rho_o \]: reference density of water;
\[ \eta(x,y,t) \]: water surface elevation;
\[ H(x,y) \]: local depth of water.

The above equations are formally integrated over the small volumes defined by the computational grid, and a set of algebraic equations results, for which an appropriate time-stepping methodology must be found. Backhaus (1983, 1985) presents such a procedure, referred to as a semi-implicit method. The spatially-discretized version of the continuity equation is written as:

\[
\eta^{(1)} = \eta^{(0)} - \alpha \frac{\Delta t}{\Delta l} (\delta_x U^{(1)} + \delta_y V^{(1)}) - (1 - \alpha) \frac{\Delta t}{\Delta l} (\delta_x U^{(0)} + \delta_y V^{(0)}) \tag{A8}
\]

where superscript \((0)\) and \((1)\) refer to the present and the advanced time, \(\delta_x\) and \(\delta_y\) are spatial differencing operators, and \(U\) and \(V\) are vertically integrated velocities. The factor \(\alpha\) represents an implicit weighting, which must be greater than 0.5 for numerical stability. \(U^{(0)}\) and \(V^{(0)}\) are known at the start of each computational cycle. \(U^{(1)}\), and similarly \(V^{(1)}\), can be expressed as:

\[
U^{(1)} = U^{(0)} - g\alpha \Delta \eta^{(1)} - g(1-\alpha)\Delta \eta^{(0)} + \Delta \chi^{(0)} \tag{A9}
\]
where $X(0)$ symbolically represents all other terms in the equation of motion for the $u$- or $v$-component, which are evaluated at time level (0): Coriolis force, internal pressure gradients, non-linear terms, and top and bottom stresses. When these expressions are substituted into the continuity equation (A4), after some further manipulations, there results an elliptic equation for $\delta_{i,k}$, the change in water level over one timestep at grid cell $i,k$ (respectively the $y$ and $x$ directions):

$$
\delta_{i,k} = -(c_1\delta_{i+1,k+1} + c_2\delta_{i-1,k+1} + c_3\delta_{i,k+1} + c_4\delta_{i+1,k}) = Z_{i,k}
$$

(A10)

where $c_1$, $c_2$, $c_3$, and $c_4$ are coefficients depending on local depths and the weighting factor ($\alpha$), and $Z_{i,k}$ represents the sum of the divergence formed from velocities at time level (0) plus a weighted sum of adjacent water levels at time level (0).

Once equation (A10) is solved for $\delta_{i,k}$, the water level can be updated:

$$
\eta_{i,k}^{(1)} = \eta_{i,k}^{(0)} + \delta_{i,k}
$$

(A11)

and equation (A9) can be completed.

At the end of each timestep, volume conservation is used to diagnostically compute the vertical velocity $w(j,i,k)$ from the two horizontal components $u$ and $v$.

### 2.1 Vertical Grid Geometry

In the vertical, the levels near the surface are typically closely spaced to assist with resolving near-surface dynamics. In addition, the model is capable of dealing with relatively large excursions in overall water level as the water level rises and falls in response to varying inflows and outflows, by allowing the number of near-surface layers to change as the water level varies. That is, as water levels rise in a particular cell, successive layers above the original layer are turned on and become part of the computational mesh. Similarly, as water levels fall, layers are turned off. This procedure has proven to be quite robust, and allows for any reasonable vertical resolution in near-surface waters. When modelling thin river plumes in areas of large tidal range, the variable number of layers approach allows for much better control over vertical resolution than does the $\sigma$-coordinate method.

In addition to tides, the model is able to capture the important response, in terms of enhanced currents and vertical mixing, to wind-driven events. This is achieved by applying wind stress to each surface grid point on each time step. Vertical mixing in the model then re-distributes this horizontal momentum throughout the water column. Similarly, heat flux through the water surface is re-distributed by turbulence and currents in temperature simulations.
2.2 Turbulence Closure

Turbulence modelling is important in determining the correct distribution of velocity and scalars in the model. The diffusion coefficients for momentum \((A_H \text{ and } A_V)\) and scalars \((N_H \text{ and } N_V)\) at each computational cell are dependent on the level of turbulence at that point. H3D uses a shear-dependent turbulence formulation in the horizontal, (Smagorinsky, 1963). The basic form is:

\[
A_H = A_{H0} \, dx \, dy \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y}\right)^2} \tag{A12}
\]

The parameter \(A_{H0}\) is a dimensionless tuning variable, and experience has shown it to lie in the range of 0.25 to 0.45 for most water bodies such as rivers, lakes and estuaries.

