SITE C CLEAN ENERGY PROJECT

VOLUME 2 APPENDIX G

DOWNSTREAM ICE REGIME TECHNICAL DATA REPORT

FINAL REPORT

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EXECUTIVE SUMMARY

This report presents the predicted changes to the ice regime on the Peace River as a result of the proposed Site C Clean Energy Project (the Project), as determined from the application of river ice computer models. Predicted changes to the ice regime with both the Project and the proposed Dunvegan Hydro Project in Alberta were also included in the analysis as were predicted changes under two future climate scenarios . Sixteen winters that represent a wide range of climate conditions were simulated for each of the three scenarios (existing conditions; the Project; the Project and Dunvegan) to quantify the maximum extent of the ice cover, timing of ice cover formation and break-up, water levels related to freeze-up and break-up, changes to ice thickness and changes to ice conditions as they relate to river transportation.

With the Project in place the model predicts that the maximum upstream extent of the ice cover would be on average about 30 to 50 km further downstream then under existing conditions. However, the ice cover would still advance upstream of the Town of Peace River in every year as it does today. For the range of winters examined in the study, results suggest that the ice front would not advance upstream to Taylor and would advance very rarely into British Columbia. Under the Project and Dunvegan scenario two ice fronts would form, one upstream and one downstream of the proposed Dunvegan Project. Results suggest that the upstream ice front would still not advance upstream to Taylor under the range of winters examined in the study.

The Project is predicted to lead to a delay in freeze-up at the Town of Peace River (approximately 290 km downstream of the Site C dam), in the order of 3 days on average. With both the Project and the Dunvegan Project, the average delay in freeze-up at the Town of Peace River is predicted to be 10 days. The duration of the BC Hydro control flow (to promote a stable ice cover at the Town of Peace River) is predicted to be about the same duration as today with the Project and about a week longer with both the Project and the Dunvegan Project. The closer proximity of the Site C dam to the Town of Peace River than the existing Peace Canyon Dam would allow for faster implementation of control flow for ice jam mitigation at freeze-up and break-up since the travel time for flows from the point of regulation to the Town of Peace River would be about half a day less.

The freeze-up water level at the Town of Peace River would not be expected to change as a result of the Project alone or the combination of the Project and the Dunvegan Project. The frequency of secondary consolidations that can cause high freeze-up water levels is expected to be reduced due to the slower advancing ice fronts. The amount of freeboard below the dykes to protect against secondary consolidations is not expected to change with the Project alone or with the Project and the Dunvegan Project. The frequency and severity of groundwater seepage in the Lower West Peace Subdivision would decrease due to the reduced frequency of secondary consolidations that would be attributable to a slower moving ice front which would be expected under either Project scenario.

Results suggest that the timing of break-up at the Town of Peace River would not change as a result of the Project alone or the combination of the Project and the Dunvegan Project. Thus the probability of the Smoky River breaking up dynamically into an intact Peace River ice cover and causing potential ice jam flooding at the Town of Peace River would not change.

The total combined durations of ferry and ice bridge operations at Shaftesbury Crossing (approximately 265 km downstream of the Site C dam) would not change as a result of the Project alone. However, with both the Project and the Dunvegan Project the total combined duration of ferry and ice bridge operations at Shaftesbury Crossing is expected to decrease by about 15 days. Durations of ferry and ice bridge crossings at Tompkin's landing would not change as a result of the Project or the combination of the Project and the Dunvegan Project.

The downstream extent of influence of the Project and the Dunvegan Project was different for every winter simulated. Results suggested that on average over the 16 winters simulated, no changes would be expected at Carcajou (approximately 550 km downstream of the Site C dam). These results indicate that the adopted downstream boundary of the ice models (Fort Vermilion) was sufficiently far downstream to capture the entire extent of Project influence.

Simulations under a future warmer climate indicated that ice formation would be pushed further downstream by between 10 and 100 km depending on location and winter severity. The influence of the Project or the combination of the Project and the Dunvegan Project would still be within the study boundaries under future climate scenarios.

ABBREVIATIONS AND ACRONYMS

CRISSP .... Comprehensive River Ice Simulation System Program (river ice model)

PRICE .... Peace River Ice (river ice model)

PRTIGM .... Peace River Thermal Ice Growth Model

GLOSSARY

Consolidated ice cover	Formed when a “juxtaposed ice cover” is pushed on by downstream forces of water flow and gravity and thickens beyond one frazil ice pan floe in thickness (see Juxtaposed Ice Cover).
Degree-days of Freezing	A cumulative total of daily average below freezing temperatures – used as an index for calculating ice processes such as lodgement or for determining winter severity.
Dynamic Break-up	When the ice cover is still strong and thick and the water discharge increases substantially enough to break-up the ice cover mechanically by exerting forces on the ice cover. These types of break-up can lead to ice jam flooding. (See also Thermal Break-up).
Erosion velocity	The water velocity at or above which a granular ice cover erodes.
Frazil ice	Small ice crystals that form in turbulent flow once the river temperature reaches the freezing point. These are present throughout the water column. They eventually stick together, float to the surface and form frazil pans that flow down the river.
Eulerian-Lagrangian technique	A numerical method used for tracking particle properties and concentrations in fluid flow. In this study: ice floes in rivers
Freeboard	The vertical distance between the top of a dyke or dam and the expected maximum water level behind it.
Hanging Dam	When frazil ice is deposited downstream of rapids in low velocity areas where it cannot be eroded. The hanging dam keeps getting thicker as long as frazil ice is being generated upstream. This leads to continuously increasing water levels at and upstream of the hanging dam.
Ice Front	Also known as “leading edge”. The upstream extent of the solid ice cover.
Juxtaposed ice cover	Formed when the ice floes gently come to rest edge to edge without overturning and form an ice cover that consists of ice pans a single layer thick. (See also Consolidated ice cover).
Lodgement	When frazil ice pans pass through a constriction, freeze together and stop moving. This creates an ice front that travels upstream.
Open Lead	An area of open water within an ice cover.
Primary Consolidation	When a juxtaposed ice cover initially consolidates (usually within a few hours or less than a day of the initial formation). This produces normal freeze-up water levels at the Town of Peace River.
River chainage	The distance in kilometres along the river centreline downstream of the W.A.C. Bennett Dam.
Secondary Consolidation	When a consolidated ice cover consolidates a second time, a few days after the primary consolidation. This produces above-normal freeze-up water levels at the Town of Peace River.

Stage	Water level measured vertically from a reference level or elevation.
St. Venant equations	Equations that represent the momentum of water flow commonly used to describe the physics of the flow of water in rivers.
Thermal Break-up	When the ice in the river melts in place due to warm air and water temperatures and solar radiation without substantive increases in river flow. This type of break is benign and does not lead to threat of ice jam flooding. (See also Dynamic Break-up).
Thermal Ice Thickness	That portion of the ice cover that is solidly frozen.
Total Ice Thickness	Includes the “Thermal Ice Thickness” plus the thickness of frazil slush underneath the thermal ice.

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1 INTRODUCTION

The objectives of the study are to describe the existing ice conditions in the Peace River and to predict changes as a result of the proposed Site C Clean Energy Project (the Project). The analyses of changes due to the Project were conducted using the CRISSP and PRTIGM models, the calibration, validation and expected accuracy of which are described in this report. Sixteen winters were simulated to provide a representative range of meteorological conditions on which to base the conclusions of the study.

Potential changes are described in terms of the following ice characteristics:

- maximum upstream extent of ice cover
- timing of ice cover formation and break-up
- freeze-up and break-up water levels at the Town of Peace River
- ice thickness
- changes in ice conditions relevant for river transportation

The analyses also included predicting changes in these ice characteristics for the Project with the proposed Dunvegan Hydro Project in Alberta and two future climate scenarios.

2 EXISTING CONDITIONS

2.1 Characteristics of the Peace River in B.C. and Alberta

The Peace River flows eastward from the W.A.C. Bennett and Peace Canyon Dams for about 400 km to the Town of Peace River, Alberta where the river turns north for about another 300 km. At Tompkin's Landing, a ferry crossing near High Level, it turns east once again (Figure 1) and from there it flows for another 500 km, passing through the Town of Fort Vermilion before entering the Peace-Athabasca Delta. Within the Peace-Athabasca Delta, the river joins up with a number of distributary channels to form the Slave River which eventually flows into Great Slave Lake in the Northwest Territories.

A longitudinal profile of the Peace River is shown in Figure 2. The river is steeper in its upstream reaches in British Columbia and, with the exception of a few rapids, its slope generally gets milder as the river flows through Alberta and northward to the Peace-Athabasca Delta. In British Columbia the typical slope is about 0.00050 m/m, but with a somewhat higher slope for a few tens of kilometres immediately downstream of Peace Canyon Dam. The channel is braided in some reaches, especially just downstream of Peace Canyon and between the District of Taylor and the British Columbia and Alberta border. River widths vary from 200 m to 600 m.

As the river flows into Alberta its slope flattens to about 0.00030 m/m and remains at around that value for about 300 km, through Dunvegan, the Town of Peace River and Sunny Valley. River widths are typically between 400 m and 700 m but mean values generally increase from around 400 m near the border to 550 m at Sunny Valley. Downstream of Sunny Valley, the slope reduces to 0.00020 m/m for about 80 km and then to about 0.00010 m/m at Tompkin's Landing. Average widths in this reach range from 550 m to 700 m.

Downstream of Tompkin's Landing, through Fort Vermilion and to the Vermilion Chutes, the slope reduces further to 0.00005 m/m. In this reach the channel widths can exceed 1,000 m, but with average values around 800 m. At a location about 915 km downstream of the W.A.C. Bennett Dam (85 km downstream of Fort Vermilion) the river drops about 10 m in just 3 km through the Vermilion Chutes. The Vermilion Chutes extend from the Vermilion Rapids, starting at km 913 to the Vermilion Falls at km 916. The slope is slightly steeper (0.00009 m/m) between the falls and Boyer Rapids where the river drops a few more meters over a short distance, and the channel returns to a milder 0.00005 m/m slope from there to the Peace-Athabasca Delta and the beginning of the Slave River. River widths can be quite variable in this reach, ranging between 600 and 2000 m.

Throughout this report locations on the Peace River are referenced based on river chainage (the distance in kilometres along the river centerline downstream of the W.A.C. Bennett Dam).

2.2 Description of Current Ice Regime

In the fall and winter months, as water is released from the Peace Canyon dam, the water cools due to its exposure to cooler air temperatures as it travels downstream. At some point the water temperature cools sufficiently to start producing suspended frazil (small ice crystals) which eventually stick together, become more buoyant, and float up to the water surface as their buoyancy overcomes the influence of turbulence. The point at which the water temperature reaches 0 ^{0}C and the water is cold enough to start forming ice is referred to as the zero-degree isotherm.

After the frazil rises to the water surface, it forms frazil pans, which are more or less circular ice floes of a few metres in diameter. These pans continue to travel downstream, and in doing so, they grow in number and extent and can join together to form frazil rafts. The pans also start to solidify (forming a frozen crust on the top) and thicken due to more frazil rising to the surface and depositing on the underside of existing pans. On the Peace River, the frazil pans can have solid ice crusts that range in thickness from a few centimetres up to about 0.2 m to 0.3 m. Total ice pan thicknesses, including the frozen crust underlain by very porous slush, can be 0.3 to 1 m. The solid ice that forms the top of these pans is referred to as thermal ice.

Downstream of the zero-degree isotherm, border ice also starts to form in low velocity areas close to shore, in back channels and around gravel bars. Border ice reduces the open water area, which ultimately reduces frazil ice generation but also reduces the channel top width. The reduction in channel width increases the propensity for frazil pans or rafts to jam and initiate the formation of a solid ice cover. Once the ice cover is initiated, frazil pans or rafts accumulate at the leading edge of the ice cover and the location of this stoppage point advances upstream. This is referred to as an ice front. Each year since 1973, Alberta Environment and BC Hydro have collected a large number of observations of the ice front locations. These observed locations are presented in Figure 3. When viewed as an ensemble, they provide a concise representation of timing of freeze-up and break-up and the duration of the ice cover each year at any location along the river.

The location of the restriction that initiates the ice cover (or ice front) is not well known because the initial formation of the ice cover has proven difficult to observe. However, it is thought to form either somewhere in the lower-velocity/milder-sloped reaches between Tompkin’s Landing (km 694) and the Vermilion Chutes (km 912) or further downstream in the Peace-Athabasca Delta reach. It also is possible that multiple lodgement sites occur and since systematic observations of freeze-up in these reaches have not been made, it is difficult to ascertain how and where exactly the ice cover is initiated. This lack of observational data is not problematic for this study as lodgement in the model was selected such that the date at which the simulated ice front passed through the most downstream point corresponded to the observed date on which it passed that point. Modelling is described in more detail below.

One field observation in these lower reaches - as far downstream as Vermilion Falls - was made by BC Hydro on November 30, 2011. Only one substantive open lead (area of open water within an ice cover) was found, suggesting that there was only one lodgement location above Vermilion Chutes in that year. The open lead was 13 km long and extended from a point 10 km upstream of the Vermilion Rapids (km 903) through to the downstream end of the Vermilion Falls (km 916). Occasional observations by Alberta Environment of the Vermilion Chutes have always observed them to be open, with apparent lodgement upstream of the Vermilion Rapids around km 900 (Willi Granson, personal communication April 2012). Other studies have suggested that the ice cover initiates downstream of the chutes, “stages up” (i.e.,the water level rises and allows the ice front to progress further upstream) over the chutes and then continues its advancement upstream (Andres and Healy 2006). One possibility is that the chutes form a backwater with very low velocities upstream allowing lodgement to occur there due to the limited ice cover induced stage-up that occurs in backwater reaches compared to that in uniform flow reaches. The other possibility is that a hanging dam forms downstream of the chutes, which allows the ice to lodge and then work its way up over the chutes.

Once lodgement occurs, the leading edge of the ice cover (or ice front) continues to advance upstream (Figure 3). Depending on the severity of the winter, freeze-up at Fort Vermilion has occurred anytime between mid-November and late December. At the Town of Peace River it has occurred anywhere from early December to late February.

As the ice front advances upstream it increases the stage (water level) by between 1 and 5 m due to the increased resistance and thickness of the ice cover. It is important to note that the increase in water level is not attributable to any change in the flow releases from Peace Canyon Dam. That is, changes in water levels are a result of the ice processes only and not due to changing flow releases during the ice cover formation period. However, since the winter flows are three to four times those of pre-regulation conditions, the winter water levels are higher at locations where the ice cover forms. At these locations, the annual peak water levels generally exceed the summer peak water levels but are generally below bank-full levels.

As the ice front progresses upstream, it can either form a juxtaposed ice cover, and the ice cover can remained juxtaposed over the entire winter, or a consolidated (thickened) ice cover. The type of ice cover affects the magnitude of the resulting increase in water levels. A juxtaposed ice cover would cause the river to stage-up 1 or 2 m whereas a consolidated ice cover would cause it to stage-up 3 to 5 m. The process by which the juxtaposed ice cover forms will be described first since it is usually a precursor to a consolidated ice cover.

Initially the ice floes arrive at the ice front and gently come to rest edge to edge without overturning and form an ice cover that consists of ice pans a single layer thick. This is referred to as a juxtaposed ice cover. In the milder-sloping downstream reaches, this type of ice cover is stable due to the lower slope and remains so for the entire winter. Historically, a juxtaposed ice cover tends to form downstream of the confluence of the Notikewin River (km 565) where the Peace River starts to transition to a more mildly-sloped channel. However, it is unclear if this is precisely where the change in river slope occurs, as the next known geodetic elevation downstream of the Notikewin River is not until the Carcajou gauge at km 651. The river does appear to substantially widen at km 624; perhaps this is where a change in river slope occurs. This point is discussed further in the calibration portion of this report (Section 3.4 Calibration Summary and Appendix B).

Air temperature also plays a role in determining if an ice cover initially forms as a juxtaposed or a consolidated ice cover. Cold temperatures freeze the juxtaposed ice pans together more rapidly, thereby providing extra strength to resist consolidations. Therefore, depending on the air temperature when the ice cover forms, some reaches can experience a juxtaposed ice cover in one year and a consolidated ice cover in the next. Water velocity also has an influence. Higher water velocities tend to produce a more consolidated ice cover and lower water velocities favour a juxtaposed ice cover. Since the water velocity is a function of discharge, river slope, cross section shape and bed roughness, there can be large spatial and temporal variability in the local ice cover characteristics.

In the steeper upstream reaches of the river, consolidation processes that cause the collapse of the temporarily juxtaposed covers and produce thicker consolidated ice covers almost always occur, except under extremely cold weather. As the ice pans juxtapose for tens of kilometres the cumulative forces from water drag along the bottom of the ice cover and from gravity due to the river slope can cause the ice cover to consolidate. The ice pans then overturn on each other and thicken the ice cover in just a few minutes from less than a metre thick to several metres. This process typically occurs every few hours as the ice front is advancing, and is generally limited to the first 2 to 5 km of ice cover downstream of the ice front. These types of collapses are termed primary consolidations and produce a more or less uniformly thick ice cover over many kilometres of channel length. The thickened ice cover provides a greater contact area between the channel banks, thereby transferring the forces on the ice cover laterally to the banks rather than relying on the transfer of forces downstream to produce the force required for a stable ice cover. In fact, this is the primary mechanism for a stable ice cover to form in steeper reaches of the Peace River upstream of the Notikewin River. However, juxtaposed ice covers can occur in the steeper reaches of the Peace River on occasion during extremely cold weather, usually at temperatures below -30 or -35 ^{o}C. This is because the rapid freezing together of frazil pans gives the ice cover enough strength to resist primary consolidations.

Larger consolidations that produce locally high freeze-up levels can occur from time to time. Every year, at some location on the Peace River, the ice cover advances rapidly due to colder than normal air temperatures, perhaps in the juxtaposed mode. Under such cold conditions the ice cover can advance longer distances without primary consolidations since additional stability is gained from the ice floes freezing together. However, this strength is relatively tenuous and cumulative local ice loads from the rapidly advancing ice cover may eventually create instability. The more rapid the advance, the more unstable the ice cover. For example, an ice cover can advance up to 100 km upstream over several days in this mode. The entire 100 km length then can suddenly consolidate and, due to the build-up of momentum, the disruption of the ice cover can extend downstream of the juxtaposed reach into an already consolidated ice cover, increasing water levels another 1 to 4 m above the 3 to 5 m already associated with the initial freeze-up. These events are referred to as "secondary consolidations" and can be triggered by a warming in the weather after a cold spell. For an example, a secondary consolidation occurred in the Dunvegan area in January 2004 after several days of -40^{o}C weather that was followed by a warm up to -20^{o}C (Andres, et al. 2005).   This occurred in the vicinity of Dunvegan in January of 2004.

Even though secondary consolidations occur every year, they only produce higher water levels in a 5 to 10 km long reach of the river, near to where the consolidation stops. Therefore, the annual probability of a secondary consolidation affecting any particular populated location would be about 10 to 20% (once every 5 to 10 years). Since these secondary consolidations can be random, arising out of natural variability in the local weather, there is no way to completely mitigate them. Secondary consolidations can also be triggered if a long consolidated ice cover forms at a low discharge and then the flow is increased later in the winter. This type of operation is avoided when the ice cover is forming at and upstream of the Town of Peace River and is central to the Joint Task Force procedures described in Section 2.4 and Appendix A. However, secondary consolidations triggered by temperature fluctuations can occur in spite of taking precautions with discharge fluctuations.

A reach of river is generally safe from secondary consolidations once the ice cover has solidified sufficiently at that location. When the ice cover initially forms it consists of ice pan crusts and loose frazil slush. As freezing temperatures continue the interstitial water in this slush freezes from the surface downward forming a solid crust. This crust is called “thermal ice” and is what provides stability to the ice cover to resist forces generated by secondary consolidations. Studies on the Peace River - Andres et al (2005), Jasek (2006) - determined that 0.25 m of thermal ice was sufficient to resist secondary consolidations and recommended a thickness of 0.4 m to provide a sufficient factor of safety. This thickness criterion is specific to the Peace River because the depth of the river also factors into the forces exerted on the thermal ice sheet during a consolidation event.

Once freeze-up occurs at a specific location, the frazil slush underneath the cover continues to move and is eroded from high velocity areas and deposited in lower velocity areas. This increases the channel conveyance capacity and causes the river level to gradually decrease after freeze-up even if discharges remain constant or increase. Water levels can slowly decrease by 0.5 m to 1.5 m over several months due to this mechanism. This phenomenon allows for increasing generation and outflows from BC Hydro’s Peace River facilities later in the winter once the ice cover has sufficiently solidified.

After freeze-up at the Town of Peace River (typically between late December and late February), the ice cover continues to advance further upstream and generally reaches its maximum upstream position in March. The normal range of its maximum extent is from just downstream of Dunvegan (km 300) in warm years to around the Site C dam location (km 105) in cold years. However, the winter of 2011 - 2012 was the warmest on record and the ice front advanced upstream only as far as Shaftesbury Crossing (km 368), about 27 km upstream of the Town of Peace River. There have been no extreme cold winters in the last 15 years and as a result the ice front has not advanced upstream of Taylor (km 123) since 1997.

With the onset of warming temperatures, longer days and increased solar radiation in March, the ice front starts its recession downstream. The ice front passes through the Town of Peace River anywhere from late March to late April. In most years the break-up at the Town of Peace River is relatively benign, with the ice cover melting in place with little or no increase in water level. This is known as a thermal break-up. In some years, discharges in the river at break-up can increase dramatically as a result of snowmelt runoff from the prairies. A major source of this runoff is the Smoky River, which enters the Peace River just

6 km upstream of the Town of Peace River. This runoff can cause what is termed a dynamic break-up, and can lead to the formation of ice jams that can flood the Town. Three conditions must be met before a break-up ice event at the Town of Peace River becomes a potential threat: 1) the ice front on the Peace River is located upstream of the Town, 2) the snow pack in the lower elevation (prairie portion) of the Smoky River Basin is above normal and 3) there is a rapid and sustained warming in the weather. A historical as well as a Monte Carlo analysis of break-ups from 1971 to 1999 by Andres (2002) indicated that dynamic break-ups can threaten the Town of Peace River in about 30% of the years; in 70% of the years the break-up was determined to be a benign thermal event. A dynamic break-up at the Town of Peace River has historically occurredin the first three weeks of April. The timing of a thermal break-up at the Town of Peace River has ranged from mid-March to late April.