A shear and stratification dependent formulation, the Level 2 model of Mellor and Yamada (1982), is used for the vertical eddy diffusivity. The basic theory for the vertical viscosity formulation is taken from an early paper, Mellor and Durbin (1975). The evaluation of length scale is based on a methodology presented in Mellor and Yamada (1982).

For scalars, both horizontal and vertical eddy diffusivity are taken to be similar to their eddy viscosity counterparts, but scaled by a fixed ratio from the eddy viscosity values. Different ratios are used for the horizontal and vertical diffusivities. If data is available for calibration, these ratios can be adjusted based on comparisons between modelled and observed data. Otherwise, standard values based on experience with similar previously modelled water bodies are used. For the Site C model, the ratio of vertical eddy diffusivity to vertical eddy viscosity was 0.75 and the ratio between horizontal eddy diffusivity and horizontal eddy viscosity was 1.0.

2.3 Scalar Transport

The scalar transport equation implements a form of the flux-corrected algorithm (Zalesak, 1979), in which all fluxes through the sides of each computational cell are first calculated using a second-order method. Although generally more accurate than a first order method, second order flux calculations can sometimes lead to unwanted high frequency oscillations in the numerical solution. To determine if such a situation is developing, the model examines each cell to see if the computed second order flux would cause a local minimum or maximum to develop. If so, then all fluxes into or out of that cell are replaced by first order fluxes, and the calculation is completed. As noted, the method is not a strict implementation of the Zalesak method, but is much faster and achieves very good performance with respect to propagation of a Gaussian distribution through a computational mesh. It does not propagate box-car distributions as well as the full Zalesak method, but achieves realistic simulations of the advection of scalars in lakes, rivers and estuaries, which is the goal of the model. This scheme as implemented is thus a good tradeoff between precision and execution time, important since in many situations, where more than one scalar is involved, the transport-diffusion algorithm can take up more than half the execution time.
2.4 Heat Flux at the Air-Water Interface

The contribution of heat flux to the evolution of the water temperature field can be schematized as:

\[ \frac{dT}{dt} = \frac{\Delta Q}{\rho \cdot c_p \cdot h} \]

where \( \Delta Q \) is the net heat flux per unit area retained in a particular layer, \( \rho \) is the density of water, \( c_p \) is the heat capacity of water and \( h \) is the layer thickness.

Heat flux at the air-water interface incorporates the following terms:

- \( Q_{\text{inc}} \): incident short wave radiation. Generally, this is not known from direct observations. For Site C, it was estimated from the cloud cover and opacity observations at Fort St. John, a theoretical calculation of radiation at the top of the atmosphere based on the geometry of the earth/sun system, and an empirical adjustment based on radiation measurements at Vancouver Airport and UBC respectively for the period 1974-1977. Although this correlation was determined for a location considerably south of the Site C Reservoir, this procedure has worked well for other water bodies, notably Okanagan Lake and the waters of the north coast of British Columbia, in terms of allowing H3D to reproduce the observed temperature distributions in space and time. Values for albedo as a function of solar height are taken from Kondratyev (1972).

- \( Q_{\text{back}} \): net long wave radiation, calculated according to Gill (1982), involving the usual fourth power dependence on temperature, a factor of 0.985 to allow for the non-black body behaviour of the ocean, a factor depending on vapor pressure to allow for losses due to back radiation from moisture in the air, and a factor representing backscatter from clouds.

- \( Q_L \) and \( Q_S \): latent and sensible heat flux. Latent heat flux \( (Q_L) \) is the heat carried away by the process of evaporation of water. Sensible heat flux \( (Q_S) \) is driven by the air-water temperature difference and is similar to conduction, but assisted by turbulence in the air. Latent and sensible heat flux is described by:

\[
Q_L = 1.32e^{-3} \cdot L \cdot \text{windspeed} \cdot (q_{\text{obs}} - q_{\text{sat}}) \cdot \text{latent\_factor}
\]

\[
Q_S = 1.46e^{-3} \cdot \rho_{\text{air}} \cdot c_p \cdot \text{windspeed} \cdot (T_{\text{air}} - T_{\text{water}}) \cdot \text{sensible\_factor}
\]

Where \( q_{\text{obs}} \) and \( q_{\text{sat}} \) are the observed and saturated specific humidities, \( T_{\text{air}} \) and \( T_{\text{water}} \) are the air and water temperatures, \( L \) is the latent heat of evaporation of water, and \( c_p \) is the heat capacity of water. 'latent\_factor' and 'sensible\_factor' are scaling factors introduced to account for local factors, and can be adjusted, when needed, to achieve better calibration of the model. Typically, the only adjustment is that Sensible\_factor is doubled when the air temperature is less than the water or ice surface temperature to account for increased turbulence in an unstable air column.