2.3 History of Ice Jam Flooding at the Town of Peace River

Break-up ice jams that caused flooding at the Town of Peace River have occurred both prior to and after the impoundment by the W.A.C. Bennett Dam and the filling of Williston Reservoir. These flooding events are thought to have been triggered by the unregulated Smoky River. Break-up ice jam flooding occurred at the Town of Peace River in 1963 and 1965. Williston Reservoir started filling in 1968 and finished filling in 1972. This was followed by ice-related flooding at break-up in 1973 and 1974 because of high spring runoff in the Smoky River basin in those years. Another break-up ice jam occurred in 1979. In 1997, in the Town of Peace River, an operational error requiring the sealing of a hole in the dyke for allowing bridge traffic across the Heart River occurred. As a result the Town of Peace River flooded even though the ice-related water levels were below the top of the dykes. After this event, the bridge was upgraded so that that type of breach would not be repeated. In 2007 a break-up flood was averted when BC Hydro reduced flows to compensate for the increased contribution from the Smoky River (Jasek 2007).

The first known freeze-up high water event at the Town of Peace River occurred in 1982 when a secondary consolidation traveled from Dunvegan down past the Town of Peace River (more than 100 km). No overland flooding occurred, although subsequent seepage into basements did take place in the Lower West Peace Subdivision. Another event occurred on February 29, 1992. This freeze-up event was rather unusual as the cold spell was followed by a warm spell sufficient enough to cause snowmelt run-off that produced higher than normal winter discharges. This event caused dykes in the Town of Peace River to overtop. After this event the dykes were upgraded to their current elevation and now are constructed to the 1:100 year regulated open water event (Andres 1996) and a 1:40 year ice jam event (Andres 2002).

Secondary consolidations at the Town of Peace River during freeze-up have occurred more recently in 2005 and 2008. These produced high water levels but did not come close to overtopping the dykes. However, seepage into basements in the Lower West Peace Subdivision has occurred during freeze-up in 2005 and 2008, as well as in 1982 and 1992.

2.4 Description of Joint Task Force and Procedures for Influencing the Freeze-up and Break-up on the Peace River

The Alberta – British Columbia Joint Task Force on Peace River Ice (the Joint Task Force) was formed in 1975, with membership from BC Hydro, B.C. Environment and Alberta Environment (now Alberta Environment and Sustainable Resource Development). After the 1974 break-up flood at the Town of Peace River, the Joint Task Force was formed to coordinate general break-up ice observations on the Peace River system in the provinces of British Columbia and Alberta; and, in particular, to make recommendations related to BC Hydro operations to reduce the ice jam flooding hazard at the Town of Peace River at break-up. After the first high water freeze-up event in 1982, the Joint Task Force also started conducting observations during freeze-up and providing operational recommendations that would apply during freeze-up. Operational procedures have continuously been updated and improved as better science and more information about ice processes on the Peace River have become available. The Joint Task Force does not have any enforcement capability regarding the recommendations it puts forward. However, BC Hydro and Alberta have always been able to agree on operational recommendations of the Joint Task Force.

Appendix A includes details related to BC Hydro and Alberta operations during freeze-up and break-up of the ice cover at the Town of Peace River.

2.5 River Crossings on the Peace River

There are two public river crossings on the Peace River upstream of Fort Vermilion - Shaftesbury Crossing at km 371 (25 km upstream of the Town of Peace River), and Tompkin's Landing crossing at km 694 (300 km downstream of the Town of Peace River). A ferry operates in the open water season and an ice bridge is constructed in the winter at both of these locations. The Shaftesbury Crossing provides shorter access for the members of the rural community of Tangent to the Town of Peace River and Grimshaw. The Tompkin's Landing Crossing (also referred to as La Crete Ferry or Ice Bridge) provides an alternative transportation link to the community of La Crete.

An ice bridge is also constructed at a private crossing in the community of Sunny Valley at km 486, about 90 km downstream of the Town of Peace River.

Additional crossings exist downstream of Tompkin's Landing but results of this study suggest that even the Tompkin's Landing crossing is too far downstream to be influenced by the Project. As such, this study did not consider these additional crossings.

2.6 Water Supply Intakes

There are several municipal and industrial water supply intakes or wells on the Peace River. Listed from upstream to downstream these are for the District of Hudson's Hope, City of Fort St. John, District of Taylor, Spectra, Town of Fairview, Town of Peace River, Daishowa-Marubeni International Ltd., Shell, and the hamlets of La Crete and Fort Vermilion. There is no ice formation at Hudson's Hope due to its close proximity to the Peace Canyon Dam. Taylor has wells in a river gravel bar that can become submerged if ice cover forms in its vicinity. This is not a problem for the intake themselves but it prevents access to the wells if maintenance is required. Therefore, potential changes in the annual probability of ice formation in the vicinity of Taylor are important to determine the potential for adverse ice conditions to develop as a result of the Project. The other intakes on the Peace River experience ice cover formation every year with little or no complications associated with ice formation or frazil ice.

3 MODELLING APPROACH AND EVALUATION METHODOLOGY

CRISSP and PRTIGM models were used to assess changes to the ice regime as a result of the Project. These models are described below.

CRISSP (Comprehensive River Ice Simulation System Program) was used to simulate most of the ice processes and to quantify frazil ice generation, suspended and surface ice concentrations, total ice thickness, ice affected water level, ice front progression rates and thermal recession rates of the ice cover. The ice front results were useful in determining the timing and durations of the ice cover at various locations of interest. Surface ice concentrations from CRISSP were used to determine the cessation of ferry operations and ice front positions from CRISSP were used as input for the start of the growth of thermal ice in PRTIGM.

Although CRISSP simulates the growth of thermal ice, its output was not used for predicting the changes in thermal ice (see Section 4.4.1). Instead, PRTIGM (Peace River Thermal Ice Growth Model) was used to simulate thermal ice growth at selected location. These simulations were used specifically to determine when the thermal ice cover would be thick enough for ice bridge construction, and to determine when BC Hydro could resume normal operations after flow control was in place for managing freeze-up water levels at the Town of Peace River. The growth of thermal ice occurs after the ice cover forms so the fact that it is being simulated outside of CRISSP does not lead to inaccurate predictions of other parameters like ice front progression and ice related water levels, the latter being a function of the total ice thickness and not the thermal ice thickness.

The following sections provide a description of the models, the selection and justification of spatial and temporal study boundaries, input data and assumptions, and finally the calibration and validation of the models.

Three scenarios were simulated as follows.

1. Existing conditions
2. With the Project
3. With the Project and the proposed Dunvegan Hydro Project

The Dunvegan Hydro Project is a proposed run-of-river hydro-electric facility in Alberta near Dunvegan. The location of the Dunvegan Project is indicated in Figure 1 and Figure 2 and is about 190 km downstream of the proposed Site C dam. The headpond elevation would be about 6.6 m above the present mean river level. The headpond would be entirely contained within the natural river channel and would be 26 km long. Glacier Power, a wholly owned subsidiary of Canadian Hydro received environmental approval for the project in 2008. Since then the project was purchased by TransAlta Corporation and construction has not started as of this writing. Additional details about the project can be found in the Environmental Impact Assessment for the Dunvegan Project (Jacques Whitford 2006) and the details of the ice regime analysis is described in Andres and Healy (2006).

3.1 Model Description

3.1.1 CRISSP

CRISSP1D is a comprehensive state-of-the-art ice simulation model that is used to simulate river ice processes and associated flow conditions. The ice processes include water temperature and ice concentration distributions of suspended and surface ice; ice cover formation, progression, and consolidation; undercover transport and accumulation; ice jam evolution; thermal growth and decay of the ice cover including the influence of a snow cover; cover stability; initiation of break-up; break-up ice runs and jam formation. Specific features of the model include the ability to treat river networks, transitional flows, and internal hydraulic structures.

The model is used by hydroelectric utilities and others concerned with river ice issues. The model is capable of addressing both ice-related design and operational issues including the development of procedures for establishing favourable ice formation conditions in the early ice formation period. It also can be used to establish operating policies compatible with ice conditions which contribute to the maximization of the productivity of generation stations. The model is also applicable to a wide range of hydraulic engineering needs, including ice jam-related flood analysis studies, applications to wintertime navigation and transportation, climate change studies, and ice related environmental and ecological studies.

A more detailed description of CRISSP1D can be found in Shen (2005) and Chen et al. (2006). In CRISSP1D the four-point implicit model for river networks developed by Potok and Quinn (1979) is used for solving the St. Venant equations for flow hydraulics. Calculation of ice processes are calculated separately from the hydraulic processes using an Eulerian-Lagrangian technique with a much smaller time step than the time step used in the hydraulics calculation. The two calculations are coupled at every hydraulics time step.

3.1.2 PRTIGM

PRTIGM is a thermal ice growth model that was developed in-house at BC Hydro based on the theoretical equation developed by Ashton (1980) for simulating thermal ice growth. The model has been used operationally and successfully by BC Hydro to forecast the timing of the cessation of control flow, which depends on the thermal ice thickness downstream. More details about PRTIGM can be found in Jasek (2006).

3.2 Study Boundaries

3.2.1 Spatial Study Boundaries

For existing conditions the model domain extends from the tailrace of Peace Canyon (km 20.4) to Fort Vermilion (km 831.5). For the scenarios with the Project, with and without the Dunvegan Project, the model domain extends from the tailrace of the Site C dam (km 105.7) to Fort Vermilion (km 831.5).

The downstream extent of the model domain is Fort Vermilion. This location was chosen as this is usually the first location at which the ice front location is recorded in each ice season. Also, previous modelling results indicated that this location is well downstream of where changes to the ice regime would occur as a result of the two proposed projects.

3.2.2 Temporal Study Boundaries

A total of 16 winters (1995-1996 through 2010-2011) were selected as the basis for the modelling. The ice front trace for each of these 16 winters is shown in Figure 3. The range of years chosen was based on data availability and their representativeness of winter severity. Although ice front locations and weather data were available back to 1973, accurate water temperature data from Peace Canyon from prior to 2000 were not available. However, no very cold years occurred in the new millennium. The most recent very cold years were 1995 - 1996 and 1996 – 1997. Thus in order to simulate a representative range of climatic conditions, the Peace Canyon outlet water temperatures were reconstructed from 1995 to 1999 as described in Section 3.3.2. One can see that the coloured traces in Figure 3 cover most of the entire domain and range of all the ice front traces in grey. This illustrates that the 16 years selected are a reasonable representation of a range of climatic conditions for the last 39 years.

Another way to assess the representativeness of the 16 winters used in this analysis is to consider the maximum degree-days of freezing[1] for the each winter. The Environment Canada climate station at the Town of Peace River Airport was selected to calculate this index and the results are presented in Table 3.1. The minimum and maximum degree-days of freezing over the 16 winter period range from 69% to 144% of the historical mean degree-days of freezing. The historic range is only slightly greater, from 64% to 145% of the historic mean. This comparison suggests that the 16 years chosen are representative of the distribution of climatic years for the longer duration dataset back to 1973. There appears to be a slight bias in recent years towards more very warm years and less very cold years.

Table 3.1 Maximum degree-days of freezing at Town of Peace River from October 1st

Degree-Days of Freezing (°C – Days)			
Town of Peace River Airport			
Ice Season	**All Years**	**Modelled Years**	**Other Years**
1973 - 1974	2466		2466
1974 - 1975	1736		1736
1975 - 1976	1780		1780
1976 - 1977	1150		1150
1977 - 1978	2001		2001
1978 - 1979	2437		2437
1979 - 1980	1438		1438
1980 - 1981	1322		1322
1981 - 1982	2459		2459
1982 - 1983	1782		1782
1983 - 1984	1431		1431
1984 - 1985	2064		2064
1985 - 1986	1604		1604
1986 - 1987	1407		1407
1987 - 1988	1091		1091
1988 - 1989	1863		1863
1989 - 1990	1472		1472
1990 - 1991	1843		1843
1991 - 1992	1394		1394
1992 - 1993	1656		1656
1993 - 1994	1694		1694
1994 - 1995	1803		1803

[1] See explanation in Glossary

Degree-Days of Freezing (^{o}C – Days)			
Town of Peace River Airport			
Ice Season	**All Years**	**Modelled Years**	**Other Years**
1995 - 1996	2436	2436	
1996 - 1997	2303	2303	
1997 - 1998	1306	1306	
1998 - 1999	1696	1696	
1999 - 2000	1284	1284	
2000 - 2001	1299	1299	
2001 - 2002	1950	1950	
2002 - 2003	1550	1550	
2003 - 2004	1724	1724	
2004 - 2005	1441	1441	
2005 - 2006	1167	1167	
2006 - 2007	1712	1712	
2007 - 2008	1851	1851	
2008 - 2009	1955	1955	
2009 - 2010	1501	1501	
2010 - 2011	1942	1942	
2011 - 2012	1161		1161
Minimum	1091	1167	1091
Mean	1697	1695	1698
Maximum	2466	2436	2466
Legend			
2200 – 2500 Very Cold			
900 – 2200 Cold			
1600 – 1900 Neutral			
1300 – 1600 Warm			
1000 – 1300 Very Warm			

3.3 Input Data and Assumptions

3.3.1 River Geometry

The CRISSP model can accept naturally shaped cross sections based on data from bathymetric and bank surveys. However, natural geometry on any river can vary substantially in short distances. For any hydraulic or river ice model to give accurate solutions, the differences between adjacent cross sections cannot vary substantially, otherwise model instabilities can develop. Therefore, in this study gradually varying widths with steep banks were used following the approach developed by Andres and Healy (2006). These widths varied gradually, not more than a few percent between cross sections, whereas the adjacent natural cross sections on the Peace River could vary by more than 100%. The adopted cross sections were trapezoidal in shape with steep banks so that the river width did not vary substantially with stage (water level). The "smoothing" of river geometry in numerical models allows for more accurate solutions of the governing equations. This mimics the behavior in nature where abrupt changes are smoothed out naturally through second order effects that are not accounted for by the models. This leads to more reliable solutions and decreases uncertainty due to numerical noise.

3.3.2 Boundary Conditions

Upstream Discharge

Hourly average discharges calculated from turbine rating curves at Peace Canyon were used to define the flow at the upstream boundary of the model for the entire 1995-2011 study period. Historically, during the November to April ice season, spillway discharges have been zero at Peace Canyon and so were not added to turbine flows. Although the maximum possible turbine flows at the Site C generating station would be on the order of 2,500 m^3/s compared to 1,982 m^3/s at Peace Canyon, it was assumed that Peace Canyon flows would be representative of those at Site C. This is not an unreasonable assumption because the active storage in the Site C reservoir would be limited, and due to the lack of local inflows into the reservoir in the winter, higher turbine flows would not last for a long enough period to influence the overall ice regime. Flows at the Site C generating station that could be systematically higher than the maximum Peace Canyon turbine flows would also be limited by considerations of the downstream ice conditions that would require Site C generating station flows to be similar in magnitude to those at Peace Canyon (this relates to managing the risk of secondary consolidations downstream as discussed in Section 2.4). Sensitivity testing was performed to test this expectation, and results confirmed that the ice regime was not sensitive to the small changes in flows that could be attributed to the Project.

Upstream Water Temperature

The outlet water temperature at Peace Canyon has been measured at various levels of accuracy for different time periods. These levels of accuracy can be split up into three time periods, pre-1999, 1999 to 2001, and 2001 to present. Prior to 1999 water temperature at the Peace Canyon tailrace was recorded on strip charts and then digitized. However, the accuracy prior to 1999 is suspected to be +/- 3^{o}C, which is not sufficient for input into an ice model. This conclusion was arrived at on the basis of the water temperatures recorded during the 1995-1996 winter. In January 1996 the Peace Canyon outlet water temperature was reported to be more than + 3°C for one of the coldest winters on record. Normally, the January water temperature would have been about +0.5°C.

From 1999 to 2001 a digital temperature probe was installed in a cooling water conduit for the Peace Canyon plant. Although more accurate, it only represented the Peace Canyon outlet temperature when it was withdrawing water from the river for cooling. In 2001 the sensor was moved from the cooling water conduit to the tailrace to provide a more accurate measurement of water temperature. The accuracy of the measurement was confirmed by independent measurements by two data loggers over the course of two winters. Therefore, from 2001 to present, the Peace Canyon water temperatures can be taken at face value, with the exception of brief periods where sensor maintenance and telemetry issues arose. From 2001 to 2011 water temperature data from the Peace Canyon tailrace was input directly into the CRISSP model as an upstream boundary condition for the existing conditions scenario. Short episodes of missing data were interpolated.

From 1999 to 2001 the water temperature was corrected to account for it being inside the cooling water conduit. The water temperature appeared to spike downward when the cooling water conduit was active. However, when it was not active the trend in the water temperature still remained, decreasing in the early winter, then stabilizing in mid-winter and then increasing in the spring. Thus it was possible to correct the temperatures when the cooling water was not active to match the downward spikes when the cooling water intake was in use.

From 1995 to 1999 the water temperatures were iteratively determined using the CRISSP model. Initially, the recorded (but inaccurate) temperatures were assumed and then adjusted, usually downward, to better match the simulated and observed ice fronts. As the sensor was in the cooling water conduit at this time, a downward adjustment makes sense. The downward adjustments also made sense based on the fact that in colder winters the downward adjustment was more than in milder winters.

For the simulations with the Project, the water temperature at the outlet of the Site C reservoir (the upstream boundary of the model) was taken as that determined on the basis of a three-dimensional thermodynamic model of the Site C reservoir (described in Volume 2 Appendix H Reservoir Water Temperature and Ice Regime Technical Data Report).

Downstream Water Level

For simplicity, the water level at the downstream boundary was taken as a constant water level with an elevation of 250.0 m above mean sea level – close to the expected water level for a juxtaposed ice cover at Fort Vermilion. Since the ice cover is juxtaposed in this reach, the forcing of a constant elevation does not influence the ice cover progression at this point in the model domain because the ice cover thickness is independent of the friction slope.

3.3.3 Meteorological Data

Meteorological or weather data from three long term Environment Canada stations were used as input to the CRISSP model. The three climate stations are located at the Fort St. John, Town of Peace River and High Level airports (Figure 1). The meteorological data from these stations were applied at km 112.0, km 396.7 and km 764.3 respectively and linearly interpolated for points in between using river channel distance.

Hourly air temperatures and dew point temperatures from the three airport stations were used as model input. A sensitivity analysis was done for wind but it appeared that the model results were not very sensitive to this parameter. Furthermore, the airport stations on the plains are more exposed than the river valleys, and thus the influence of wind would have been overestimated. Therefore, wind speed and direction were neglected.

CRISSP allows for the inclusion of cloud cover (in tenths) to calculate the amount of solar radiation. The ice regime would be sensitive to cloud cover in March and April during the ice front recession when the days are longer and the sun angle is high, but not sensitive during November to January when the days are shorter and there is limited solar radiation. Hourly cloud cover (in tenths) and cloud opacity (in tenths) were available from Environment Canada for the three airport weather stations. Cloud opacity was found to be slightly better than cloud cover at simulating the recession rate of the ice cover. Therefore, hourly cloud opacity was used as input to the model.

Daily snowfall was used to account for the insulation influences of the snow cover on the thermal ice growth simulated by the model although ultimately, the thermal ice cover growth calculation was performed outside of the CRISSP model for reasons sighted in Section 4.4.1. The daily values of snowfall were spread evenly throughout the day into 24 hourly values for compatibility with the other data that was in hourly format.

3.3.4 Tributary Inflows

During the November to April period, most of the total tributary inflow between Peace Canyon and Fort Vermilion can be accounted for by two main tributaries, the Pine River in British Columbia and the Smoky River in Alberta. Other tributaries such as Halfway, Moberly and others contribute less than 1% of the total river flow at the Town of Peace River during the winter months. Since tributary inflows vary much more gradually than flow releases from Peace Canyon, it was determined that daily average flows from the Smoky and Pine Rivers were sufficient.

3.4 Calibration Summary

This section provides a high-level description of the calibrations of the CRISSP and PRTIGM ice models. More calibration details for each of these two models can be found in Appendix B and Jasek (2006) respectively.

The starting point for the CRISSP model calibration were the calibrated parameters used in the PRICE model used by Andres and Healy (2006) to simulate the changes to the ice regime as a result of the proposed Dunvegan project. However, there were some differences between the two models and so some of the calibration coefficients had to be altered in order for the CRISSP model to adequately fit the field data. These are explained in more detail in Appendix B. An example of differences was the heat transfer coefficient between air and water; in PRICE 20 W/^{o}C/m^{2} was selected and in CRISSP 17 W/^{o}C/m^{2} was adopted. However, this difference is not of concern as this variable and others were calibrated to observed ice fronts and more than one equally acceptable calibration is possible. The important thing is that the field data are well simulated. Despite these differences, the calibrated CRISSP model produced results similar to those produced by the PRICE model.

The first step in the CRISSP calibration was to ensure that water temperatures and the timing of the zero-degree isotherm were modelled correctly by comparing simulated and measured water temperatures at various locations between Fort St. John and the Town of Peace River. This was done by selecting a suitable heat transfer coefficient. Next the porosity of the frazil slush in the frazil pans was selected in order to reproduce observed frazil ice pan thicknesses and surface ice concentrations. Then ice jam parameters and ice jam roughnesses were selected to give the correct total ice cover thickness, the correct rate of ice front recession and ultimately to reproduce water levels at measured locations.

Additional adjustments to the calibration were made after 2006 as the model was used operationally by BC Hydro to forecast ice front position for the implementation of control flow.

Calibration of PRTIGM consisted of selecting the appropriate heat transfer coefficient, the porosity of the frazil slush under the thermal ice, the thermal conductivity of the snow cover and the settlement ratio of the snow.

3.5 Accuracy and Limitation of Ice Models

3.5.1 Accuracy and Limitations of CRISSP

The accuracy of the CRISSP model is study-specific; in the current study, the maximum upstream extent of the ice front was simulated to within 10 km with some outliers of 30 km. The average maximum extent over the 16 winters simulated was within 5 km of observed. The model was able to predict the timing of freeze-up of the ice cover at the Town of Peace River to within 3 days and break-up to within 9 days. The average timing of freeze-up and break-up at the Town of Peace River over the 16 winters simulated was within 1 day of observed.