Light absorption in the water column. As light passes through the water column it is absorbed and the absorbed energy is a component of the energy balance that drives water temperature. H3D assumes that light attenuation follows an exponential decay law:

\[ E(z) = E(z_0) \cdot e^{-k \cdot (z - z_0)} \]
The model computes the energy at the top and bottom of each layer and the difference is applied to the general heat equation in that layer. The extinction coefficient \( (k) \) is related to the Secchi depth \( (D_s) \) by

\[
k = \frac{2.1}{D_s}
\]

Temperature is treated like any other scalar as far as advection and diffusion are concerned. Heat flux at the water-sediment interface is not currently included in H3D.

2.5 Ice

The ice model is generally based on processes described in Patterson and Hamblin (1988). The ice cover is characterized by a thickness, a fraction of the cell covered, and an ice surface temperature. The temperature of the bottom of the ice is assumed to be the temperature of melting, usually 0º C. The strategy is to compute the differences in heat flux at the top and bottom of the ice layer and use this difference to determine the growth or decay rate and the change in temperature of the ice. The heat flux at the bottom of the ice layer is dependent on lake temperature and water velocity. The heat flux at the top is dependent on meteorological processes and the surface temperature of the ice. The surface heat flux to the top of the ice sheet is calculated in a similar way as for open water, except that latent heat flux term (\( Q_L \)) also includes the heat of fusion. Albedo is also altered to account for ice/snow cover.

In order to start ice formation, once the surface water temperature drops below 3º C in a particular cell, a test ice layer of thickness 1 cm is initialized. If the test thickness melts in one time step, then the system cannot support ice cover in that cell at that time. If it survives, then the amount of ice in that cell is converted to a 1 cm thick region with coverage calculated from the mass of ice formed. In this way, a relatively robust start is made to ice formation.

The frictional interaction between the bottom of the ice and the immediately adjacent water is parameterized according to Nezhikhovskyi (1964).

2.6 Validation

Three validations, outside of those presented in the Site C report, are discussed below.

2.6.1 Strait of Georgia/Point Atkinson Tide: Wave Propagation

A fundamental concern with a circulation model such as H3D is how well it propagates waves, the carriers of information through the system. Figure A-1 presents results of a simulation of tides in the Strait of Georgia and Juan de Fuca Strait, with tidal elevations prescribed at the entrance to Juan de Fuca Strait and at a section north of Texada Island in the Strait of Georgia. The complex dynamics of the northern passes, such as Discovery Passage and Seymour Narrows, are thus avoided, allowing a test of H3D’s wave propagation capabilities. The figure plots the modelled water level at Point Atkinson in red, and the observed water level in black. There is nearly perfect agreement, with the slight difference resulting from small storm surge events. This validation demonstrates that the selection of grid schematization (Arakawa C-grid) and the semi-implicit time-stepping approach have produced a system than can accurately propagate information through a water body.
2.6.2 Okanagan Lake Temperature Profiles

Obtaining good reproduction of the seasonally-evolving temperate structure of a lake indicates that the heat flux across the air-water interface is accurately parameterized and that the transport-diffusive processes operating in the water column are also accurately reproduced by the model. Figure A-2 presents a comparison of observed and computed temperature profiles at the northern end of Okanagan Lake near Vernon, in April, August, October and December of 1997. The agreement is very good as the model reproduced the transition from a well-mixed condition in the spring to the development of a strong thermocline in the summer, the deepening of the upper layer during the fall cooling period, and a return to isothermal conditions in winter. There is little doubt that H3D can compute accurate temperature distributions in water bodies, as long as adequate meteorological data is available. For this simulation, the meteorological data was obtained from Penticton Airport: winds, rotated to follow the thalweg of the valley; cloud cover, air temperature and relative humidity.