The model was able to reproduce normal ice related water levels and open water levels to within about 0.5 m of observed but as the model is unable to accurately simulate secondary consolidations at freeze-up it cannot predict the extreme high water levels resulting from these events. Finally, the model cannot accurately simulate a dynamic break-up of the Peace River triggered by a dynamic break-up of the Smoky River and thus cannot predict either the timing or severity of such events. However, since the model is able to simulate the necessary conditions for these to occur (the presence or absence of an ice cover) this is not an impediment for assessing the influence of the Project on the frequency of secondary consolidations and dynamic break-up events triggered by the Smoky River.

The calibration of the CRISSP model to adequately simulate the observed ice fronts, water levels, water temperatures and ice production and melt rates gives confidence of the reliability of the model. The fact that the model is able to simulate 16 winters with the same calibration coefficients indicates that uncertainties in the input variables and calibration coefficients are not high enough to manifest themselves as large errors in the output.

3.5.2 Accuracy and Limitations of PRTIGM

The accuracy of the thermal ice thickness calculated by PRTIGM was about +/- 0.1 m in this study. Much of this variability was due to the lack of snowfall data away from the vicinity of meteorological station sites. This is because snow produces an insulating barrier between the air and the thermal ice; therefore the snow depth plays an important role in limiting the growth of the thermal ice. However, this is not a concern for assessing the influence of the Project since the same assumptions were used for all Project scenarios.

3.6 Validation

The calibration of the CRISSP model has been ongoing since the development of the model in 2006. The original calibration was based on four winters; 1995-1996, 2002-2003, 2003-2004, and 2005-2006. The last three winters were chosen as they contained the most comprehensive field data information to date and 1995-1996 was chosen in order to include a very cold year which did not occur during the intensive 3-year field program. The simulated and observed ice front plots are shown in Appendix C. When these calibration coefficients were applied to the other 12 years in the study, the model was reasonably accurate in predicting the ice fronts for those years as well. This accuracy can be measured by comparing simulated and observed freeze-up and break-up dates at the Town of Peace River and by comparing simulated and observed maximum upstream ice cover extent (Table 3.2).

The comparison shows that the CRISSP ice front simulations are a valid representation of the observed ice front positions. On average the maximum upstream extent of the ice cover was represented to within 5 km by the model. The largest deviation was 27 km (simulated ice front was further upstream than the observed ice front). This was due to a secondary consolidation that occurred in the winter 2009-2010 near Dunvegan that was not well simulated by the model. The average simulated freeze-up dates at the Town of Peace River were close to the observed freeze-up dates with a range of between three days early to two days late. The simulation of the break-up date was slightly more variable but still good. On average the break-up date at the Town of Peace River was simulated to be one day later than observed, with ranges from as much as five days early to four days late and one extreme value of nine days late. The nine day late value also occurred during the 2009-2010 simulation; probably because the model did not simulate the recession of the ice cover during the secondary consolidation event.

Table 3.2 Comparison of observed and simulated maximum upstream ice cover extents and freeze-up and break-up dates at the Town of Peace River[2]

	Maximum Ice Front Progression (km)			Date of Freeze-Up at Town of Peace River			Date of Break-up at Town of Peace River		
Winter	Observed	Simulated	Difference	Observed	Simulated	Difference	Observed	Simulated	Difference
1995-1996*	101	98	-4	10-Dec-95	10-Dec-95	0	20-Apr-96	21-Apr-96	1
1996-1997*	125	123	-2	21-Dec-96	21-Dec-96	0	17-Apr-97	19-Apr-97	2
1997-1998	280	270	-10	13-Jan-98	13-Jan-98	0	29-Mar-98	27-Mar-98	-2
1998-1999	217	215	-3	05-Jan-99	06-Jan-99	1	03-Apr-99	03-Apr-99	0
1999-2000	219	220	1	16-Jan-00	14-Jan-00	-2	31-Mar-00	30-Mar-00	-1
2000-2001	298	298	0	10-Feb-01	10-Feb-01	0	19-Mar-01	15-Mar-01	-4
2001-2002*	207	197	-10	19-Jan-02	17-Jan-02	-2	22-Apr-02	26-Apr-02	4
2002-2003	228	226	-1	27-Jan-03	29-Jan-03	2	14-Apr-03	15-Apr-03	1
2003-2004	217	226	9	9-Jan-04	11-Jan-04	2	3-Apr-04	3-Apr-04	0
2004-2005*	169	174	6	5-Jan-05	5-Jan-05	0	3-Apr-05	29-Mar-05	-5
2005-2006	310	289	-21	27-Feb-06	26-Feb-06	-1	3-Apr-06	5-Apr-06	2
2006-2007	178	178	-1	11-Jan-07	13-Jan-07	2	24-Apr-07	22-Apr-07	-2
2007-2008	205	202	-3	10-Jan-08	8-Jan-08	-2	30-Mar-08	1-Apr-08	2
2008-2009*	195	193	-2	27-Dec-08	27-Dec-08	0	13-Apr-09	17-Apr-09	4
2009-2010	254	227	-27	31-Dec-09	30-Dec-09	-1	21-Mar-10	30-Mar-10	9

[2] Differences may not be exact due to rounding to the nearest kilometre or day.

	Maximum Ice Front Progression (km)			**Date of Freeze-Up at Town of Peace River**			**Date of Break-up at Town of Peace River**		
2010-2011	140	134	-6	29-Dec-10	26-Dec-10	-3	19-Apr-11	20-Apr-11	1
Average	209	204	-5	11-Jan	11-Jan	0	07-Apr	08-Apr	1
Std. Dev.	59	56		19	19		11	12	

NOTE
An asterisk (*) indicates a winter in which there was at least one juxtaposed reach imposed

The other important validation criterion is the ability of the model to reproduce observed water levels. This is particularly important at the Town of Peace River where dykes are in place to protect the town from flooding, and the Joint Task Force makes operational decisions to manage ice-related water levels at freeze-up and break-up. As mentioned previously, the freeze-up process is highly stochastic (i.e., non deterministic) so it is not expected that CRISSP or other models would reproduce exact water levels every year. However, if calibrated correctly, the model should reproduce average water levels over several years.

Figure 4 shows the simulated and observed water level at the Town of Peace River for the 2003-2004 ice season. There is a slight over-prediction of the open water levels in November-December. This is due to the necessary reduction in the bed roughness variability (for stability reasons described in Appendix B) from those that originally provided a better simulation of open water levels. The larger discrepancy in late April is due to some additional tributary inflows not accounted for in the model. However, this is after the ice season and so this is not an issue for the purpose of this study.

Figure 5 shows the observed and simulated maximum freeze-up stage for all 16 winters considered in this study. The data show that on average the freeze-up water level is represented but that the observed values have a greater variance than the simulated ones. This is due to the fact that CRISSP does not model the infrequent secondary consolidations such as those that occurred in January 2005 and January 2008, and also does not simulate the extremely low freeze-up levels that are probably caused by a locally juxtaposed ice cover downstream of the Water Survey of Canada gauge. The important result is that the average simulated freeze-up elevation is within about 0.1 m of the average observed freeze-up elevation.

Another CRISSP output parameter that is important to validate is the surface ice concentrations and the frazil ice pan thicknesses. Jasek et al (2011) compared the data extracted from upward-looking sonar measurements to CRISSP simulated values. The comparison is illustrated in Figure 6 and shows good agreement. An accurate simulation of surface ice concentration is particularly important because the operation of the Shaftesbury Ferry is estimated to be limited by a surface ice concentration of 20% and it is important to be able to determine when that occurs. Figure 6 shows that timing of the arrival of this threshold is simulated accurately with CRISSP.

4 RESULTS

A general understanding of the changes to the ice regime as a result the Project, or the combination of the Project and the Dunvegan Project can be ascertained by examining Figure 7 and considering the information in Appendix C. In Figure 7 it is evident that the ice regime downstream of km 650 (about 250 km downstream of the Town of Peace River or 150 km downstream of Sunny Valley) is not affected by the addition of the Project or by the combination of the Project and the Dunvegan Project. In this reach, ambient air temperatures in the winter and solar radiation in the spring play a dominating role in determining the ultimate ice characteristics than the changes in Site C reservoir outlet water temperature and/or the ice trapped by the Dunvegan project. Upstream of km 650, the advance of the ice front in the early winter would be slowed and the closer the proximity of the ice front to the Site C dam or to the Dunvegan dam, the stronger the delaying influence. This is due to the relatively warm outlet temperature at the tailrace of the Site C dam and the fact that the Project and the Dunvegan Project would trap ice and not allow it to contribute to the ice volumes downstream.

With the Project and the Dunvegan Project, a second ice front is created upstream of Dunvegan but its upstream advance is moderated in comparison to present conditions because of the relatively warmer water released from the Site C reservoir.

4.1 Maximum Upstream Extent of Ice Cover

The Project and the proposed Dunvegan Project would both change the maximum upstream extent of the ice cover on the Peace River. Figure 7 shows an example of the ice front simulations for two years out of the 16 analysed. Plots of the simulated ice fronts for the other years are shown in Appendix C. Figure 7 shows that generally the Project would move the maximum extent of the ice cover further downstream since the relatively warmer water discharge associated with a reservoir would be moved downstream by 85 km[3] from Peace Canyon Dam (present conditions) to the Site C dam site. On the other hand, Figure 7 shows that the Dunvegan Project would trap ice floes and would initiate a second ice front upstream of Dunvegan causing this maximum upstream extent to move in the opposite direction (further upstream). Whether the Project or the Dunvegan Project would have greater influence on the maximum upstream extent of the ice cover in any one year would depend on the winter severity. Figure 8 presents the frequency of the ice front reaching

[3] The river centerline distance between Peace Canyon Dam and the Site C dam is 85 km. This is 2 km longer than the centerline distance of the Site C reservoir (which is commonly referred to as being 83 km in length) due to the sinuosity of the existing river channel.

certain locations based on the 16 winters simulated; it appears that in colder winters the Project would dominate and move the ice front further downstream compared to present conditions. In milder winters the two Projects together would be more dominant and advance the ice front further upstream compared to the present conditions.

The estimated annual probability of the ice front reaching certain locations is shown in Figure 8 and described below.

Site C dam site: With the Project, the ice front would not advance upstream to the Site C tailrace even if the proposed Dunvegan project were in place.

District of Taylor: With the Project, the ice front would not reach the District of Taylor even if the proposed Dunvegan project were in place.

British Columbia-Alberta Border: Under the existing conditions, the annual probability of the ice front advancing into B.C. is about 22%. With the Project this would decrease to about 10%. With both the Project and the Dunvegan Project the annual probability of the ice cover advancing into B.C. would decrease from 22% to about 16%.

Shaftesbury Crossing: In the simulation of existing conditions for the 16 historic winters, the ice cover always advanced upstream as far as Shaftesbury Crossing. This would not change with the Project. With both the Project and the Dunvegan Project, the estimated annual probability of an ice cover forming at this location would be reduced to about 88%.

The Town of Peace River: Under all scenarios, the 16 years of simulation indicate that an ice cover would advance past the Town of Peace River every winter.

4.2 Timing of Freeze-up and Break-up

Due to the potential for flooding at freeze-up and break-up at the Town of Peace River, and the fact that a large portion of Joint Task Force guidelines are based on the timing of the arrival and departure of the ice cover in the vicinity of the Town, the timing of the freeze-up and break-up of the ice cover at this location was examined in more detail. Table 4.1 shows the simulated freeze-up dates at the Town of Peace River for the 16 winters simulated.

Freeze-up: Table 4.1 shows that on average the Project would delay freeze-up at the Town of Peace River by 3 days; the Project and the Dunvegan Project together would delay freeze-up at the Town of Peace River by 10 days. As mentioned, the Project would cause an average delay in the arrival of the ice front at the Town of Peace River of about 3 days. This would shift the timing of the freeze-up monitoring that the town staff carry out by a few days but would not change the duration of their monitoring efforts as the rate that the ice front advances through town would not change substantially as a result of the Project. Results suggest that the average delay due to the Project in freeze-up at Sunny Valley (approximately 90 km downstream of the Town of Peace River) is two days, and the average delay in freeze-up at Dunvegan (approximately 100 km upstream of the Town of

Peace River) is nine days, though the ice front did not reach Dunvegan in two of the simulated years. The combination of the Project and the Dunvegan Project leads to an average delay in freeze up at Sunny Valley of three days, and the ice front never reaches Dunvegan.

Break-up: Figure 4 shows the simulated break-up dates at the Town of Peace River for the 16 winters simulated. There are small variations from year to year of plus or minus a few days but the average date of break-up remains unchanged given any scenario. The Town of Peace River's break-up monitoring duration by town staff would not change as a result of the Project or because of the Project and the Dunvegan Project together. Results suggest that the timing of break-up would not change at Sunny Valley or Dunvegan due to the Project, or the combination of the Project and the Dunvegan Project.

Table 4.1 Simulated dates of freeze-up at the Town of Peace River

				Delay (days)	
Winter	**Existing**	**With the Project**	**With the Project + Dunvegan**	**With the Project vs. Existing Conditions**	**With the Project + Dunvegan vs. Existing Conditions**
1995-1996	10-Dec-95	14-Dec-95	18-Dec-95	4	8
1996-1997	21-Dec-96	24-Dec-96	24-Dec-96	3	3
1997-1998	13-Jan-98	15-Jan-98	27-Jan-98	2	14
1998-1999	6-Jan-99	09-Jan-99	18-Jan-99	3	12
1999-2000	14-Jan-00	17-Jan-00	02-Feb-00	3	19
2000-2001	10-Feb-01	13-Feb-01	18-Feb-01	3	8
2001-2002	17-Jan-02	23-Jan-02	25-Jan-02	6	8
2002-2003	29-Jan-03	4-Feb-03	16-Feb-03	6	18
2003-2004	11-Jan-04	16-Jan-04	24-Jan-04	5	13
2004-2005	5-Jan-05	7-Jan-05	12-Jan-05	2	7
2005-2006	26-Feb-06	1-Mar-06	14-Mar-06	3	16
2006-2007	13-Jan-07	14-Jan-07	22-Jan-07	1	9
2007-2008	8-Jan-08	11-Jan-08	15-Jan-08	3	7
2008-2009	27-Dec-08	29-Dec-08	2-Jan-09	2	6
2009-2010	30-Dec-09	2-Jan-10	5-Jan-10	3	6
2010-2011	26-Dec-10	29-Dec-10	4-Jan-11	3	9
Average	11-Jan	14-Jan	21-Jan	3	10

Table 4.2 Simulated dates of break-up at the Town of Peace River

				Delay (days)	
Winter	**Existing**	**With the Project**	**With the Project + Dunvegan**	**With the Project vs. Existing Conditions**	**With the Project + Dunvegan vs. Existing Conditions**
1995-1996	21-Apr-96	23-Apr-96	22-Apr-96	2	1
1996-1997	19-Apr-97	22-Apr-97	22-Apr-97	3	3
1997-1998	27-Mar-98	28-Mar-98	29-Mar-98	1	2
1998-1999	3-Apr-99	03-Apr-99	03-Apr-99	0	0
1999-2000	30-Mar-00	31-Mar-00	30-Mar-00	1	0
2000-2001	15-Mar-01	13-Mar-01	14-Mar-01	-2	-1
2001-2002	26-Apr-02	26-Apr-02	25-Apr-02	0	-1
2002-2003	15-Apr-03	13-Apr-03	13-Apr-03	-2	-2
2003-2004	3-Apr-04	4-Apr-04	4-Apr-04	1	1
2004-2005	29-Mar-05	29-Mar-05	29-Mar-05	0	0
2005-2006	5-Apr-06	3-Apr-06	31-Mar-06	-2	-5
2006-2007	22-Apr-07	22-Apr-07	20-Apr-07	0	-2
2007-2008	1-Apr-08	5-Apr-08	4-Apr-08	4	3
2008-2009	17-Apr-09	16-Apr-09	16-Apr-09	-1	-1
2009-2010	30-Mar-10	31-Mar-10	29-Mar-10	1	-1
2010-2011	20-Apr-11	19-Apr-11	19-Apr-11	-1	-1
Average	08-Apr	08-Apr	08-Apr	0	0

4.3 Freeze-up and Break-up Water Levels

4.3.1 Freeze-up Water Levels

The most extreme water levels at freeze-up occur because of secondary consolidations – whose occurrence and magnitude the CRISSP model cannot simulate. However, one can comment on the change in frequency of these events as a result of the Project or as a result of the Project and the Dunvegan Project together. It is known from field observations that the largest secondary consolidations occur just after the ice front advances rapidly due to extreme cold weather. Since the Project and the Dunvegan Project together would reduce the amount of ice arriving at the ice front, thereby reducing the advance rate of the ice cover, this should reduce the frequency of secondary consolidations and the associated extreme winter freeze-up levels. However, it is difficult to quantify to what degree these events would be reduced.

Figure 9 illustrates the historical and simulated maximum freeze-up water levels at the Town of Peace River for the 16 winters simulated. An obvious difference between the historical (measured) and simulated existing conditions occurred in the 2004-2005 and the 2007-2008 winters. A secondary consolidation occurred in each of those years and since CRISSP cannot simulate the secondary consolidations, the post-freeze-up water levels were under-predicted. This does not substantially affect the model results because the models are being used to determine if there is change in the freeboard to contain these secondary consolidations should they occur. The results show that on average there is not much difference in the initial freeze-up water levels, and subsequently the available freeboard. The average simulated freeze-up water level for existing conditions is less than 0.1 m higher than the observed historical average. This is well within modelling error. The average freeze-up water level with the Project is about 0.1 m less than the simulated existing conditions. The scenario with both the Project and the Dunvegan Project is about 0.1 m higher than the existing conditions. All the differences in the average freeze-up water level at the Town of Peace River for the various project scenarios are within modelling and measurement error, suggesting that there would be no changes to freeze-up water levels.

However, Figure 9 shows that some year-to-year variability can exist. This is due to the difference in discharge at the ice front for the various project scenarios at the time of ice formation at the Town of Peace River. The higher the discharge at the ice front, the higher the freeze-up water level. Although the discharge at the ice front is related to the discharge out of Peace Canyon about two days earlier (due to the travel time of water from Peace Canyon dam to the ice front), the advance rate of the ice front has a second order effect on the discharge downstream of the ice front. A faster moving ice front places water into storage in the backwater zone upstream of the ice front more quickly, abstracting a larger proportion of the flow arriving from Peace Canyon. Therefore, faster moving ice fronts typically would produce lower freeze-up stages than slower moving ones all other things being equal. Even though the projects can systematically alter slightly the average celerity (speed) of the ice front at the Town of Peace River, larger year-to-year variability in the freeze-up water level would occur as a result if the ice front arrives faster during a cold spell or slower when it is not so cold. On average, the initial freeze-up stage would be slightly higher due to a slower moving ice front, but still within bounds of normal levels, and the probability of above-normal water levels due to secondary consolidations would be less because of the projects.

Figure 10 shows various percentiles of observed and simulated freeze-up water levels at the Town of Peace River based on the 16 winters simulated. None of the simulated scenarios have as large a range in freeze-up water levels as the historical conditions. This is largely due to the fact that CRISSP does not model secondary consolidations of which there were two at the Town of Peace River in the 16 year period of study. Figure 10 shows that there are small changes in the freeze-up water level ranges and medians between project scenarios. Therefore, the frequency of groundwater seepage into Lower West

Peace River basements should not increase as a result of the Project or as a result of the Project in combination with the Dunvegan Project. Figure 10 also shows a typical open water elevation and as well as the top of dyke elevation. It is evident that there would be no large and systematic change in freeboard available to accommodate secondary consolidations under any of the project scenarios. Although secondary consolidations occurred in 1982 and 1992 as well, they are not presented on Figure 10 or considered in the analysis. Information collected during these events was paramount in the development of the current operational procedures that are used by the Joint Task Force today to reduce the risk of flooding downstream.

To show freeze-up water levels at other locations along the Peace River, Figure 11, Figure 12, and Figure 13 respectively plot the minimum, maximum, and percentile values of the relative freeze-up stage (i.e. the increase in water level due to freeze-up) from the 16 years of simulation for the various project scenarios. The freeze-up stages are measured relative to an open water level that corresponds to a discharge of 1,600 m^3/s. Comparing Figure 11 and Figure 12 shows that the Project would not increase the freeze-up stage anywhere along the Peace River. Figure 13 suggests that there may be more extreme freeze-up stage variability downstream of the proposed Dunvegan project. In warm years the stages could be much lower because the ice front may not arrive at a particular location. In cold years the freeze-up stages downstream of Dunvegan, between Dunvegan and Elk Island Park, could be up to about 1 m higher. This is largely because control flow would already be lifted when the ice front is forming in this reach, whereas under existing conditions the control flow would still be in effect, the discharge would be lower, and consequently the freeze-up water level would be lower.

4.3.2 Break-up Water Levels

High water levels at break-up would remain unchanged from existing conditions as they are a function of the prevailing flows when the Smoky River breaks up dynamically into an intact Peace River ice cover. Since neither the Project nor the combination of the Project and the Dunvegan Project change the average timing of the thermal break-up of the Peace River ice cover at the Town of Peace River, peak break-up water levels would not change from those experienced under existing conditions. Also, the Project would allow about a 12 hour faster response time to implement flow controls to offset increasing flows in the Smoky River, due to the reduced travel time of flow changes. The reduced travel time is due to the fact that the Site C dam would be about 85 km closer to the Town of Peace River than the Peace Canyon Dam.

4.4 Ice Control Flows

Control flows are dam discharges that are set at certain values to influence river ice processes at freeze-up and break-up in order to reduce the chances of high water levels and flooding, particularly at the Town of Peace River. The selection of an appropriate control flow is a balance between flood reduction and optimized power production. The Project and the Dunvegan Project have the potential to change the ice regime and therefore also alter the control flow duration. The change in control flow duration is important in determining the ability of BC Hydro to meet winter energy and capacity needs as well for optimizing the BC Hydro system in order to minimize costs to ratepayers.

4.4.1 Implementation and Cessation of Control Flow during Freeze-up at the Town of Peace River

As described in Appendix A, control flow is implemented two days prior to when the ice cover is forecasted to arrive at the Rendezvous Point (km 411). For the CRISSP simulations, this was the criterion used to determine when control flow was implemented for each winter and for all the scenarios. Figure 14 shows the results of the simulations carried out to assess the flow control implementation date for all four Project scenarios. Generally, control flow can be implemented anytime between early December and late February depending on the severity of the winter, and this does not change much with one or with both projects in place. Under existing conditions the average date of control flow implementation is January 5, with the Project it would be January 10 (i.e., a delay of 5 days), with both the Project and the Dunvegan Project it would be January 15 (i.e., a delay of 10 days).