2.6.3 Thermistor Response: Okanagan Lake

Okanagan Lake is subject to significant fluctuations in the vertical thermal structure during the summer stratified period. Figure A-3 shows a temperature time-series at a site on the north side of the William R. Bennett Bridge which exhibits significant temperature excursions at periods of about 60 hours, or 2.5 days. Figure A-4 shows the modelled time series of temperature at three selected depths, 51 m, 21 m and 9 m. The occurrence and magnitude of the temperature fluctuations is generally predicted by the model, but the reproduction is not perfect: the occurrence and timing of the temperature events is quite good, but the modelled peaks appear to be generally somewhat broader in time. It was found that there were considerable differences in the simulated behaviour depending on whether winds at Kelowna Airport, which is situated in a side-valley, were included in the model or not. It is also clear that H3D can generally reproduce internal seiches in a lake, as long as adequate spatial resolution is used. This is particularly apparent when the coherent internal waves that propagate up and down the lake are examined in a longitudinal section, illustrated in two snapshots from a model simulation of such an event in Figure A-5.

2.6.4 Coefficients used in the Site C Simulation

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical levels</td>
<td>-4., -0.5, 0., 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 23, 26, 30, 34, 38, 42, 46, 50, 55</td>
<td>In depth coordinates, not elevations.</td>
</tr>
<tr>
<td>Horizontal grid size</td>
<td>100 m across valley, 200 m along valley except 100 m along valley at tributaries</td>
<td></td>
</tr>
<tr>
<td>Δt</td>
<td>20-22 s, varied according to water velocity</td>
<td>Timestep</td>
</tr>
<tr>
<td>A</td>
<td>0.75</td>
<td>Weighting for implicit/explicit solution, more implicit than explicit in this case</td>
</tr>
<tr>
<td>Bottom friction coefficient</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Coefficient</td>
<td>Value</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Wind drag coefficient at sea surface</td>
<td>1.5x10^{-3}</td>
<td></td>
</tr>
<tr>
<td>$A_{Ho}$</td>
<td>0.35</td>
<td>Horizontal eddy viscosity coefficient in Smagorinsky formulation</td>
</tr>
<tr>
<td>Ah_floor</td>
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<td>Horizontal eddy viscosity minimum (m²/s)</td>
</tr>
<tr>
<td>Kh_factor</td>
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<td>Ratio between horizontal scalar and velocity mixing</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.75</td>
<td>Ratio between vertical scalar and velocity mixing</td>
</tr>
<tr>
<td>$A_{V_{min}}$</td>
<td>1 x10^{-5}</td>
<td>Vertical eddy viscosity minimum (m²/s)</td>
</tr>
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<td>latent_factor</td>
<td>0.8 if water colder than air, 0.6 if water warmer than air</td>
<td>Latent heat coefficient</td>
</tr>
<tr>
<td>sensible_factor</td>
<td>0.8 if water colder than air, 0.6 if water warmer than air</td>
<td>Sensible heat coefficient</td>
</tr>
<tr>
<td>Secci</td>
<td>4</td>
<td>Secci disk depth (m)</td>
</tr>
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</table>
REFERENCES


Figure A-1

BC HYDRO
SITE C CLEAN ENERGY PROJECT
H3D VALIDATION
TIDAL REPRODUCTION

WATER LEVEL

May 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Jun

May 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Jun

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

MODELLED POINT ATKINSON DATA

OBSERVED POINT ATKINSON DATA

NOTES

BC HYDRO

Figures A-1

Tuesday August 2, 2011

v:\V13201028 Fraser River Class C Study\Working\EW\H3D-SOG\Run006\Figure1.png
Comparison of Observed and Modelled Temperature Profiles at Vernon

- Solid lines represent observed profiles
- Dash lines represent modelled profiles

Figure A-2
Figure A-3

BC Hydro Site C Clean Energy Project

H3D VALIDATION
SEICHES IN OKANAGAN LAKE
(OBSERVED DATA)

Legend

NOTES

BC Hydro

CLIENT

HOURS (APRIL 26 - JUNE 7, 2000)

DEPTH (M)

0

5

10

15

20

Temperature Scale (°C)

5 6 7 8 9 10 11 12 13 14 15 16

0

5 20

30

40

50

250 500 750

1000
Figure A-4

TS-A: NORTH STRING

Dashed Lines: Observed Temperature
Solid Lines: Modelled Temperature

BC Hydro
Site C Clean Energy Project
H3D VALIDATION
INTERNAL SEICHE DYNAMICS
OKANAGAN LAKE

LEGEND

Dashed Lines: Observed Temperature
Solid Lines: Modelled Temperature
BC Hydro Site C Clean Energy Project

H3D VALIDATION
INTERNAL SEICHE DYNAMICS
OKANAGAN LAKE

Figure A-5
APPENDIX B

H3D Technical Description
1.0 INTRODUCTION

Accurate meteorological data along the entire Peace River valley is essential for reservoir temperature modelling. Previous work by EBA used a simple scheme which applied valley orientation to winds recorded at Fort St. John Airport to estimate winds at all points in the valley. Subsequently, five meteorological stations were installed by RWDI, and one year of WRF model output was made available for comparison purposes. This memo summarizes predictive statistical methods for winds in the Peace River Valley developed based on relating the winds at each station with the long-term record at Fort St. John. The statistical prediction is compared to station data and to the WRF model output.

2.0 SITE AND VALLEY DESCRIPTION

The proposed Site C reservoir would fill a section of the Peace River valley 83 km long and 1-2 km wide from the Peace Canyon Dam to a site seven kilometres south of Fort St. John. The valley would be flooded to an elevation of approximately 461 metres.

In March 2009, RWDI installed five temporary wind stations in the Peace River Valley at elevations ranging from 481 to 602 metres. The locations of the five stations are shown in Figure 1.

Previous modelling work by EBA was conducted by modifying winds measured at the Fort St. John (FSJ) airport. This single long-term meteorological station, at an elevation of 695 metres, is seven kilometres away from the Peace River valley and measures a substantially different wind environment than the five stations in the valley.

3.0 DATA ANALYSIS AND STATISTICAL METHODS

Winds at Fort St. John come from three primary directions – NNW, SE and SSW. A wind rose for the FSJ station is shown in Figure 2. Wind roses for the five RWDI stations are shown in Figures 3 through 7. Winds recorded at the RWDI station closest to FSJ, Site 5, show a similar directional distribution to FSJ, but the other four sites are strongly
influenced by the local valley orientation and the presence of any intersecting valleys. Site 3D, for example, records winds from the northwest due to the confluence of the Cache Creek valley with the Peace River valley.

Statistical methods were developed to relate recorded wind data at the five RWDI met stations to winds at FSJ. Speed and direction data for all stations were converted into the north (V) and east (U) components of velocity. A rotation and a scaling factor was assumed to relate east and north velocity at each station to both components at FSJ. The scaling factor $c$ and rotation $\theta$ were determined iteratively by minimizing the RMS error between the predicted time series and the observed station data.

$$U_{pred} = c \times \cos \theta \times U_{FSJ} - c \times \sin \theta \times V_{FSJ}$$

$$V_{pred} = c \times \cos \theta \times V_{FSJ} + c \times \sin \theta \times U_{FSJ}$$

Equation 1

Applying this basic statistical method to the entire data set resulted in a prediction based on FSJ winds that was rotated to minimize the error in the above prediction equation, but was also found to match the local valley orientation. However, errors were noticed for stations with only two primary wind directions. Two of the three common wind directions at FSJ may induce the exact same wind direction in the valley, but a single set of coefficients cannot represent both situations. For example, both east and north winds at FSJ often correspond to a north wind in the valley at Site 4A due to the valley orientation at Site 4A. The method was refined by ‘binning’ the data into three separate datasets based on the wind direction at FSJ. The data fitting was repeated three times for each wind station, once for each of the three directional bins, and winds were predicted using different coefficients depending on the direction measured at FSJ.

Stick plots of the predicted time series for the month of October at each of the five RWDI sites are shown in Figures 8 through 12, along with observed winds, winds at FSJ, and the previous EBA model prediction based only on the valley-rotated east-west component of the FSJ wind. All three common wind directions at FSJ are seen in the month of October, 2009. The statistical prediction reproduces the direction and magnitude of strong wind events, as in October 5 and 17 for most sites. The method also ‘damps’ strong FSJ winds not aligned with the valley orientation, as in October 7-12 at Site 2C (Figure 10). Wind roses for the five predictions are shown in Figures 13 through 17, and compare well with the magnitudes and directions present in the data.

4.0 PREDICTION SKILL

The predictions were assessed based on visual inspection as well as root-mean-square (RMS) error and a comprehensive ‘model skill’ equation (Equation 2). RMS error is presented in the
same units as the original data and represents the magnitude of all errors over the entire predicted time period. Model skill, as defined by Wilmott (1981), is a measure of the agreement between predicted and observed data, with a skill of 1 representing a perfect match. It differs from the statistical correlation statistic r or \( r^2 \) in that a prediction that was perfect in magnitude but inverted in sign would still have a perfect \( r^2 \), whereas the skill would be negligible. As an example, an alteration of winds at FSJ consisting of a 30 degree rotation in direction and a three hour lag in time would have an r of only 0.69, but a model skill of 0.82 as the mean and variance of the data are still well-matched. Conversely, a time series increased by a constant 5 m/s would have an \( r^2 \) of 1.00 but a skill of only 0.62.