Although it was assumed for all scenarios that control flow was implemented 2 days before the ice front reached the Rendezvous Point (km 411), in reality with the Project the travel time for flow control to reach the Town of Peace River would be about half a day less (1.5 days). This would provide more operational certainty in implementing the flow control on time.

Control flow is lifted when the ice cover upstream of the Town of Peace River is determined to be competent. The current definition of competence is that a thickness of 0.4 m of thermal ice is attained for at least a 10 km reach upstream of the Town of Peace River (between McLeod Cairn and Dunvegan).

Although CRISSP models the growth of thermal ice downward into frazil slush of a specified porosity, and keeps track of snowfall on the ice cover to account for its insulating influences, CRISSP was not used in this study to determined when the 0.4 metre criteria was reached. This was because in CRISSP it was not possible to have complete control of the porosity of the ice cover (further discussion is provided in Appendix B) and so it proved difficult to properly account for the influences of the porosity of the slush near the surface of the ice cover on the growth rate of thermal ice.

Instead, the BC Hydro in-house model (PRTIGM) was used to calculate the thickness of the thermal ice. The ice front positions from CRISSP were fed into the PRTIGM model to determine the start of thermal ice growth for each location and then the model was used to determine when the 0.4 m criterion was reached. The model results are given in Table 4.3

and Table 4.4 and Figure 15 shows the duration of flow control for the 16 years for the various hydro projects and combinations thereof. The variability of the data is complex but explainable. In some years there is a decrease in the control flow duration and in some years an increase for the same project or project combination. This is because the timing of the ice front is very important relative to the occurrences of snowfall events. In one year a delay in the ice front arriving at a particular point due to the influences of a particular project could mean that a major snow fall event was missed, no snow would accumulate on the ice cover, and its insulating influence would be lost. So it can happen that even though thermal ice growth at a particular location starts later due to a delayed ice front, it grows faster than it would under present conditions since there would be less snow on the ice cover, and it would eventually surpass the thermal ice growth of the present condition case, allowing it to reach the 0.4 m thermal ice thickness sooner. Because of this year-to-year variability it is instructive to talk about the “average” change on control flow duration over the simulation period. Under present conditions the average control flow duration is about 23 days, about 20 days with the Project, and about 30 days with both the Project and the Dunvegan Project.

4.4.2 Implementation of Control Flow during Break-up at the Town of Peace River

The implementation of flow control during break-up is based upon the expected severity of break-up of the Smoky River as it can trigger a break-up on the Peace River and cause subsequent ice jamming and increase the risk of flooding at the Town of Peace River. Three criteria have to be met in order for break-up ice jamming to threaten the town.

1. An intact ice cover on the Peace River at the Town of Peace River.
2. An above average snowpack in the lower Smoky Basin allowing for the potential for a high snowmelt runoff event.
3. A rapid warming in the spring that could create a sudden snowmelt runoff event that triggers a dynamic break-up event on the Smoky River.

The Project and the Dunvegan Project have no influence on the snowpack conditions or the rate of warming in the springtime. The only potential for a Project influence would be if the timing of the thermal break-up on the Peace River was changed as a result of either or both of the projects.

Table 4.2 indicates that there is no systematic change in the date of thermal break-up as a result of the Project, or as a result of the combination of the Project and the Dunvegan Project.

The Project would allow BC Hydro to respond sooner with a flow decrease pending a Smoky River induced dynamic break-up at the Town of Peace River. Since the Site C dam would be 85 km closer to the Town of Peace River than the Peace Canyon dam, the response time to mitigate ice jamming at the Town of Peace River would be about half a day less.

Table 4.3 Simulated Timing and Duration of Control Flows

	Existing Conditions			With the Project			With the Project + Dunvegan		
	Control Flow Start	Control Flow End	Control Flow Duration	Control Flow Start	Control Flow End	Control Flow Duration	Control Flow Start	Control Flow End	Control Flow Duration
1995 - 1996	07-Dec-95	29-Dec-95	22	10-Dec-95	01-Jan-96	22	14-Dec-95	17-Jan-96	34
1996 - 1997	18-Dec-96	27-Dec-96	9	21-Dec-96	30-Dec-96	9	21-Dec-96	03-Jan-97	13
1997 - 1998	10-Jan-98	27-Jan-98	17	11-Jan-98	04-Feb-98	24	21-Jan-98	27-Feb-98	37
1998 - 1999	02-Jan-99	25-Jan-99	23	05-Jan-99	30-Jan-99	25	10-Jan-99	02-Feb-99	23
1999 - 2000	11-Jan-00	20-Jan-00	9	14-Jan-00	27-Jan-00	13	23-Jan-00	07-Mar-00	44
2000 - 2001	14-Jan-01	03-Mar-01	48	08-Feb-01	26-Feb-01	18	12-Feb-01	13-Mar-01	29
2001 - 2002	31-Dec-01	29-Jan-02	29	19-Jan-02	31-Jan-02	12	20-Jan-02	02-Feb-02	13
2002 - 2003	25-Jan-03	03-Mar-03	37	29-Jan-03	06-Mar-03	36	11-Feb-03	05-Mar-03	22
2003 - 2004	07-Jan-04	29-Jan-04	22	12-Jan-04	31-Jan-04	19	19-Jan-04	01-Feb-04	13
2004 - 2005	02-Jan-05	15-Jan-05	13	03-Jan-05	18-Jan-05	15	08-Jan-05	21-Jan-05	13
2005 - 2006	21-Feb-06	05-Apr-06	43	24-Feb-06	03-Apr-06	38	02-Mar-06	30-Mar-06	28
2006 - 2007	09-Jan-07	29-Jan-07	20	10-Jan-07	03-Feb-07	24	15-Jan-07	05-Mar-07	49
2007 - 2008	04-Jan-08	20-Jan-08	16	07-Jan-08	24-Jan-08	17	08-Jan-08	01-Feb-08	24
2008 - 2009	23-Dec-08	08-Jan-09	16	25-Dec-08	08-Jan-09	14	29-Dec-08	22-Feb-09	55
2009 - 2010	26-Dec-09	13-Jan-10	18	29-Dec-09	11-Jan-10	13	01-Jan-10	23-Jan-10	22
2010 - 2011	22-Dec-10	10-Jan-11	19	25-Dec-10	19-Jan-11	25	29-Dec-10	23-Feb-11	56
Average	05-Jan-03	28-Jan-03	23	10-Jan-03	30-Jan-03	20	15-Jan-03	14-Feb-03	30

1 **Table 4.4 Simulated Differences in Timing and Durations of Control Flow***

Delay (Days)	The Project vs. Existing Conditions			The Project and Dunvegan vs. Existing Conditions		
	Control Flow Start	Control Flow End	Control Flow Duration	Control Flow Start	Control Flow End	Control Flow Duration
1995 - 1996	3	3	0	7	19	12
1996 - 1997	3	3	0	3	7	4
1997 - 1998	1	8	7	11	31	20
1998 - 1999	3	5	2	8	8	0
1999 - 2000	3	7	4	12	47	35
2000 - 2001	25	-5	-30	29	10	-20
2001 - 2002	19	2	-17	20	4	-16
2002 - 2003	4	3	-1	17	2	-15
2003 - 2004	5	2	-3	12	3	-9
2004 - 2005	1	3	2	6	6	0
2005 - 2006	3	-2	-5	9	-6	-15
2006 - 2007	1	5	4	6	35	29
2007 - 2008	3	4	1	4	12	8
2008 - 2009	2	0	-2	6	45	39
2009 - 2010	3	-2	-5	6	10	4
2010 - 2011	3	9	6	7	44	37
Average	5	3	-2	10	17	7

2 **NOTE:**
3 *delay is positive

4.5 Changes at the Ice Bridge and Ferry at Shaftesbury Crossing

The Project and the Dunvegan Project both have the potential to change the timing and duration of the ice bridge crossing and ferry operations. The Shaftesbury crossing is located about 25 km upstream of the Town of Peace River, about 349 km downstream of Peace Canyon and about 266 km downstream of the Site C dam. Crossing at this location is by ferry in the summer and ice bridge in the winter. Both crossings are operated by La Prairie Group Contractors (Alberta) Ltd. There are a few weeks or even months in some years where neither the ferry can operate nor an ice bridge crossing is possible. Typically, the ferry starts operating soon after the ice front recedes past the crossing location at km 370.6 in late March to mid-April. Ice floes in high enough concentrations to end ferry operations typically occur in November or December. After that, additional time is required for the ice front to arrive at Shaftsbury and for the ice cover to gain sufficient strength for an ice bridge to be constructed. This could occur as early as December in a cold winter or as late as March in a warm winter. In the warmest of winters, an ice bridge is not possible. The ice bridge remains in place until shortly before break-up of the ice cover.

The expected changes to ferry operations as a result of the Project and the Dunvegan Project together are described next, followed by a discussion of the expected changes on ice bridge operations.   The combined change in total crossing days (ferry or ice bridge) is presented at the end of this section.

4.5.1 Changes in Shaftesbury Ferry Operations

In order to establish the duration of ferry operations for various years and for various combinations of projects, the date of the first ferry operation needs to be established. Some time is needed for ferry and ferry ramp preparation and launching after the ice breaks up at the crossing. Table 4.5 shows historical dates for ferry operations as well as historical break-up dates at the crossing. For those years where a break-up date at the crossing was not available, a date was interpolated from observed ice fronts upstream and downstream of the crossing.

For the 30 years of record, on average the ferry has operated about 230 days out of the year, with an average of 16 days needed for ferry preparation after break-up. There is a good correlation between the break-up dates and the ferry being launched; later ferry start-up coincided generally with later break-ups. However, there were three outlying years in which it took in the order of 40 days to get the ferry operational. This would possibly have been due to mechanical issues as opposed to ice conditions. Neglecting those years and years prior to 1995 so as to coincide with the 16 years simulated in this study, the ferry has operated on average for about 231 days out of the year, with an average of 15 days needed for ferry preparation after break-up. For the current study it was assumed that the ferry came into operation 15 days after the ice front receded past the crossing location. Table 4.6 shows simulated break-up dates at Shaftesbury for the various project scenarios.

Table 4.5 Actual Shaftesbury Ferry start and end dates and actual ice front recession dates

Year	Ferry In	Ferry Out	Operating Days	Operating Agency	Actual Ice Out	Ice Out to Ferry In (days)	Comment	*Ice Out to Ferry In (days)	Ferry Duration (days)
1982					25-Apr-82				
1983	15-Apr-83	28-Nov-83	227	Alberta Transportation	23-Mar-83	23			
1984	20-Apr-84	26-Nov-84	220	Alberta Transportation	10-Apr-84	10			
1985	18-Apr-85	17-Nov-85	213	Alberta Transportation	09-Apr-85	9			
1986	28-Apr-86	09-Nov-86	195	Alberta Transportation	17-Apr-86	11			
1987	17-Apr-87	05-Jan-88	263	Alberta Transportation	04-Apr-87	13			
1988	14-Apr-88	21-Dec-88	251	Alberta Transportation	09-Mar-88	36			
1989	15-Apr-89	11-Nov-89	210	Alberta Transportation	22-Apr-89	-8	Ferry in date suspect as ice front was still upstream		
1990	20-Apr-90	22-Nov-90	216	Alberta Transportation	07-Apr-90	13			
1991	23-Apr-91	03-Dec-91	224	Alberta Transportation	17-Apr-91	6			
1992	21-Mar-92	17-Dec-92	271	Alberta Transportation	29-Feb-92	21			
1993	05-Apr-93	02-Jan-94	272	Alberta Transportation	27-Mar-93	9			
1994	18-Apr-94	02-Dec-94	228	Alberta Transportation	26-Mar-94	23			
1995	25-Apr-95	25-Nov-95	214	Alberta Transportation	16-Apr-95	9			
1996	03-May-96	18-Nov-96	199	Ruel Brothers	20-Apr-96	13		13	199
1997	07-May-97	03-Jan-98	241	Ruel Brothers	19-Apr-97	18		18	241
1998	06-Apr-98	19-Dec-98	257	Ruel Brothers	26-Mar-98	11		11	257
1999	14-Apr-99	16-Dec-99	246	Ruel Brothers	01-Apr-99	13		13	246
2000	10-Apr-00	10-Dec-00	244	Ruel Brothers	06-Apr-00	4		4	244
2001	07-May-01	01-Dec-01	208	Ruel Brothers Contracting	28-Mar-01	40	Possibly a ferry maintenance issue (like 2006)		
2002	07-May-02	28-Dec-02	235	Ruel Brothers	19-Apr-02	18		18	235
2003	01-May-03	08-Dec-03	221	Ruel Brothers	10-Apr-03	21		21	221

Year	Ferry In	Ferry Out	Operating Days	Operating Agency	Actual Ice Out	Ice Out to Ferry In (days)	Comment	*Ice Out to Ferry In (days)	Ferry Duration (days)
2004	22-Apr-04	06-Dec-04	228	LaPrairie Group Contractors (Alberta) Ltd.	30-Mar-04	23	Marine gear overhaul November, 2004	23	228
2005	15-Apr-05	05-Dec-05	234	LaPrairie Group Contractors (Alberta) Ltd.	01-Apr-05	14	Engine overhaul, driveline alignment March-April,2005	14	234
2006	13-Apr-06	23-Nov-06	224	LaPrairie Group Contractors (Alberta) Ltd.	02-Mar-06	42	Marine gear overhaul, driveline alignment, March-April,2006		
2007	02-May-07	28-Nov-07	210	LaPrairie Group	24-Apr-07	8		8	210
2008	16-Apr-08	13-Dec-08	241	LaPrairie Group	25-Mar-08	22		22	241
2009	28-Apr-09	08-Dec-09	224	LaPrairie Group	12-Apr-09	16		16	224
2010	03-Apr-10	18-Nov-10	229	LaPrairie Group	15-Mar-10	19		19	229
2011		22-Nov-11		LaPrairie Group	17-Apr-11				
2012	03-Apr-12			LaPrairie Group					
Average			230			16		15	231

*Considering only study years and neglecting outlier years with 40 or more days between ice out and Ferry in.

Table 4.6 Date of break-up at Shaftesbury Ferry crossing and differences between project scenarios

				Delay (days)	
	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995-1996	19-Apr-96	22-Apr-96	21-Apr-96	3	2
1996-1997	18-Apr-97	21-Apr-97	20-Apr-97	3	2
1997-1998	24-Mar-98	24-Mar-98	25-Mar-98	0	1
1998-1999	31-Mar-99	30-Mar-99	30-Mar-99	-1	-1
1999-2000	27-Mar-00	28-Mar-00	24-Mar-00	1	-3
2000-2001	12-Mar-01	09-Mar-01	n/a	-3	n/a
2001-2002	22-Apr-02	22-Apr-02	21-Apr-02	0	-1
2002-2003	12-Apr-03	10-Apr-03	10-Apr-03	-2	-2
2003-2004	31-Mar-04	01-Apr-04	01-Apr-04	1	1
2004-2005	14-Mar-05	26-Mar-05	27-Mar-05	12	13
2005-2006	2-Apr-06	31-Mar-06	n/a	-2	n/a
2006-2007	19-Apr-07	19-Apr-07	16-Apr-07	0	-3
2007-2008	25-Mar-08	01-Apr-08	01-Apr-08	7	7
2008-2009	14-Apr-09	14-Apr-09	13-Apr-09	0	-1
2009-2010	26-Mar-10	27-Mar-10	19-Mar-10	1	-7
2010-2011	16-Apr-11	17-Apr-11	16-Apr-11	1	0
Average				1.3	0.6

Table 4.7 Date of Shaftesbury Ferry start-up dates and differences between project scenarios

				Delay (days)	
	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995-1996	4-May-96	7-May-96	6-May-96	3	2
1996-1997	3-May-97	6-May-97	5-May-97	3	2
1997-1998	8-Apr-98	8-Apr-98	9-Apr-98	0	1
1998-1999	15-Apr-99	14-Apr-99	14-Apr-99	-1	-1
1999-2000	11-Apr-00	12-Apr-00	8-Apr-00	1	-3
2000-2001	27-Mar-01	24-Mar-01	30-Mar-01	-3	3
2001-2002	7-May-02	7-May-02	6-May-02	0	-1

				Delay (days)	
	Existing	**With the Project**	**With the Project + Dunvegan**	**With the Project vs. Existing Conditions**	**With the Project + Dunvegan vs. Existing Conditions**
2002-2003	27-Apr-03	25-Apr-03	25-Apr-03	-2	-2
2003-2004	15-Apr-04	16-Apr-04	16-Apr-04	1	1
2004-2005	29-Mar-05	10-Apr-05	11-Apr-05	12	13
2005-2006	17-Apr-06	15-Apr-06	15-Apr-06	-2	-3
2006-2007	4-May-07	4-May-07	1-May-07	0	-3
2007-2008	9-Apr-08	16-Apr-08	16-Apr-08	7	7
2008-2009	29-Apr-09	29-Apr-09	28-Apr-09	0	-1
2009-2010	10-Apr-10	11-Apr-10	3-Apr-10	1	-7
2010-2011	1-May-11	2-May-11	1-May-11	1	0
Average	20-Apr	21-Apr	20-Apr	1.3	0.5

The last date of ferry operation also needs to be defined to ascertain the length of the ferry season. Previous studies (Andres and Healy, 2006) indicated that surface ice concentrations above 20% are a good measure of when ferry operations can no longer be maintained. Generally, the ferry is removed from the river for the rest of the winter once high surface concentrations are experienced. The first instance of 20% surface concentrations from the CRISSP model was assumed to coincide with the last ferry operation date for each of the 16 winters and 4 scenarios. Table 4.8 compares the actual ferry removal dates to the CRISSP simulated first day of 20% concentration. For 11 out of 16 years the difference between the two is only one day or less. The comments in Table 4.8 explain why 6 of the 16 years may have not matched the 20% criteria. In some years the criterion was exceeded for a relatively short period followed by an extended period of no ice floes for weeks afterwards. In those years the ferry operators may have decided not to permanently shut down the ferry due to favourable (warmer) weather forecasts. In other years it is possible that they chose to shut down ferry operations before the ice concentration reached 20% - anticipating imminent and sustained cold weather. It is difficult to speculate in which years the decision to deviate from the 20% criterion was applicable. Therefore for consistency, the 20% surface ice concentration was used for all years to determine the date when the ferry would be removed. These dates and relative changes to these dates for the different development scenarios are shown in Table 4.9.

Table 4.8 Comparison of actual Shaftesbury Ferry removal date and CRISSP derived 20% ice concentration.

Winter	Ferry Out (Actual)	First Instance of 20% ice concentration	Difference (days)	Comment (Concentrations are CRISSP derived)
1995-1996*	25-Nov-95	25-Nov-95	0	Clear exceedance of 20% by first substantial ice run when ferry removed
1996-1997*	18-Nov-96	11-Nov-96	-7	Only one day greater than 20% 1 week before ferry out
1997-1998	03-Jan-98	31-Dec-97	-3	Maybe just a delay between model and actual, 20% clearly exceeded
1998-1999	19-Dec-98	18-Dec-98	-1	Clear exceedance of 20% by first substantial ice run when ferry removed
1999-2000	16-Dec-99	27-Nov-99	-19	Only two days greater than 20% 19 days prior to ferry out
2000-2001	10-Dec-00	09-Dec-00	-1	Clear exceedance of 20% by first substantial ice run when ferry removed
2001-2002*	01-Dec-01	02-Dec-01	1	Ferry pulled during first substantial ice run at 15%, ice > 20% the next day
2002-2003	28-Dec-02	28-Dec-02	0	Only one day of 15% ice a few days earlier did not shut down ferry
2003-2004	08-Dec-03	07-Dec-03	-1	3 days of 15-17% ice a few weeks earlier did not shut down ferry
2004-2005*	06-Dec-04	05-Dec-04	-1	Clear exceedance of 20% by first substantial ice run when ferry removed
2005-2006	05-Dec-05	05-Dec-05	0	Only 14%, 20% and 16% run with open water for long time afterwards before ferry was shut down
2006-2007	23-Nov-06	11-Nov-06	-12	Maximum ice concentration before ferry out was only 24% for two days 12 days prior, rest of time was less than 20%
2007-2008	28-Nov-07	02-Dec-07	4	Ferry was removed when first instance at 10 to 15% but colder weather would have been in forecast window
2008-2009*	13-Dec-08	13-Dec-08	0	Clear exceedance of 20% by first substantial ice run when ferry removed
2009-2010	08-Dec-09	07-Dec-09	-1	Only one day of 20% ice when ferry pulled and then low concentration but high again within 7-day forecast window
2010-2011	18-Nov-10	17-Nov-10	-1	Clear exceedance of 20% by first substantial ice run when ferry removed
2011-2012	22-Nov-11			
Average	7-Dec	4-Dec	-3	

Table 4.9 First instance of 20% surface ice concentration at the Shaftesbury Ferry crossing

Winter	Existing	With the Project	With the Project + Dunvegan	Delay (days) With the Project vs. Existing Conditions	Delay (days) With the Project + Dunvegan vs. Existing Conditions
1995-1996	25-Nov-95	26-Nov-95	26-Nov-95	1	1
1996-1997	11-Nov-96	23-Nov-96	11-Nov-96	12	0
1997-1998	31-Dec-97	31-Dec-97	31-Dec-97	0	0
1998-1999	18-Dec-98	19-Dec-98	19-Dec-98	1	1
1999-2000	27-Nov-99	27-Nov-99	27-Nov-99	0	0
2000-2001	9-Dec-00	9-Dec-00	9-Dec-00	0	0
2001-2002	1-Dec-01	2-Dec-01	2-Dec-01	1	1
2002-2003	28-Dec-02	29-Dec-02	29-Dec-02	1	1
2003-2004	7-Dec-03	7-Dec-03	7-Dec-03	0	0
2004-2005	5-Dec-04	5-Dec-04	5-Dec-04	0	0
2005-2006	5-Dec-05	12-Jan-06	12-Jan-06	38	38
2006-2007	11-Nov-06	23-Nov-06	22-Nov-06	12	11
2007-2008	2-Dec-07	2-Dec-07	2-Dec-07	0	0
2008-2009	13-Dec-08	13-Dec-08	13-Dec-08	0	0
2009-2010	7-Dec-09	11-Dec-09	6-Dec-09	4	-1
2010-2011	17-Nov-10	17-Nov-10	18-Nov-10	0	1
Average	4-Dec	8-Dec	7-Dec	4	3
Median	5-Dec	6-Dec	5-Dec	1	0

The Project scenario appears to produce a delay of four days on average with extreme delays of a few weeks possible in some individual years; a benefit for ferry operations. This is what one would expect since the discharge point would be moved 85 km downstream thereby decreasing the surface ice concentrations. Plots of surface ice concentrations for two years at the Shaftesbury crossing with and without the Project are shown in Figure 16 and Figure 17. It should be noted that the latest time on the plots that ice concentrations fall to zero coincide with the arrival of the ice front at Shaftesbury. Therefore comparing ice concentrations between scenarios later than these times is not applicable as the ice front arrives on different dates for different scenarios. Figure 16 shows a typical winter (1997-1998) in which the occurrence of the 20% ice concentration is not very different between existing conditions and with the Project. Figure 17 shows an atypical year (2005-2006) in which a brief period of 20% coverage occurs in December under existing conditions but not with the Project. Subsequent to this, the dates when 20% coverage was exceeded in January are close with and without the Project (only about 2 days later with the Project).

Table 4.9 shows that with the Project and the Dunvegan Project together the average delay of the 20% ice concentration is three days compared to a delay of four days with the Project alone. However, there are a few outliers in Table 4.9 that are skewing the average. The median values suggest that there is virtually no change in the first 20% ice concentration (one day or less).

The annual duration of ferry operation, estimated on the basis of the first and last date of ferry operation, is summarized in Table 4.10 and shown in Figure 18. The simulated average duration of 229 days in Table 4.10 under existing conditions compares favourably to the historical average of 231 days for the same 1995-2010 period (Table 4.10) if the years with assumed maintenance issues are ignored. The simulated average duration also compares favourably to the 1983-2010 average of 230 days. This suggests that the assumptions used to determine the ferry in and out dates from the CRISSP modelling of the various project scenarios are reasonable.

On average, the differences in operational days for the various development scenarios are small compared to the length of the ferry crossing season, typically only a few days. However, there are a few individual years with larger differences.

Table 4.10 Simulated Duration of Shaftesbury Ferry operation (days)

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995	208	208	209	0	1
1996	191	200	189	9	-2
1997	242	239	240	-3	-2
1998	254	255	254	1	0
1999	226	227	227	1	1
2000	242	241	245	-1	3
2001	250	253	247	3	-3
2002	235	236	237	1	2
2003	224	226	226	2	2
2004	234	233	233	-1	-1
2005	251	277	276	26	25
2006	208	222	221	14	14
2007	212	212	215	0	3
2008	248	241	241	-7	-7
2009	222	226	222	4	0
2010	221	220	229	-1	8
Average	229	232	232	3	3

4.5.2 Changes in Shaftesbury Ice Bridge Operations

Although there is some information available about historical ice bridge opening dates, the opening dates are inconsistent from year to year because of changing circumstances. For consistency, it was thought best to use established ice thickness guidelines for safe ice crossing as well as an assessment of when the ice would be reasonably safe from being broken up by secondary consolidations to determine a defensible opening date. The Alberta Occupational Health and Safety document “Travelling and working on ice requires extreme caution” suggests that 0.23 m of thermal ice is required for a safe crossing of light vehicle traffic. From the perspective of secondary consolidations, Jasek (2006) and Andres et al. (2005) indicate that they would not occur in the Shaftesbury reach if the thermal ice thicknesses is 0.25 m or greater. The secondary consolidation criterion is slightly more conservative than the Alberta Occupational Health and Safety standard, so the occurrence of 0.25 m of thermal ice as predicted by the PRTIGM was used to determine the date of the first ice bridge crossing in this study. Table 4.11 and Figure 19 indicate that with the Project, the ice bridge on average would be ready about five days later than under existing conditions, but with a year-to-year range of 0 days to 14 days later. With the Project and the Dunvegan Project together the average delay would be 17 days. There are two years modeled when the required ice thickness would not be attained.

Table 4.11 Simulated date of first Shaftesbury ice bridge crossing

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions (days)	With the Project + Dunvegan vs. Existing Conditions (days)
1995-1996	18-Dec-95	26-Dec-95	09-Jan-96	8	22
1996-1997	26-Dec-96	28-Dec-96	03-Jan-97	2	8
1997-1998	18-Jan-98	25-Jan-98	24-Feb-98	7	37
1998-1999	19-Jan-99	22-Jan-99	01-Feb-99	3	13
1999-2000	17-Jan-00	23-Jan-00	18-Feb-00	6	32
2000-2001	22-Feb-01	22-Feb-01	n/a	0	n/a
2001-2002	24-Jan-02	27-Jan-02	30-Jan-02	3	6
2002-2003	16-Feb-03	26-Feb-03	27-Feb-03	10	11
2003-2004	22-Jan-04	28-Jan-04	31-Jan-04	6	9
2004-2005	13-Jan-05	14-Jan-05	22-Jan-05	1	9
2005-2006	6-Mar-06	16-Mar-06	n/a	10	n/a
2006-2007	21-Jan-07	04-Feb-07	11-Feb-07	14	21
2007-2008	17-Jan-08	21-Jan-08	31-Jan-08	4	14
2008-2009	3-Jan-09	03-Jan-09	16-Jan-09	0	13
2009-2010	5-Jan-10	07-Jan-10	20-Jan-10	2	15

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions (days)	With the Project + Dunvegan vs. Existing Conditions (days)
2010-2011	1-Jan-11	12-Jan-11	02-Feb-11	11	32
Average	19-Jan	25-Jan	31-Jan	5	17

It is unclear when the ice bridge is closed as it is not generally determined by when the ice bridge breaks up but when there is melt water along the edges of the river during the spring. This is difficult to predict and would be independent of when the ice cover formed or how thick it was. However, for comparison purposes the last day of ice bridge crossing was taken as the day when the ice front receded past Shaftesbury crossing. The dates of break-up at Shaftesbury for the various development scenarios are shown in Table 4.6. The total number of ice bridge crossing days for each year and for each scenario are summarized in Table 4.12 and shown in Figure 20. The results show that under existing conditions the ice bridge is in place for 75 days on average, 71 days with the Project, and 58 days with both the Project and the Dunvegan Project.

Table 4.12 Duration of Shaftesbury ice bridge crossing (days)

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995-1996	123	118	103	-5	-20
1996-1997	113	114	107	1	-6
1997-1998	65	58	29	-7	-36
1998-1999	71	67	57	-4	-14
1999-2000	70	65	35	-5	-35
2000-2001	18	15	0	-3	-18
2001-2002	88	85	81	-3	-7
2002-2003	55	43	42	-12	-13
2003-2004	69	64	61	-5	-8
2004-2005	60	71	64	11	4
2005-2006	27	15	0	-12	-27
2006-2007	88	74	64	-14	-24
2007-2008	68	71	61	3	-7
2008-2009	101	101	87	0	-14
2009-2010	80	79	58	-1	-22
2010-2011	105	95	73	-10	-32

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
Average	75	71	58	-4	-17

4.5.3 Changes in total crossing days at Shaftesbury Crossing

The total number of crossing-days per year are shown in Table 4.13 and Figure 21 Alternatively, the total number of non-crossing days are shown in Table 4.14 and Figure 22. On average, the Project would not change the number of crossing days at Shaftesbury. On average, the Project and the Dunvegan Project together would reduce the number of crossing days by 15 days.

Table 4.13 Total crossing days per year*

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995-1996	328	321	307	-7	-21
1996-1997	305	315	297	10	-8
1997-1998	332	325	295	-7	-37
1998-1999	318	316	306	-2	-12
1999-2000	300	294	268	-6	-32
2000-2001	275	275	254	0	-21
2001-2002	297	294	291	-3	-6
2002-2003	300	291	290	-9	-10
2003-2004	305	299	296	-6	-9
2004-2005	311	310	302	-1	-9
2005-2006	259	287	272	28	14
2006-2007	279	277	269	-2	-10
2007-2008	305	301	291	-4	-14
2008-2009	329	329	316	0	-13
2009-2010	321	323	305	2	-16
2010-2011	305	294	274	-11	-31
Average	304	303	289	-1	-15

*Period is calculated from June 1 to May 31

Table 4.14 Total un-crossable days per year*

	Existing	With the Project	With the Project + Dunvegan	With the Project vs. Existing Conditions	With the Project + Dunvegan vs. Existing Conditions
1995-1996	38	45	59	7	21
1996-1997	61	51	69	-10	8
1997-1998	34	41	71	7	37
1998-1999	48	50	60	2	12
1999-2000	66	72	98	6	32
2000-2001	91	91	111	0	21
2001-2002	69	72	75	3	6
2002-2003	66	75	76	9	10
2003-2004	61	67	70	6	9
2004-2005	55	56	64	1	9
2005-2006	107	79	93	-28	-14
2006-2007	87	89	97	2	10
2007-2008	61	65	75	4	14
2008-2009	37	37	50	0	13
2009-2010	45	43	61	-2	16
2010-2011	61	72	92	11	31
Average	61	62	76	1	15
*Period is calculated from June 1 to May 31					

4.6 Changes downstream of Town of Peace River

Results presented in Figure 7 and Appendix C suggest that on average over the 16 winters simulated there would be no change in the timing of freeze-up and break-up at km 650 (near Carcajou) due to the Project, or the combination of the Project and the Dunvegan Project. It follows that no change to the operation of the ice bridge or ferry at Tompkin's Landing would be expected as a result of either Project. By this point, ambient air temperatures dominate over the changes in ice quantities attributable to the Project and the Dunvegan Project. Hence neither the Project nor the combination of the Project and the Dunvegan Project are expected to influence the ice conditions downstream of Carcajou, and the downstream extent of the model appears to capture the entire extent of project influence.

4.7 Ice Thickness

Under present conditions, the thermal ice usually gains sufficient thickness (5 to 10 cm) to support an individual or a large animal within a day or two of the ice cover formation, and this would not be expected to change with the Project or the combination of the Project and the Dunvegan Project. However, because there is still the danger of the ice cover experiencing a secondary consolidation even weeks after formation (under existing conditions and with the Project), routine use of the ice cover is not recommended without a monitoring program. There can also be small locally open areas that take longer to freeze over as there is no slush underneath, these too are dangerous. However, these small local conditions would be present with or without the Project or the Dunvegan Project. Therefore, since the thermal thickness of the ice cover reaches a sufficient thickness usually within a day or two of its formation, the changes to the ice front locations as a result of the projects as shown in Appendix C can be used to determine the possibility of small loads being supported by the ice cover.

Changes in thermal ice thickness for support of larger loads (such as vehicles at ice bridge crossings) at specific salient locations have been addressed in Sections 4.5 and 4.6.

The total ice thickness determines the freeze-up water level as discussed in previous sections of the report.

5 CHANGES TO THE ICE REGIME DURING CONSTRUCTION

Construction of the Project would occur in two main stages. Stage 1 (channelization) consists of restricting the channel and Stage 2 (diversion) consists of diverting the flow through tunnels. Stage 1 would constrict the river to a width of 220 m within the deeper, main portion of the channel. CRISSP simulations indicate that annual peak surface ice concentrations approaching the constriction would be in the 30 to 40% range. A two-dimensional analysis of the hydraulics during Stage 1 indicates that the velocities through the constriction would be in the range of 2.5 to 3.0 m/s. These moderate ice concentrations and the fact that the water velocities would well exceed the erosion velocity of ice (which is 1.5 m/s) suggests that ice would not lodge at the Stage 1 constriction. Therefore, the quantity of ice passing this reach would be the same as before; this suggests that the ice regime of the Peace River would not differ from the existing conditions during the Stage 1 construction. The rise in water level upstream of the constriction would be limited and it is expected that the corresponding influence on the hydraulic and thermal heat exchange would be negligible. Stage 1 is expected to last through two or three winters.

In Stage 2, the river would be diverted through two diversion tunnels approximately 10 m in diameter and 700 to 800 m in length. The tunnels would flow full and be submerged at both ends for all flow conditions with the discharge through them governed by incoming flow as well as the difference in water level between the upstream headpond and downstream tailrace ends of the tunnels. The headpond water level could vary by approximately 15 m for the full operational range of Peace Canyon (283 to 1,982 m^3/s). It is expected that under low headpond elevations (i.e., low Peace Canyon discharges) ice would pass through the tunnels and under high flows ice would be held upstream of the tunnels in the headpond. The velocity through the tunnels would range from 2 m/s to 13 m/s for the operational range of Peace Canyon discharges. These velocities are above the erosion velocity of 1.5 m/s for ice. Therefore, ice is not expected to jam inside the tunnels. Daily fluctuations of Peace Canyon discharge would be attenuated by the headpond and therefore winter headpond levels would be expected to be in the top 5 m of the 15 m range during the higher discharges typical in the winter, even if Peace Canyon was backed down overnight. Ultimately however, changes to the ice regime downstream of the diversion would depend upon how Peace Canyon Dam is operated and how much ice passes through the tunnels. It is difficult to quantify the future operation of the Peace Canyon Dam, but based on the hydraulics of the Stage 2 headpond, it is expected that the ice regime downstream of the Stage 2 diversion would be somewhere in between the existing conditions and those with the Project, or the combination of the Project and the Dunvegan Project. This is because the Stage 2 headpond would trap some ice and reduce heat loss since it would be deeper than the natural channel. This would cause the zero degree isotherm and ice production downstream to be between existing conditions and conditions expected with the Project. The ice regime upstream of the Stage 2 diversion would also depend on how Peace Canyon is operated. At high flows a smooth solid ice cover would form during cold weather in the headpond. At low flows ice would be drawn down through the tunnels.

Any potential issues with ice in the headpond can be dealt with operationally by maintaining higher discharges out of Peace Canyon. The Stage 2 diversion is expected to last through three winters.

6 CHANGES TO THE ICE REGIME UNDER A FUTURE CLIMATE

For the assessment of project changes to ice conditions under a future climate, monthly air temperature offsets were applied to hourly historical data from the three climate stations used in the CRISSP model (i.e., Fort St. John, Town of Peace River, and High Level) and the model was re-run for each of the 16 winters considered in the study. Although there are other climate variables that may be influenced by climate change, ice modelling experience suggests that a change in air temperature would be the single most important driver as it relates to ice conditions; hence, other climatic components were assumed to remain unchanged from historical ones. Another model input that may be affected by climate change is reservoir outlet water temperature. A sensitivity analysis conducted using the three-dimensional model of the Site C reservoir suggests that the increase in outflow temperature from the Site C reservoir averaged only 5% of the air temperature increase in the winter months; therefore it is reasonable to ignore this change for the purpose of the analysis.

The monthly air temperature offsets for the three climate stations were calculated by taking the difference between air temperatures projected for the 2050s time period (2040-2069) and the 2080s time period (2071-2098) and air temperatures observed over the 1961-1990 climate normal period. Projections for the 2050s and 2080s periods were derived from eight global climate models forced with three emissions scenarios. The global climate models and emission scenarios used in the analysis are described in Volume 2 Appendix T Climate Change Summary Report. For each month and location, the median air temperature delta from the ensemble of models and emission scenarios was selected. Table 6.1 summarizes the monthly air temperature offsets used in the analysis.

Table 6.1 Monthly Air Temperature Offsets (2050s and 2080s, ^{o}C)

Month	Fort St. John, B.C.		Town of Peace River, AB		High Level, AB		Average	
	2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s
November	2.1	3.2	2.1	3.2	2.8	3.9	2.3	3.4
December	2.9	4.3	3.2	4.3	3.7	4.8	3.3	4.5
January	2.8	4.5	2.8	4.6	3.4	5.7	3.0	4.9
February	2.9	4.5	3.2	4.9	3.4	4.9	3.2	4.8
March	2.5	3.2	2.6	3.5	2.8	3.8	2.6	3.5
April	1.6	2.3	1.4	2.1	1.7	2.5	1.6	2.3

For the purpose of this study the Peace Canyon Dam's Dinosaur Reservoir and Site C reservoir outlet water temperatures were assumed to remain unchanged with climate change. It was assumed that climate change would affect the timing of the lodgement of the ice cover at the downstream model boundary (i.e., Fort Vermilion). As there are no systematic observations of the lodgement mechanism or the lodgement location, an empirical method for determining the lodgement date was developed from considerations of the degree-days of freezing required for lodgement. This was the same method used by Andres and Healy (2006) for determining the changes from the proposed Dunvegan project under a future climate scenario. The degree-days of freezing at the High Level Airport in Alberta was used, as this climate station is the closest one to where lodgement occurs. For each of the years simulated, the degree-days of freezing required for lodgement to occur were determined from the historical air temperatures. The air temperatures were then increased as per Table 6.1 and the date with the equivalent number of degree-days with these augmented air temperatures was determined. This was taken as the ice cover initiation date at the downstream end of the model for the climate change scenarios. These dates are summarised in Table 6.2.

Table 6.2 Delay in ice cover initiation date for the 2050s and 2080s climate change scenarios

	Present Climate Ice Cover Initiation Date	Historical Degree-Days of Freezing	Climate Change Ice Cover Initiation Date		Delay in number of days	
			2050s	2080s	2050s	2080s
1995 - 1996	13-Nov	227	20-Nov	22-Nov	7	9
1996 - 1997	09-Nov	190	15-Nov	17-Nov	6	8
1997 - 1998	22-Dec	608	05-Jan	08-Jan	14	17
1998 - 1999	01-Dec	286	10-Dec	15-Dec	9	14
1999 - 2000	28-Nov	227	04-Dec	08-Dec	6	10
2000 - 2001	08-Dec	462	13-Dec	15-Dec	5	7
2001 - 2002	01-Dec	309	08-Dec	10-Dec	7	9
2002 - 2003	18-Dec	520	03-Jan	12-Jan	16	25
2003 - 2004	26-Nov	334	01-Dec	7-Dec	5	11
2004 - 2005	07-Dec	564	17-Dec	21-Dec	10	14
2005 - 2006	23-Dec	469	15-Jan	21-Jan	23	29
2006 - 2007	11-Nov	190	16-Nov	17-Nov	5	6
2007 - 2008	30-Nov	315	04-Dec	05-Dec	4	5
2008 - 2009	06-Dec	336	13-Dec	14-Dec	7	8
2009 - 2010	27-Nov	229	06-Dec	08-Dec	9	11
2010 - 2011	30-Nov	310	04-Dec	07-Dec	4	7
Average	30-Nov	343	09-Dec	13-Dec	9	12

The influences of the changed climate on the ice front locations in two winters, for the various development scenarios, are shown in Figure 23 and Figure 24 (for the 2050s future climate and 2080s future climate, respectively). As expected, the ice fronts for all scenarios under climate change conditions are further downstream than under existing conditions.

Figure 25 and Figure 26 show the simulated probabilities of the maximum upstream extent of the ice cover for the present climate and the changed climates (2050s and 2080s) for existing conditions, the Project, and the combination of the Project and the Dunvegan Project. From this figure it is possible to conclude that changes resulting from climate change are of a similar magnitude as those attributable to the Project or the Project combined with the Dunvegan Project - in the order of a few tens of kilometres to about 100 km depending on location and winter severity. There is no difference between project scenarios downstream of about km 650, with and without climate change, indicating the downstream boundary is sufficiently far removed that it is not affected by changes to the ice regime due to the Project or the combination of the Project and the Dunvegan Project. It also can be concluded that the influence of the Project on downstream ice conditions is predicted to be similar whether under a baseline climate, a 2050s climate, or a 2080s climate.

More specific comments on the estimated change of annual ice front probability as a result of climate change and project combinations are described below.

District of Taylor with climate change: With the Project the ice cover would not reach the District of Taylor even if the proposed Dunvegan project were in place with or without climate change.

British Columbia-Alberta Border with climate change: Under existing conditions, the annual probability of the ice cover advancing into B.C. is about 22%. Climate change for the 2050s and 2080s scenarios would reduce this to about 11% and 7% respectively. With the Project, the probability would decrease to near 0% under the 2050s and 2080s climate change scenarios. With both the Project and the Dunvegan Project the annual probability of the ice advancing into B.C. would decrease from 22% to about 16% with no climate change and reduce further to 6% under the 2050s climate change scenario and to near 0% under the 2080s climate change scenario.

Shaftesbury Crossing with climate change: Under existing conditions, the ice cover has always formed at Shaftesbury Crossing. However, with climate change and neither the Project nor the Dunvegan Project, the annual probability of an ice cover forming at Shaftesbury would be reduced to about 86% and 83% under the 2050s and 2080s climate change scenarios respectively. With the Project the annual probability of the ice cover forming at Shaftesbury would be 100% without climate change and about 84% and 75% under the 2050s and 2080s climate change scenarios respectively. With both the Project and the Dunvegan Project, the probability of an ice cover forming would be about 88% without climate change and about 63% and 35% under the 2050s and 2080s climate change scenarios respectively.

The Town of Peace River with climate change: Results from the 16 years simulated for the present climate showed that under all scenarios an ice cover would form at the Town of Peace River. However, with climate change the probabilities for each of the scenarios are less than 100%. With no projects in place, the annual probability of the ice front reaching the Town of Peace River would be about 88% and 84% under the 2050s and 2080s climate change scenarios respectively. With the Project and with climate change, the annual probability of the ice front advancing to the Town of Peace River would be about 86% and 83% under the 2050s and 2080s scenarios respectively. With both the Project and the Dunvegan Project and with climate change, the annual probability of an ice cover forming at the Town of Peace River would be about 83% and 61% under the 2050s and 2080s climate change scenarios respectively.

7 SUMMARY AND CONCLUSIONS

An investigation was conducted using the CRISSP and PRTIGM models to numerically simulate the changes in the ice regime on the Peace River that would result from the Project. Also considered were the changes to the ice regime associated with another proposed hydropower project at Dunvegan as well as changes under a future, changed climate. The downstream extent of the model for all scenarios was Fort Vermilion, Alberta. The results showed that the downstream boundary of the model exceeded the point of no discernible changes to the ice regime by almost 200 km.

Maximum upstream extent of ice cover

With the Project or with the combination of the Project and the Dunvegan Project, the upstream progression of the ice front in the early winter would be slowed down, with no discernible changes evident at around km 650, about 250 km downstream of the Town of Peace River or 150 km downstream of Sunny Valley. The closer the ice front advances to the Site C dam site or the Dunvegan dam, the stronger the delaying influence. This would be due to the relatively warmer outlet water temperature of the Site C reservoir and the fact that both the Project and the Dunvegan Project would trap ice and therefore reduce the amount of ice contributing to downstream ice cover advancement. Downstream of about km 650, ambient air temperatures in the winter and solar radiation in the spring dominate over the changes in water temperatures and/or ice quantities resulting from changes attributable to the Project or the Dunvegan Project.