\[
Skill = 1 - \frac{\sum |X_{\text{Model}} - X_{\text{Data}}|^2}{\sum (|X_{\text{Model}} - X_{\text{Data}}| + |X_{\text{Data}} - X_{\text{Model}}|)^2}
\]

**Equation 2**

The predictive skill and RMS difference of both the new and previous methods for each station is shown in Table 1. Results for the new method are shown first, while numbers in parentheses refer to the simple valley-oriented east-west velocity method. To evaluate both magnitude and direction, all comparison statistics were calculated separately for east-west and north-south velocities, and then averaged to produce the numbers presented in the table. The best prediction skill is seen at Site 5A, which is expected due to its proximity to the FSJ station. The more difficult sites to predict involve the confluence of other valleys, such as Sites 1A and 3D. Correlation coefficients tend to be lower than model skill due to the time lags involved in predicting local winds from a distant station. An offset in time between two time series of a few hours retains good model ‘skill’ but the linear correlation ‘r’ becomes much worse. Time lags between FSJ and the five stations were estimated at one to two hours, but not included in the statistical model. The average improvement in model skill by the new method over the old method is 0.12, or 18%, and the average increase in correlation coefficient ‘r’ is 0.2, a 44% improvement.

<table>
<thead>
<tr>
<th>Site</th>
<th>Skill</th>
<th>RMS Difference (m/s)</th>
<th>Correlation Coefficient ‘r’</th>
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<td>0.61 (0.57)</td>
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<td>0.61 (0.51)</td>
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<td>Site 5A</td>
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<td>(0.56) 1.79 (3.29)</td>
<td>0.80 (0.24)</td>
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5.0 MODEL COMPARISON

Direct comparison of the statistical predictions with RWDI’s implementation of the WRF model is not possible due to the modelled year not overlapping data availability. A comparison between WRF and the statistical model can be made, but no determination of validity is possible due to the lack of observed valley winds in 2004. One month of WRF model output for October 2004 is shown in Figures 18-22, along with the new statistical prediction applied to 2004 winds, winds at FSJ, and the simple valley-oriented prediction. Wind roses for the WRF model are shown in Figures 23-27. The WRF-predicted winds are similar to the statistical method and generally align with the valley orientation. There are strong northerly winds in all of the WRF wind roses, a feature not seen in the data nor reproduced with the statistical prediction.

Comparison of the WRF model predictions with the statistical predictions results in similar skills and RMS differences than the statistical – data comparison (Table 2). While a comparison of two models without supporting data does not produce a definitive result, it does show that the two models are approximately as similar as the statistical model and the observed winds. The best comparison between WRF and the statistical method is seen at Site 1A, while worse agreement is seen at Site 3D. Both Sites 1A and 3D are located at the confluence of two valleys.

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<th>Site</th>
<th>WRF to Statistical Skill</th>
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<th>Correlation Coefficient ‘r’</th>
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<td>Site 5A</td>
<td>0.68</td>
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The WRF model appears to contain an excessive amount of strong northerly winds, and also underestimates the percentage of time that winds are below 1 m/s. Histograms of wind speeds (Figure 28) show that the statistical model reproduces the frequency distribution well at Site 1A, while WRF under-predicts the 0-2 m/s winds and over-predicts the frequency of winds faster than 3 m/s. Histograms at the other four sites have similar patterns to Site 1A.
The simple valley-oriented prediction used by EBA in previous hydrodynamic modelling assumed that winds in the valley were 50% the strength of winds at Fort St. John. The RWDI observed wind data was analysed to test this assumption. A similar least-squares fit method was used to match each station’s time series of wind speed to a multiplier of the speed at FSJ. The directionally binned subsets of the data were tested as well. The reduction factors for the five stations are shown in Figure 29. The average speed of winds at the five stations is 46% of the wind speed at FSJ. Station 5 is the most similar to FSJ wind speeds during southwest winds, which follows logically from valley geometry and the similarities of the two wind roses (Figures 2 and 7). The assumption of the wind speeds in the valley being approximately half of wind speeds at FSJ was reasonable based on the observed wind data.

6.0 CONCLUSIONS

In recent modelling of water temperature in the proposed Site C reservoir, EBA used a simple statistical model to estimate winds in the valley from observed winds at Fort St. John. RWDI has recently completed a one-year series of hourly wind observations at five sites in the Peace River Valley. In this memo, we first compare the simple statistical model to the observed winds. Then, because of the availability of observed winds data, we develop a new statistical model for estimating winds in the valley. This new model is seen to improve considerably on statistically-predicted winds compared to the previous method. The average new statistical model skill is 0.78 (Table 1), and the average old statistical model skill was 0.62. The skill between the statistical model and the WRF prediction is 0.67.

The application of statistical coefficients to the hydrodynamic model is straightforward and requires minimal additional effort, depending only on valley orientation and wind data at Fort St. John. That is, the existing statistical model in H3D can be replaced by the new prediction method, increasing model skill by an average of 0.12 and ‘r’ by an average of 0.20.

The new statistical method compares well with more intensive WRF modelling efforts, though a direct comparison could not be made to observed data in 2004. Calm and low wind speed periods would be under-represented if WRF output were used to force the hydrodynamic model, with significant implications for both currents and vertical mixing. It is recommended that the new statistical model, which reproduces the patterns of both wind speed and direction found at the five wind stations, be used to force future hydrodynamic modelling.
7.0 CLOSURE

We trust this report meets your present requirements. Should you have any questions or comments, please contact the undersigned at your convenience.

Sincerely,
EBA Engineering Consultants Ltd.

Prepared by: 

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Project Scientist
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jrogers@eba.ca

Reviewed by: 

James Stronach
Jim Stronach, Ph. D., P Eng.
Principal Consultant
Direct Line (604) 685-0275 x251
jstronach@eba.ca

JR/JAS/rbt
Station Name: FSJ
Location:
N56° 17' 17.0" W120° 44' 25.0"
Elevation above SL: 695 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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<th>6-9 m/s</th>
<th>9-12 m/s</th>
<th>12-15 m/s</th>
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BC HYDRO
SITE C WIND ASSESSMENT
Fort St. John Observed Winds
Wind Rose 2009

EBA Engineering Consultants Ltd.

Figure 2
Station Name: Site 1A Observed
Location:
N56° 13’ 48.6” W121° 25’ 27.9”
Elevation above SL: 461 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010
Station Name: Site 2C Observed
Location:
N56° 7' 13.4" W121° 42' 2.6"
Elevation above SL: 470 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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Figure 4
Station Name: Site 3D Observed
Location:
N56° 16’ 28.8" W121° 12’ 48.0"
Elevation above SL: 471 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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Station Name: Site 4A Observed  
Location:  
N56° 3' 34.9" W121° 51' 59.8"  
Elevation above SL: 562 m  
Tower Height: 10 m  
Record Length: 456 days  
Start Date: March 1, 2009  
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

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Statistical Prediction

Fort Saint John

Rotated Grid U

Observed and Predicted Wind Data
October 2009
Observed Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U

Observed and Predicted Wind Data
October 2009

Figure 9

Mon Sep 27 12:46:07 2010:V:\V13201131 BC Hydro Site C Reservoir\Working\JR\wind_data\tsplot
Observed Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U

BC HYDRO
SITE C WIND ASSESSMENT

Site 3D
Observed and Predicted Wind Data
October 2009

Figure 10
Figure 11
Observed and Predicted Wind Data
October 2009

Observed Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U
Observed Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U

Observed and Predicted Wind Data

October 2009

BC HYDRO
SITE C WIND ASSESSMENT

Site 5A
Observed and Predicted Wind Data
October 2009

Figure 12
Station Name: Site 1A Prediction
Location: N56° 13' 48.6" W121° 25' 27.9"
Elevation above SL: 461 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

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Location: N56° 16' 28.8" W121° 12' 48.0"
Elevation above SL: 471 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

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BC HYDRO
SITE C WIND ASSESSMENT
Site 4A Prediction
Wind Rose
2009

EBA Engineering Consultants Ltd.

Mon Sep 27 12:48:10 2010:V:\V13201131 BC Hydro Site C Reservoir\Working\JRI\wind_data\roses
Station Name: Site 5A Prediction
Location:
N56° 12' 18.6" W120° 54' 43.5"
Elevation above SL: 602 m
Tower Height: 10 m
Record Length: 456 days
Start Date: March 1, 2009
End Date: June 30, 2010