With the Dunvegan project, a second ice front would be created since the Dunvegan structure would not pass ice floes (Jacques Whitford 2006). This would cause a second ice front to advance further upstream into British Columbia and towards the Site C dam site than would be expected with the Project only.

From the results of the simulation of 16 winters, some general statements can be made about the annual probability of an ice cover at various points of interest.

Site C dam site: With the Project, the ice front would not progress to the tailrace of the Site C dam, with or without the Dunvegan Project.

District of Taylor: With the Project the ice cover would not reach the District of Taylor even if the Dunvegan Project were in place.

British Columbia-Alberta Border: Under the existing conditions, the annual probability of the ice cover advancing into B.C. is about 22%. With the Project this would decrease to about 10%. With both the Project and the Dunvegan Project the annual probability of the ice cover advancing into B.C. would decrease to about 16%.

Shaftesbury Crossing: Under existing conditions, an ice cover has always formed at Shaftesbury Crossing. This would not change with the Project. With both the Project and the Dunvegan Project, the annual probability of an ice cover reaching the Shaftesbury Crossing location would decrease to about 88%.

The Town of Peace River: Under all scenarios and for each of the 16 years simulated, the simulated ice cover reached the Town of Peace River.

Timing of Freeze-up

On average the Project would delay freeze-up at the Town of Peace River by three days; the Project and the Dunvegan Project together would delay the freeze-up by 10 days. Upstream of the Town of Peace River this delay would be greater (an average delay of 9 days at Dunvegan due to the Project; with both the Project and the Dunvegan Project the downstream ice front never reaches Dunvegan), and downstream it would be less (an average delay of two days at Sunny Valley due to the Project or three days due to the combination of the Project and the Dunvegan Project).

Timing of Break-up

On average the recession of the Peace River ice front past the Town of Peace River in the spring would remain unchanged as a result of the Project, or the Project in combination with the Dunvegan Project. Thus the chances of the Smoky River breaking up into an intact Peace River ice cover and causing a threat of ice jam flooding at the town in the spring would remain unchanged. Similarly, no change in break-up timing would be expected at Sunny Valley or Dunvegan as a result of the Project or the combination of the Project and the Dunvegan Project.

Freeze-up Water Levels

With both the Project and the Dunvegan Project, the amount of ice arriving at the ice front would be reduced when the ice is forming at and upstream of the Town of Peace River. This would reduce the rate of advance of the ice front in this reach and reduce the frequency of secondary consolidations and the associated extreme winter freeze-up levels. However, it is difficult to quantify to what degree these events would be reduced.

The possibility of groundwater seepage into basements in the Lower West Peace River Subdivision because of the Project should be no higher than that which exists currently and possibly less due to the reduced likelihood of secondary consolidations.

Modelling results showed that the average freeze-up water levels at the Town of Peace River would remain unchanged as a result of the Project. A slight increase of about 0.1 m on average is possible due to the Project and the proposed Dunvegan project but this is within modelling error and much less than year-to-year variability associated with the stochastic nature of the ice formation process. There should be no change in freeboard provided by the Town of Peace River dykes to protect against secondary consolidations with the Project, or with the Project in combination with the Dunvegan Project.

Freeze-up water levels in less populated areas such as upstream and downstream of Dunvegan would change by about plus or minus 1 metre. This is largely due to the difference in the timing of the flow controls as well as the slower advancing ice cover downstream of Dunvegan.

Break-up Water Levels

With the Project (with or without the Dunvegan project), high water levels at break-up would remain unchanged from existing conditions as they are a function of the Smoky River breaking up dynamically into an intact Peace River ice cover. Since neither the Project, nor the combination of the Project and the Dunvegan Project change the average timing of the thermal break-up of the Peace River ice cover at the Town of Peace River, peak break-up water levels would not change from those experienced under existing conditions as a result of the Project. Also, the Project would allow about a 12-hour faster response time to implement flow control to mitigate Smoky River induced dynamic break-ups due to the reduced travel time of flow changes. The reduced travel time is due to the fact that the Site C dam site would be about 85 km closer to the Town of Peace River than the Peace Canyon Dam.

Since freeze-up and break-up water levels would remain unchanged as a result of the Project, there would be no additional degradation of the Town of Peace River dykes as a result of the project.

The timing of control flow to assist in the stable formation of the ice cover at the Town of Peace River would change slightly with the Project and with both the Project and the Dunvegan Project. Under existing conditions the average date of control flow implementation is January 5; with the Project it would be January 10 (i.e., a delay of 5 days), and with both the Project and the Dunvegan Project it would be January 15 (i.e., a delay of 10 days). As for the duration of control flow, under existing conditions the average control flow duration is about 23 days; it would be about 20 days with the Project and about 30 days with both the Project and the Dunvegan Project. Control flow for freeze-up would arrive about 12 hours sooner from the Site C generating station than it would from Peace Canyon.

Results suggest that there would be no change in the average Peace River break-up date as a result of the Project or the combination of the Project and the Dunvegan Project. Thus, there would be no change in the duration or magnitude of the control flow at break-up. The Project would allow BC Hydro to respond more quickly with a flow decrease pending a Smoky River induced dynamic break-up at the Town of Peace River.

Ferry and Ice Bridge Crossings

On average there is no difference in the start-up of Shaftesbury Ferry operations in the spring as a result of the Project, or as a result of the combination of the Project and the Dunvegan Project. However, as a result of the Project there appears to be an extension of four days on average in Shaftesbury Ferry operations in the fall or early winter and longer extensions of up to a few weeks in some years. With the Project and the Dunvegan Project, Shaftesbury Ferry operations would be extended an average of three days in the fall and early winter.

The estimated average number of Shaftesbury Ferry crossing days is about 229 days for existing conditions, 232 days with the Project, and 232 days with both the Project and the Dunvegan Project. This amounts to an average increase in ferry operations of three days.

The changes to operations of the Shaftesbury ice bridge as a result of the Project and the Dunvegan Project were also determined. With the Project, results suggest that the installation of the ice bridge would be delayed on average by about 5 days relative to existing conditions with a year-to-year range of between 0 and 14 days. With both the Project and the Dunvegan Project the average delay is predicted to be 17 days with a range of 6 to 37 days; however, there were two years within the modelling period during which the ice thickness would not be sufficient to sustain an ice bridge. The average length of the ice bridge operating period under existing conditions is 75 days, and would be 71 days with the Project and 58 days with the Project and the Dunvegan Project. With respect to the total number of ferry and ice bridge crossing days, the Project alone would produce no change. The Project and the Dunvegan Project together would reduce the number of crossing days by 15 days.

Modelling results showed no systematic change in the timing of freeze-up and break-up at km 694, which is the location of the La Crete Ferry and Tompkin's Landing ice bridge, due to the Project, or the combination of the Project and the Dunvegan Project. Therefore, there should be no change to ferry or ice bridge operations at Tompkin's Landing due to the Project, or the combination of the Project and the Dunvegan Project.

Thermal Ice Thickness

Under present conditions, the thermal ice usually gains sufficient thickness to support an individual or a large animal within a day or two of the ice cover formation, and this would not be expected to change with the Project or with the Project in combination with the Dunvegan Project. Therefore any potential changes in the availability of a competent ice cover are best reflected by the changes in timing of the ice front locations.

Construction Period

During construction of the Project the ice regime of the Peace River would not be different from the existing conditions during Stage 1 of construction. The characteristics of the ice regime of the Peace River during Stage 2 of construction would be somewhere in between existing conditions and those with the Project, or with the combination of the Project and the Dunvegan Project.

Climate Change

It is expected that changes to the ice regime due to a general climate warming would be similar in magnitude as those attributable to the Project and the Dunvegan Project; the ice front would be pushed further downstream in the order of a few tens to about 100 km depending on its location and on the winter severity. However, results suggest that there would be no difference in ice front location between project scenarios downstream of about km 650 under a climate change scenario.

8 CLOSURE

This report was prepared and reviewed by the undersigned.

Prepared by:	Reviewed by:
Martin Jasek	Amy PP
Martin Jasek, M.Sc., P.Eng.	Amy Pryse-Phillips, M.Eng., P.Eng.
Specialist Engineer	Hydrotechnical Engineer
Generation Resources Management	Site C Environmental & Regulatory
BC Hydro	BC Hydro

9 REFERENCES

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9.2 Personal Communication

Willi Granson (retired Alberta Environment and Water river ice observer), personal communication April 2012.

10 FIGURES

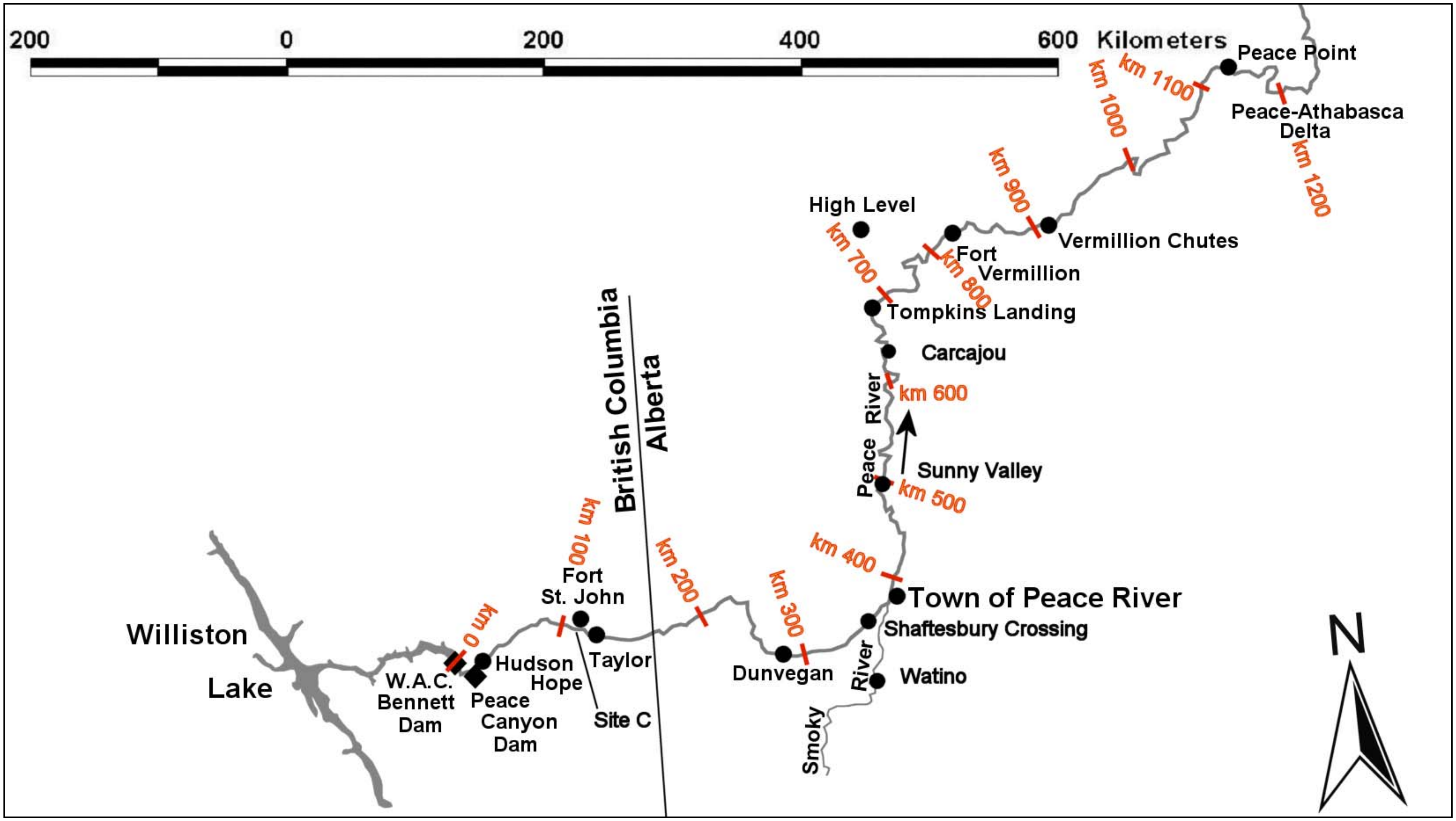

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Figure 1 Map of the Peace River in B.C. and Alberta

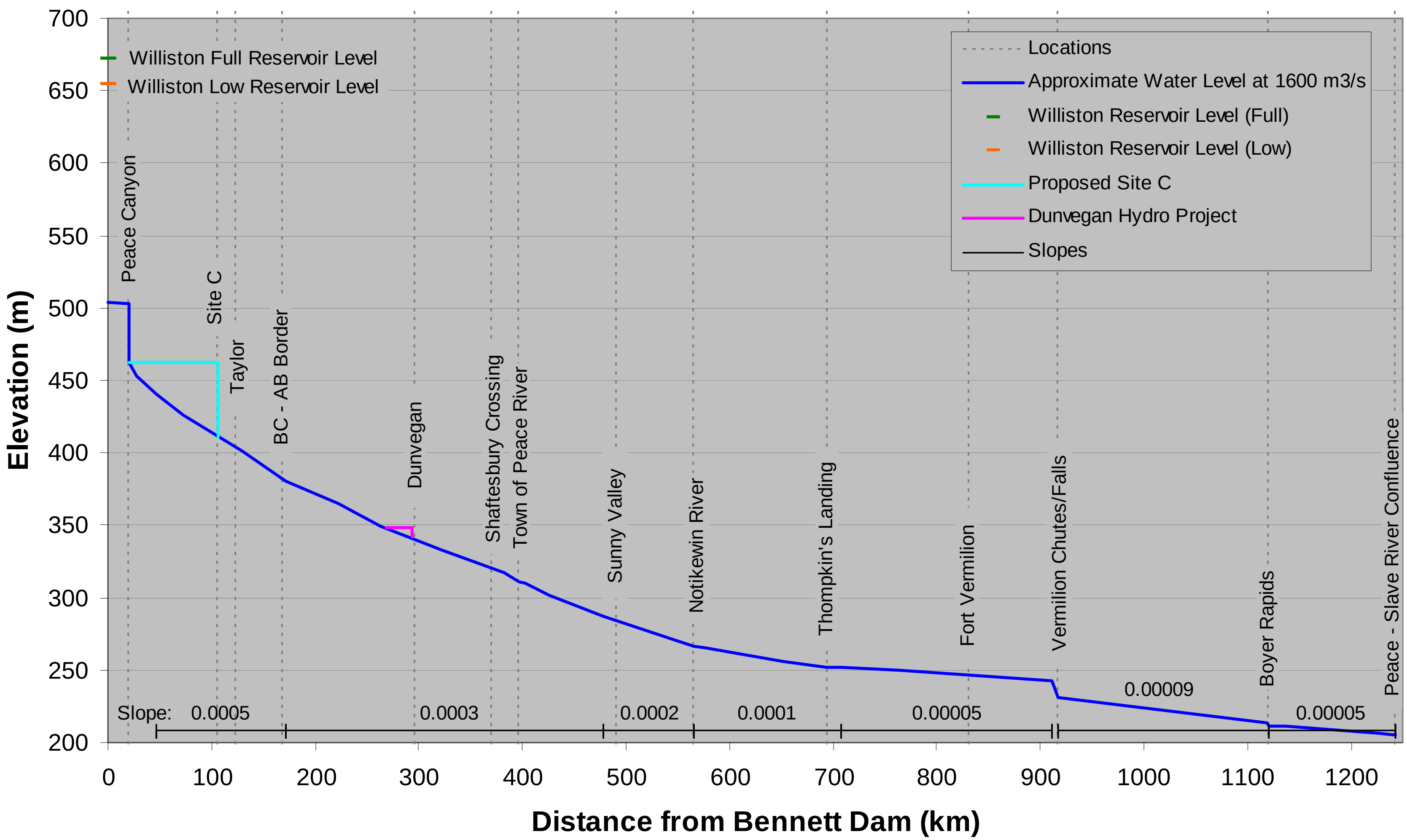

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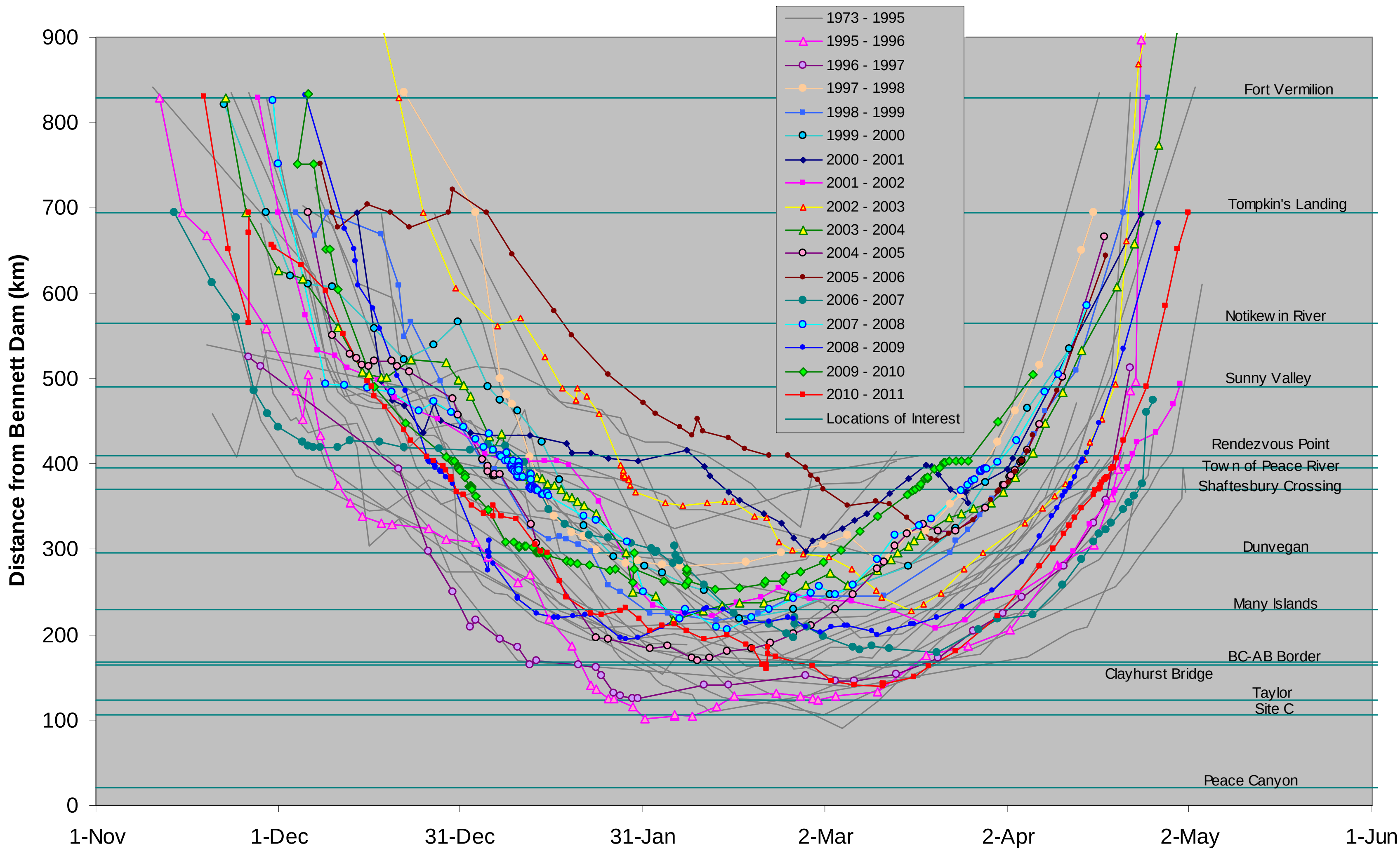
Figure 2 Longitudinal Profile of the Peace River



NOTES:
1. COLOURED TRACES INDICATE THOSE WINTERS SIMULATED IN THE CURRENT STUDY (1995-2011).
2. GREY TRACES INDICATE OTHERS YEARS OF OBSERVED ICE FRONT POSITIONS (1973-1995).