Wind Speed & Direction Frequency Distribution Table

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NOTES

BC HYDRO
SITE C WIND ASSESSMENT

Site 1A
WRF Modelled Wind Data
October 2004

Figure 18
Figure 19

WRF Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U

BC HYDRO
SITE C WIND ASSESSMENT

Site 2C
WRF Modeled Wind Data
October 2004

NOTES
WRF Wind Data

Statistical Prediction

Fort Saint John

Rotated Grid U
Figure V13201131      JMR JAS  0
August 2010
BC HYDRO
SITE C WIND ASSESSMENT
Site 4A
WRF Modelled Wind Data
October 2004

NOTES
Station Name: Site 1A WRF Model
Location:
N56° 13' 48.6" W121° 25' 27.9"
Elevation above SL: 461 m
Tower Height: 10 m
Record Length: 365 days
Start Date: Sept 30, 2004
End Date: Sept 30, 2004

Wind Speed & Direction Frequency Distribution Table

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Elevation above SL: 470 m
Tower Height: 10 m
Record Length: 365 days
Start Date: Sept 30, 2004
End Date: Sept 30, 2004

Wind Speed & Direction Frequency Distribution Table

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Elevation above SL: 471 m
Tower Height: 10 m
Record Length: 365 days
Start Date: Sept 30, 2004
End Date: Sept 30, 2004

Wind Speed & Direction Frequency Distribution Table

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Location:
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Elevation above SL: 562 m
Tower Height: 10 m
Record Length: 365 days
Start Date: Sept 30, 2004
End Date: Sept 30, 2004

Wind Speed & Direction Frequency Distribution Table

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Elevation above SL: 602 m  
Tower Height: 10 m  
Record Length: 365 days  
Start Date: Sept 30, 2004  
End Date: Sept 30, 2004

Wind Speed & Direction Frequency Distribution Table

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Figure 28

Site 1A

Wind Speed Frequency Histogram

LEGEND

- Observed
- Statistical Model
- WRF Model
Figure 29

Reduction of Observed Wind Speed in the Peace River Valley as a Function of Speeds at Fort St. John

**LEGEND**

- Period of Record is average reduction factor for entire RWDI time series.
- NNW, SW and SEE represent the speeds of winds in the valley during times when winds at FSJ are from the north-northwest, southwest, and southeast-by-east, respectively.

**NOTES**
DESIGN REPORT – GENERAL CONDITIONS

This Design Report incorporates and is subject to these “General Conditions”.

1.0 USE OF REPORT AND OWNERSHIP

This Design Report pertains to a specific site, a specific development, and a specific scope of work. The Design Report may include plans, drawings, profiles and other support documents that collectively constitute the Design Report. The Report and all supporting documents are intended for the sole use of EBA’s Client. EBA does not accept any responsibility for the accuracy of any of the data, analyses or other contents of the Design Report when it is used or relied upon by any party other than EBA’s Client, unless authorized in writing by EBA. Any unauthorized use of the Design Report is at the sole risk of the user.

All reports, plans, and data generated by EBA during the performance of the work and other documents prepared by EBA are considered its professional work product and shall remain the copyright property of EBA.

2.0 ALTERNATIVE REPORT FORMAT

Where EBA submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed EBA’s instruments of professional service), only the signed and/or sealed versions shall be considered final and legally binding. The original signed and/or sealed version archived by EBA shall be deemed to be the original for the Project.

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

Electronic files submitted by EBA have been prepared and submitted using specific software and hardware systems. EBA makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

3.0 ENVIRONMENTAL AND REGULATORY ISSUES

Unless so stipulated in the Design Report, EBA was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project specific design.

4.0 CALCULATIONS AND DESIGNS

EBA has undertaken design calculations and has prepared project specific designs in accordance with terms of reference that were previously set out in consultation with, and agreement of, EBA’s client. These designs have been prepared to a standard that is consistent with industry practice. Notwithstanding, if any error or omission is detected by EBA’s Client or any party that is authorized to use the Design Report, the error or omission should be immediately drawn to the attention of EBA.

5.0 GEOTECHNICAL CONDITIONS

A Geotechnical Report is commonly the basis upon which the specific project design has been completed. It is incumbent upon EBA’s Client, and any other authorized party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the geotechnical information that was reasonably acquired to facilitate completion of the design.

If a Geotechnical Report was prepared for the project by EBA, it will be included in the Design Report. The Geotechnical Report contains General Conditions that should be read in conjunction with these General Conditions for the Design Report.

6.0 INFORMATION PROVIDED TO EBA BY OTHERS

During the performance of the work and the preparation of the report, EBA may rely on information provided by persons other than the Client. While EBA endeavours to verify the accuracy of such information when instructed to do so by the Client, EBA accepts no responsibility for the accuracy or the reliability of such information which may affect the report.