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Figure 3 Historical Ice Front Positions

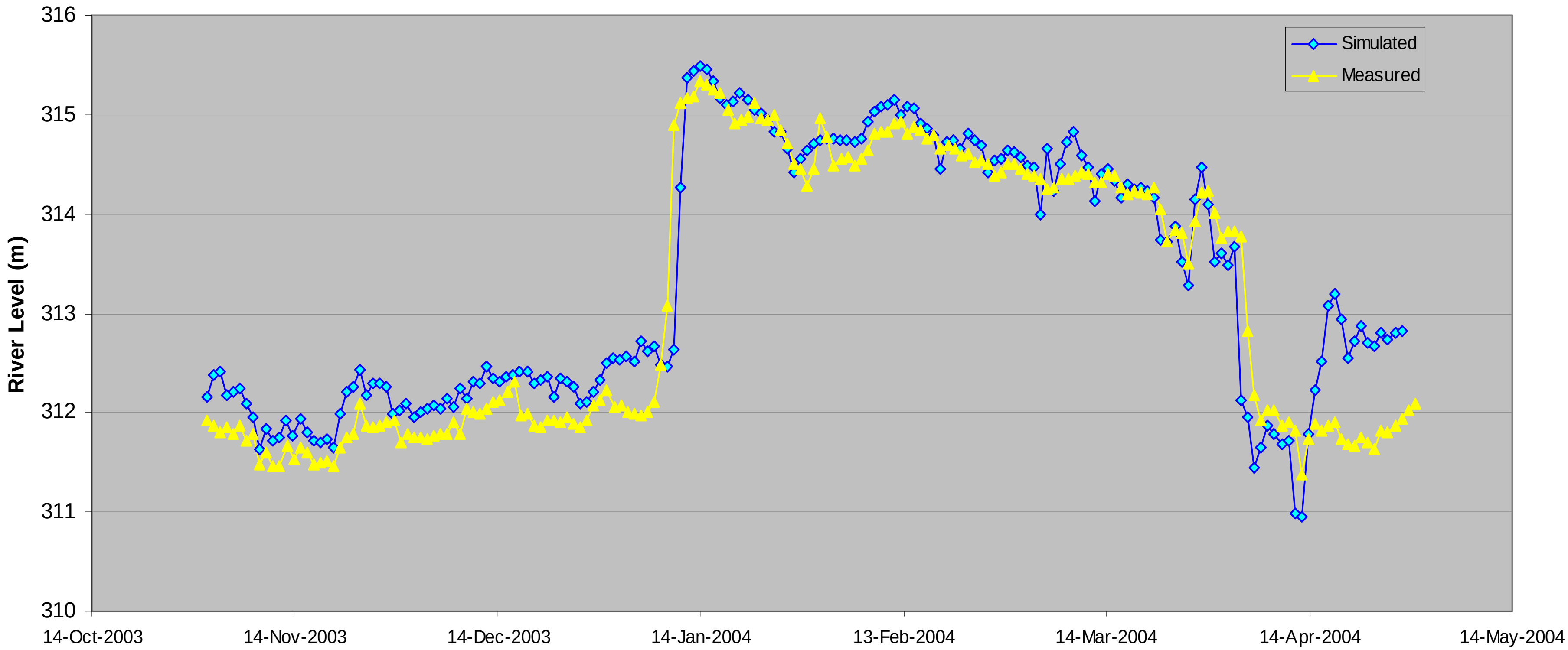

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Figure 4 Simulated and Observed Water Levels at the Town of Peace River (2003-2004)

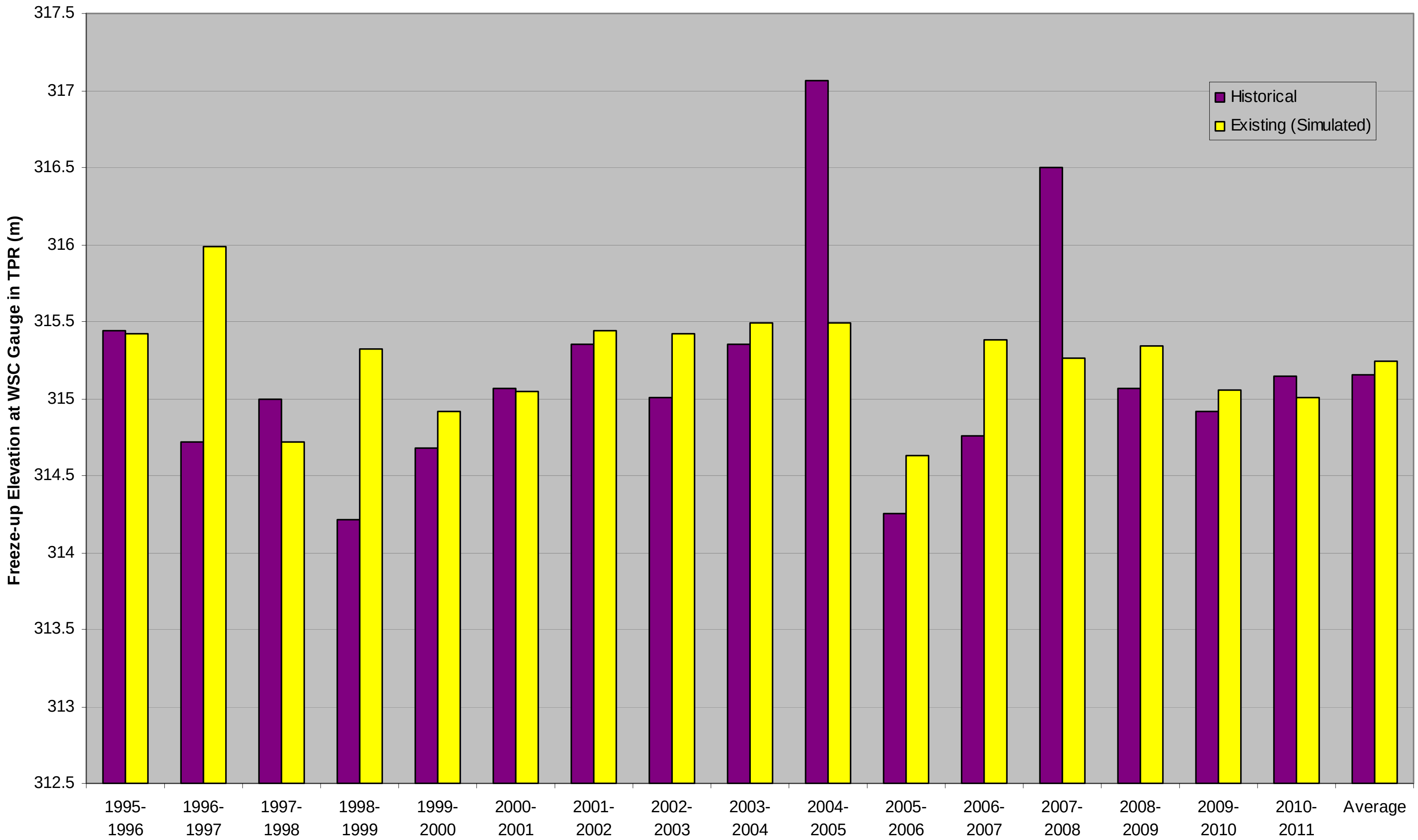

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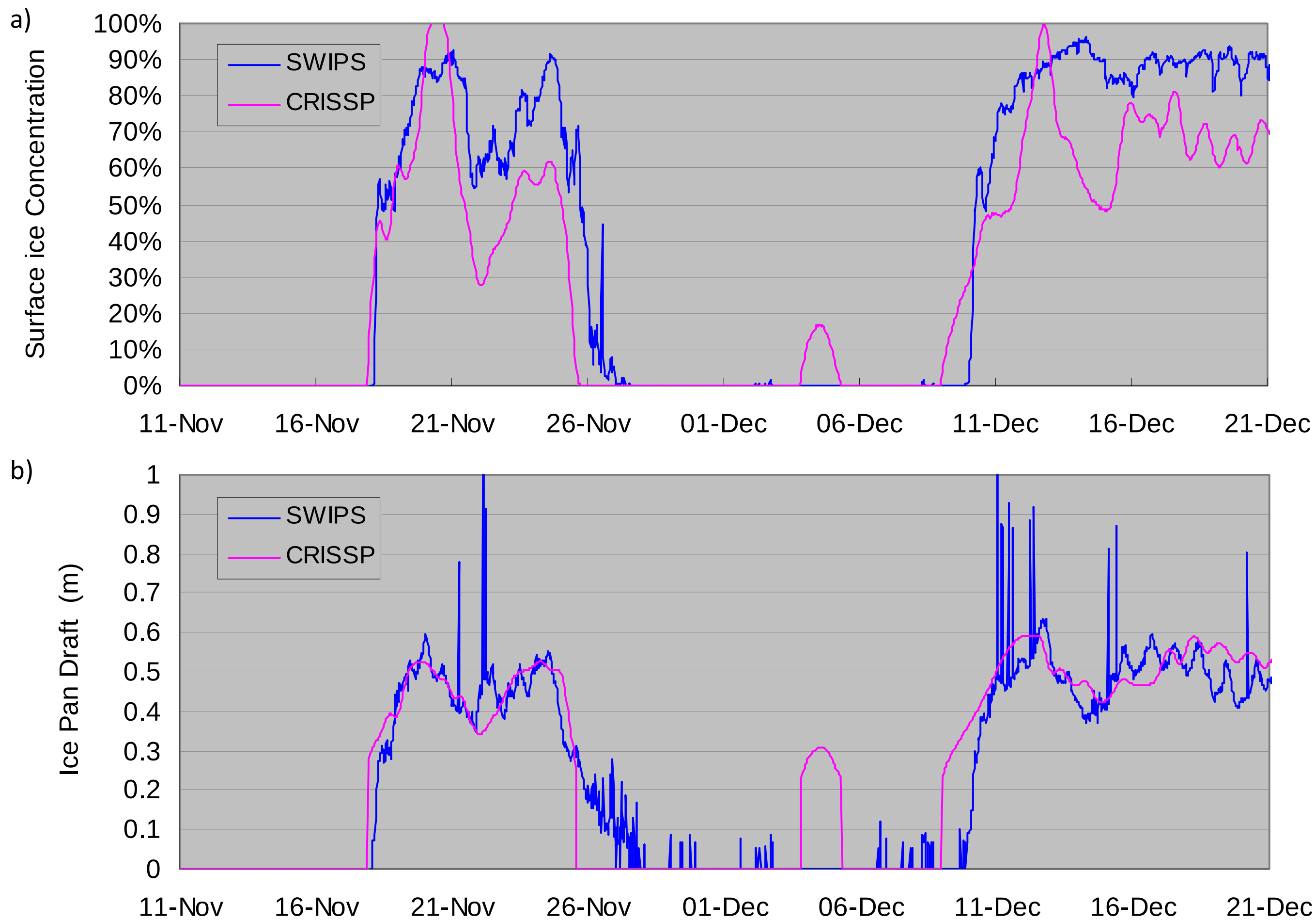
Figure 5 Simulated and Observed Maximum Freeze-up Stage at the Town of Peace River (1995-2011)



NOTES:

1. FROM JASEK ET AL, 2011.
2. SWIPS = SHALLOW WATER ICE PROFILING SONAR

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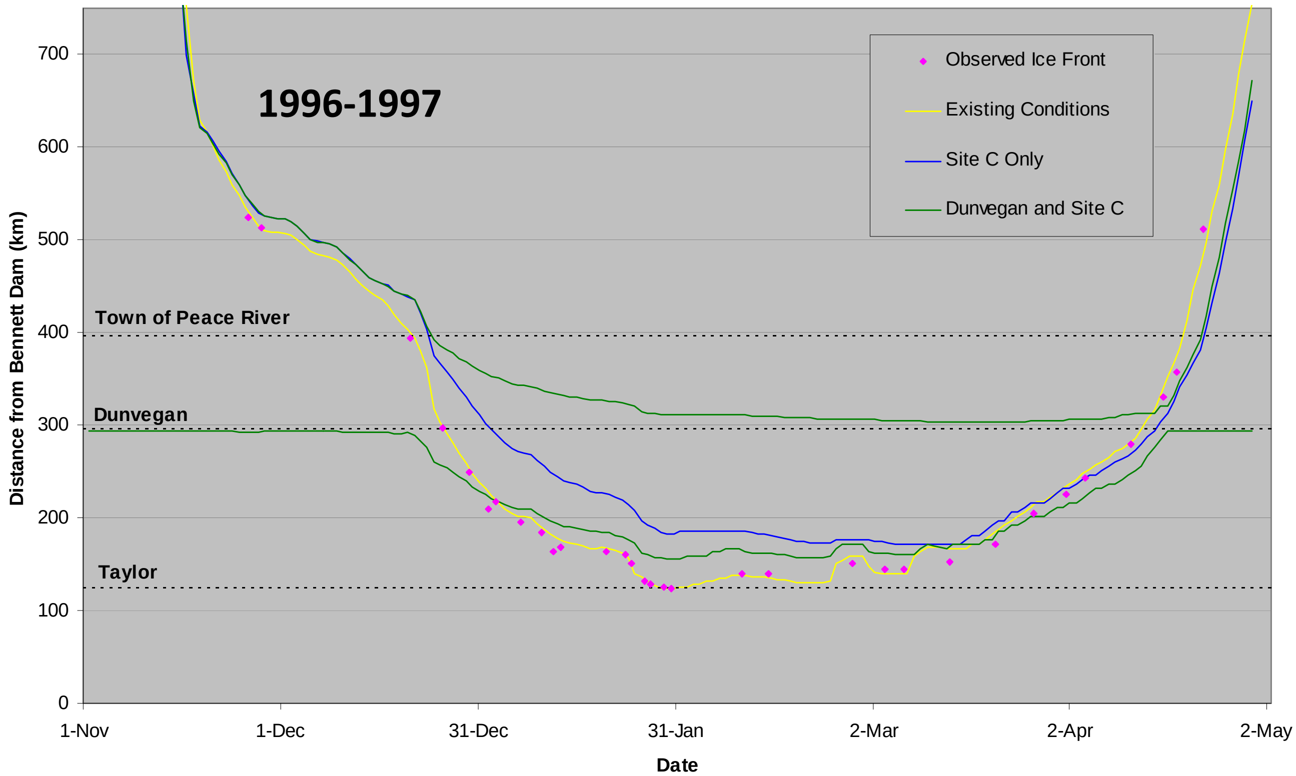
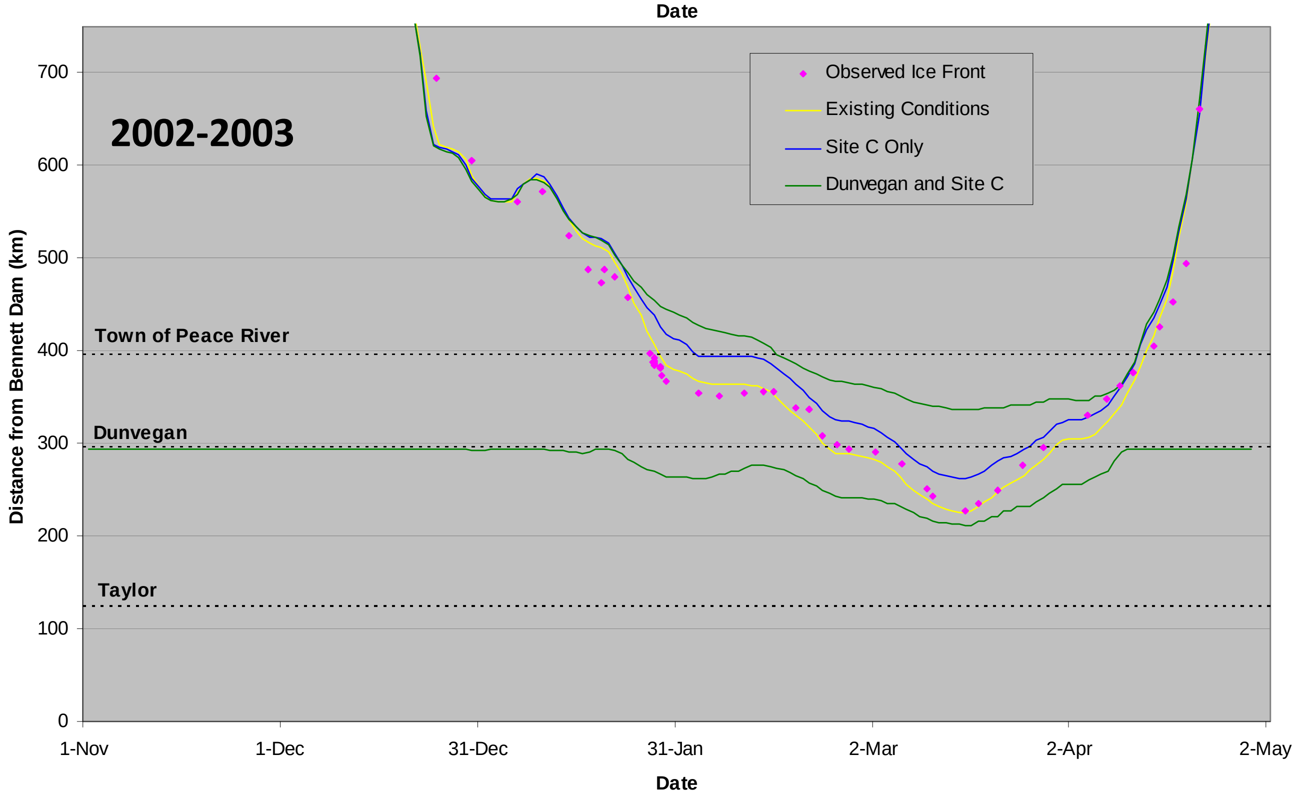
Figure 6 Simulated and Observed (a) Surface Ice Concentration and (b) Ice Pan Thickness (Nov-Dec, 2010)





NOTES:

1. "SITE C ONLY" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
2. "DUNVEGAN AND SITE C" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

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Figure 7 Simulated and Observed Ice Front Progression (1996-1997 and 2002-2003)

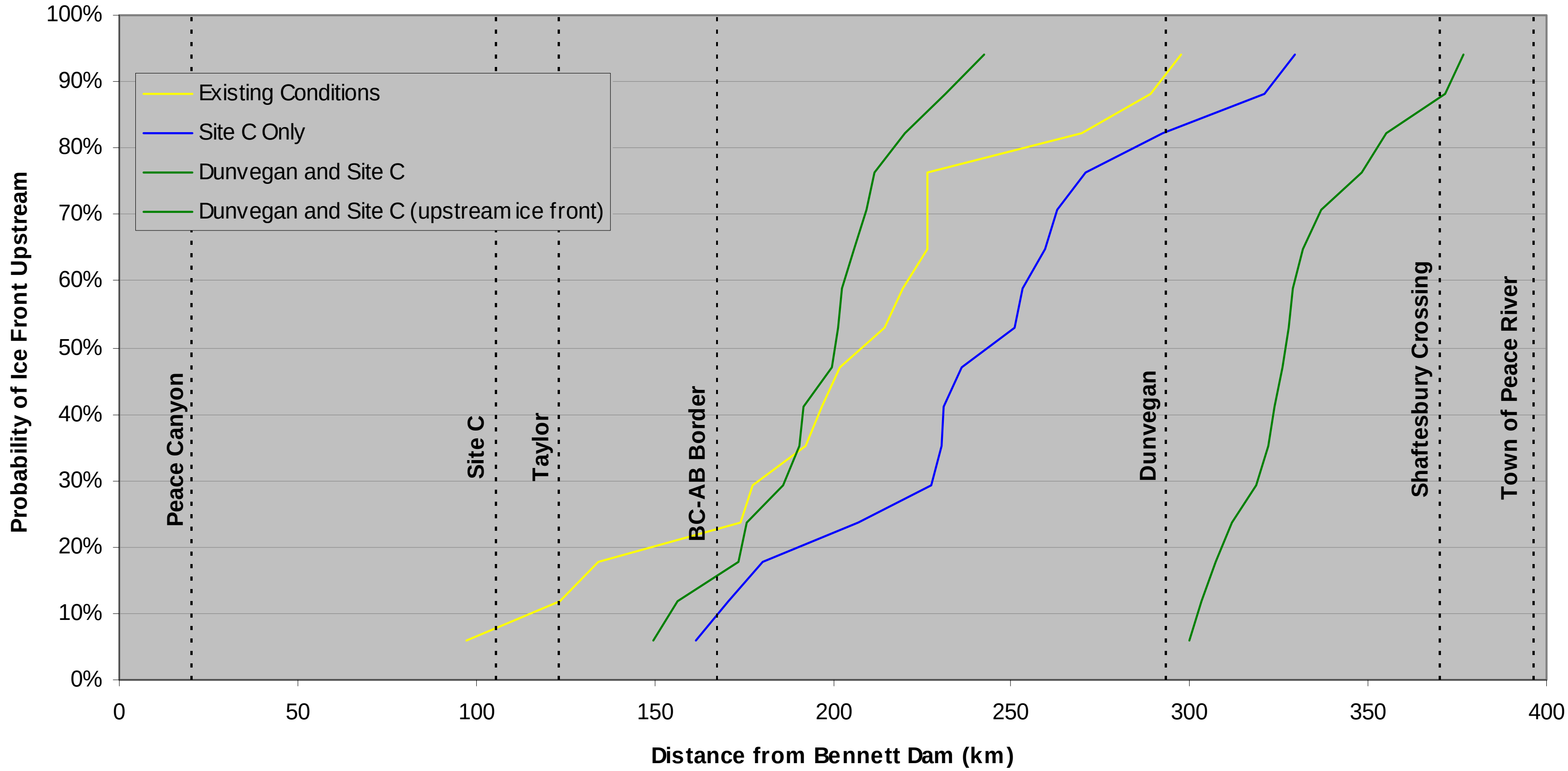

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Figure 8 Simulated Probabilities of Maximum Upstream Extent of Ice Cover

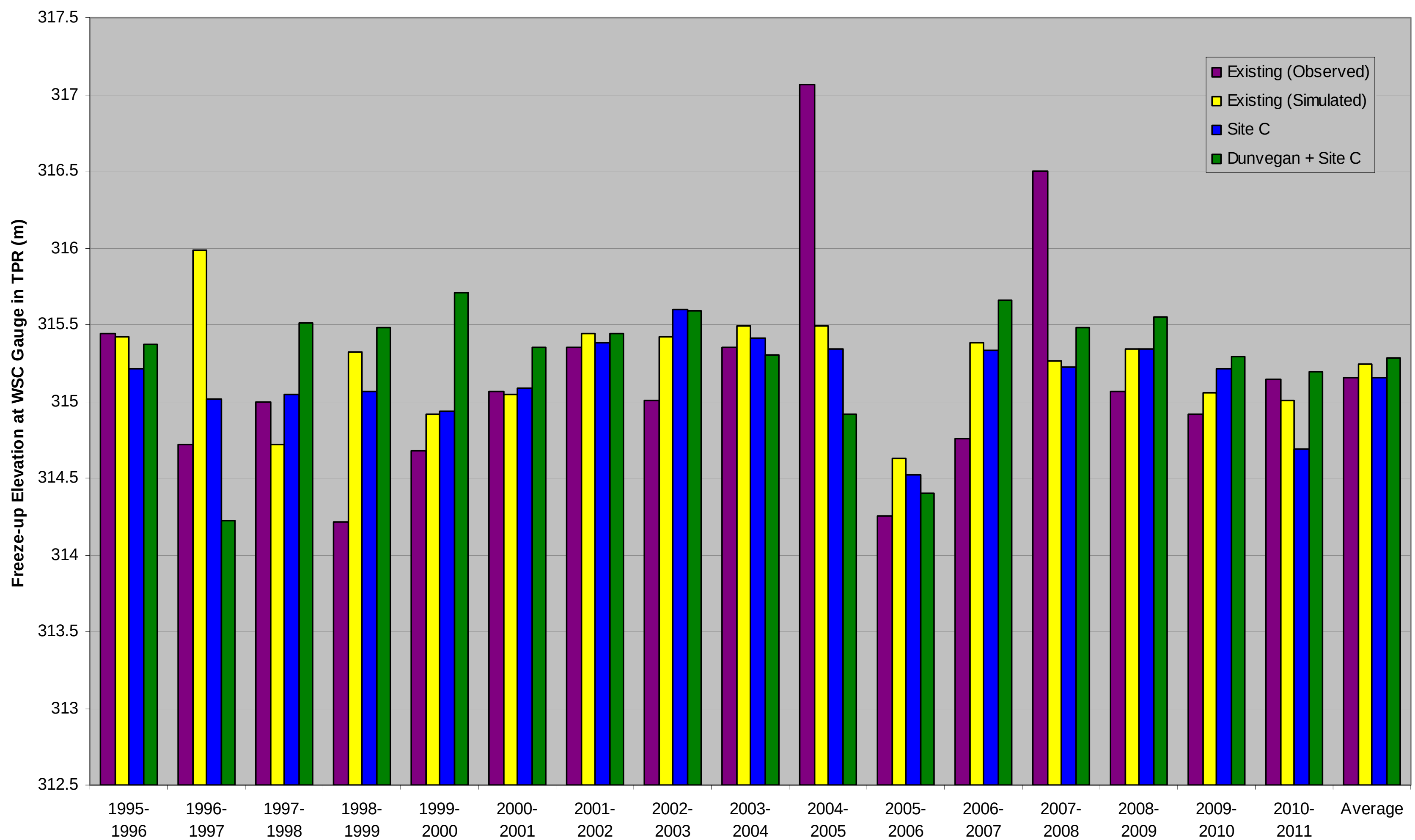

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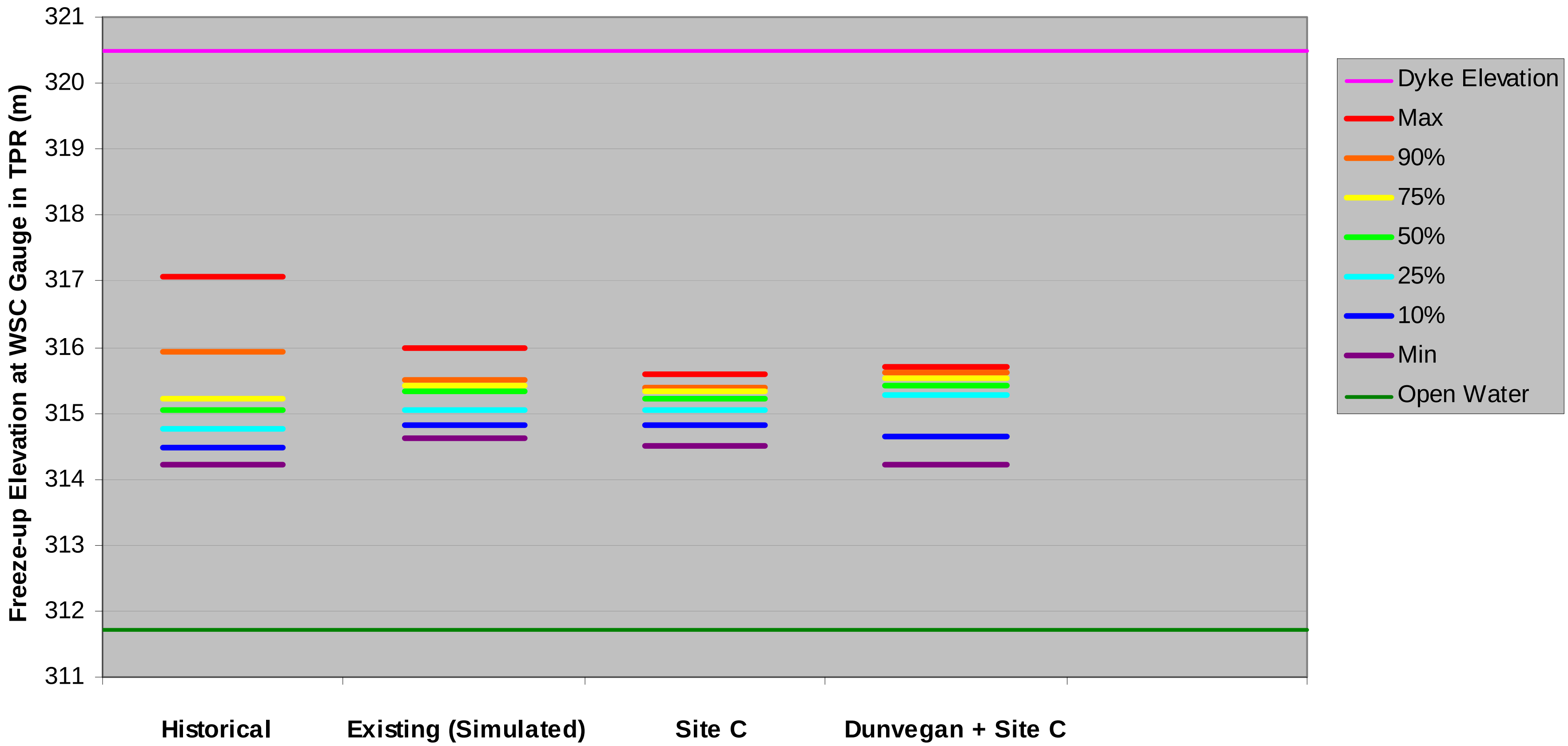
Figure 9 Simulated and Observed Maximum Freeze-up Water Levels at the Town of Peace River



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2. "DUNVEGAN + SITE C" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

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Figure 10 Simulated and Observed Freeze-up Water Levels at the Town of Peace River

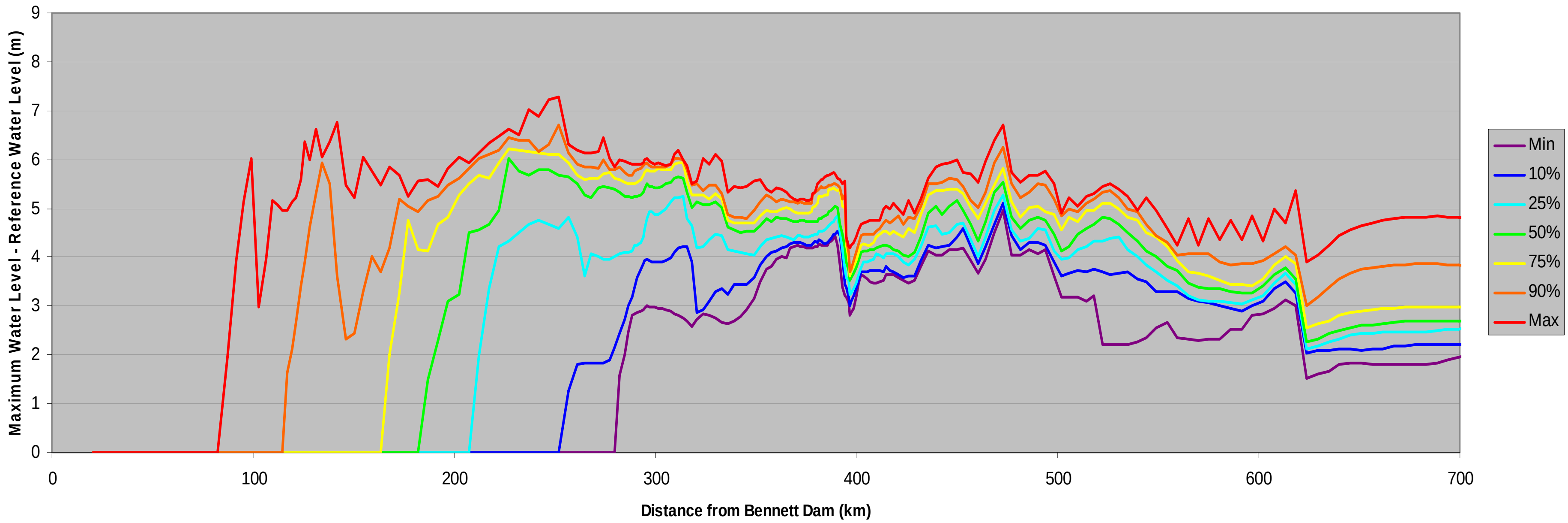

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Figure 11 Simulated Freeze-up Stage without Secondary Consolidations (Existing Conditions)

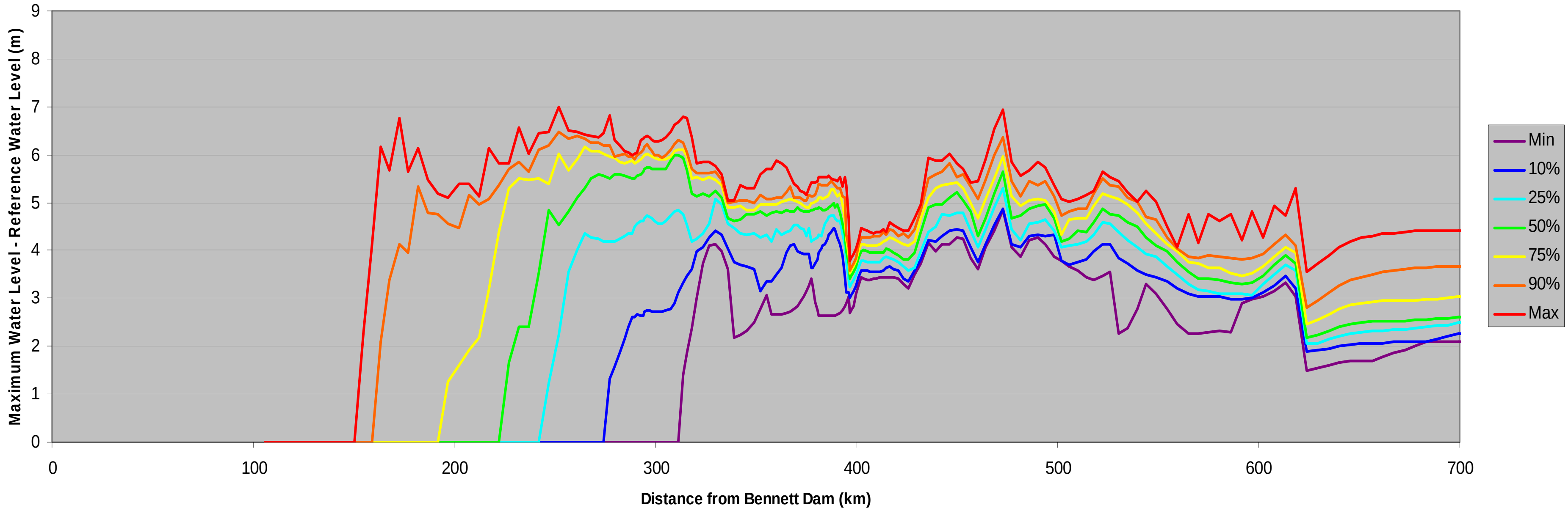

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Figure 12 Simulated Freeze-up Stage without Secondary Consolidations (With the Project)

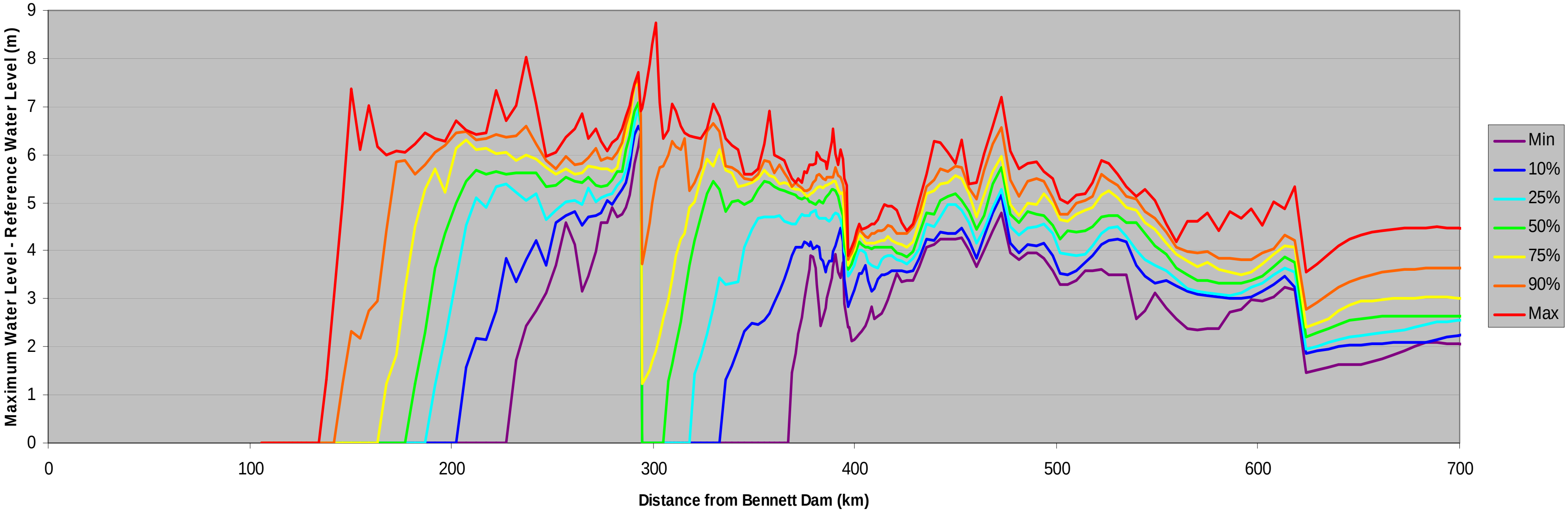

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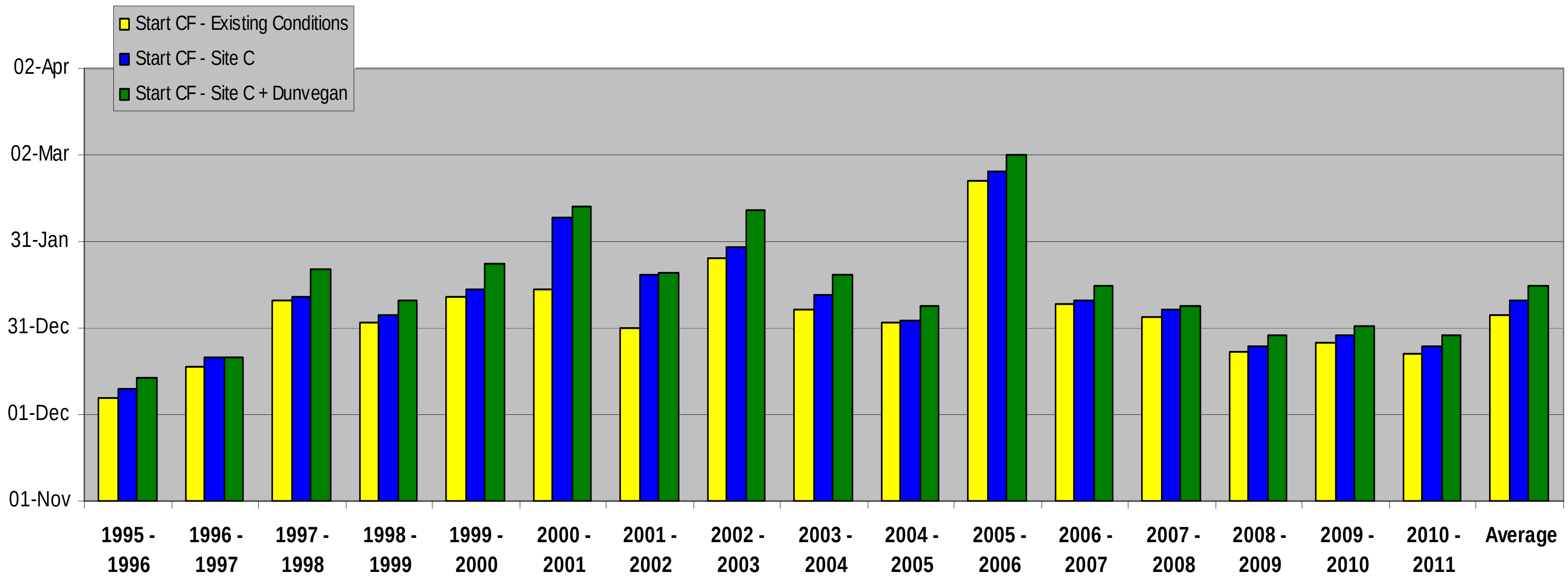
Figure 13 Simulated Freeze-up Stage without Secondary Consolidations (With the Project and the Duvegan Project)



NOTES:

1. "START CF" DENOTES THE START OF CONTROL FLOW .
2. "SITE C" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
3. "SITE C + DUNVEGAN" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

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Figure 14 Simulated Start of Control Flow Timing

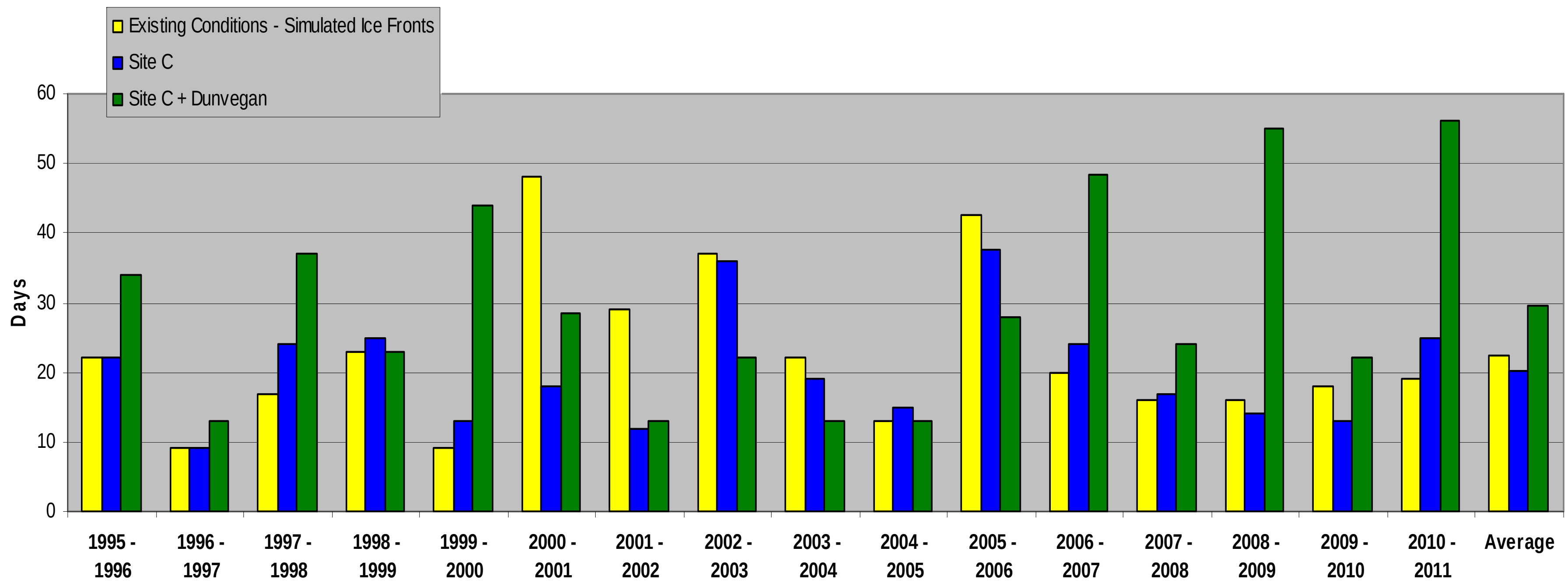

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Figure 15 Simulated Control Flow Duration

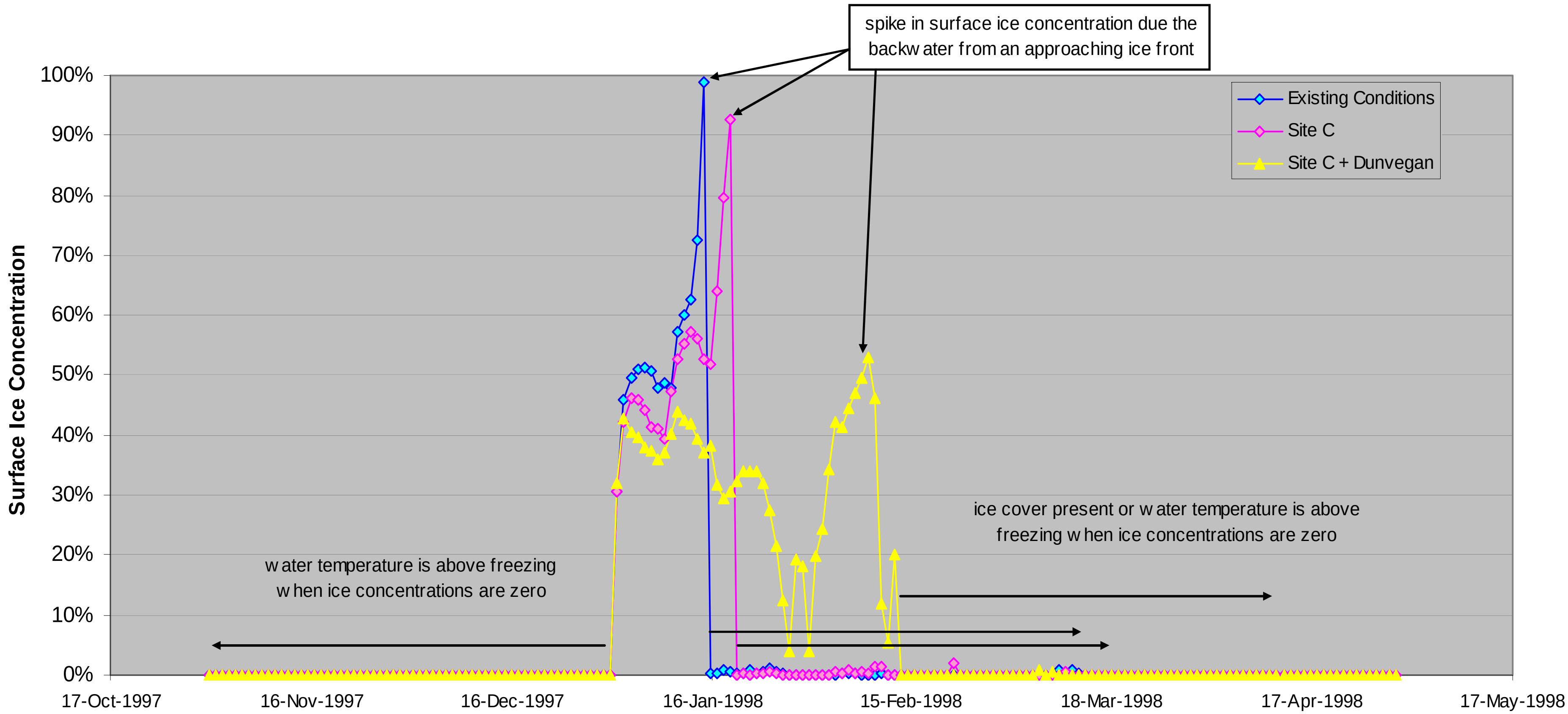

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Figure 16 Simulated Surface Ice Concentrations at Shaftesbury for Existing Conditions and with the Project (1997-1998)

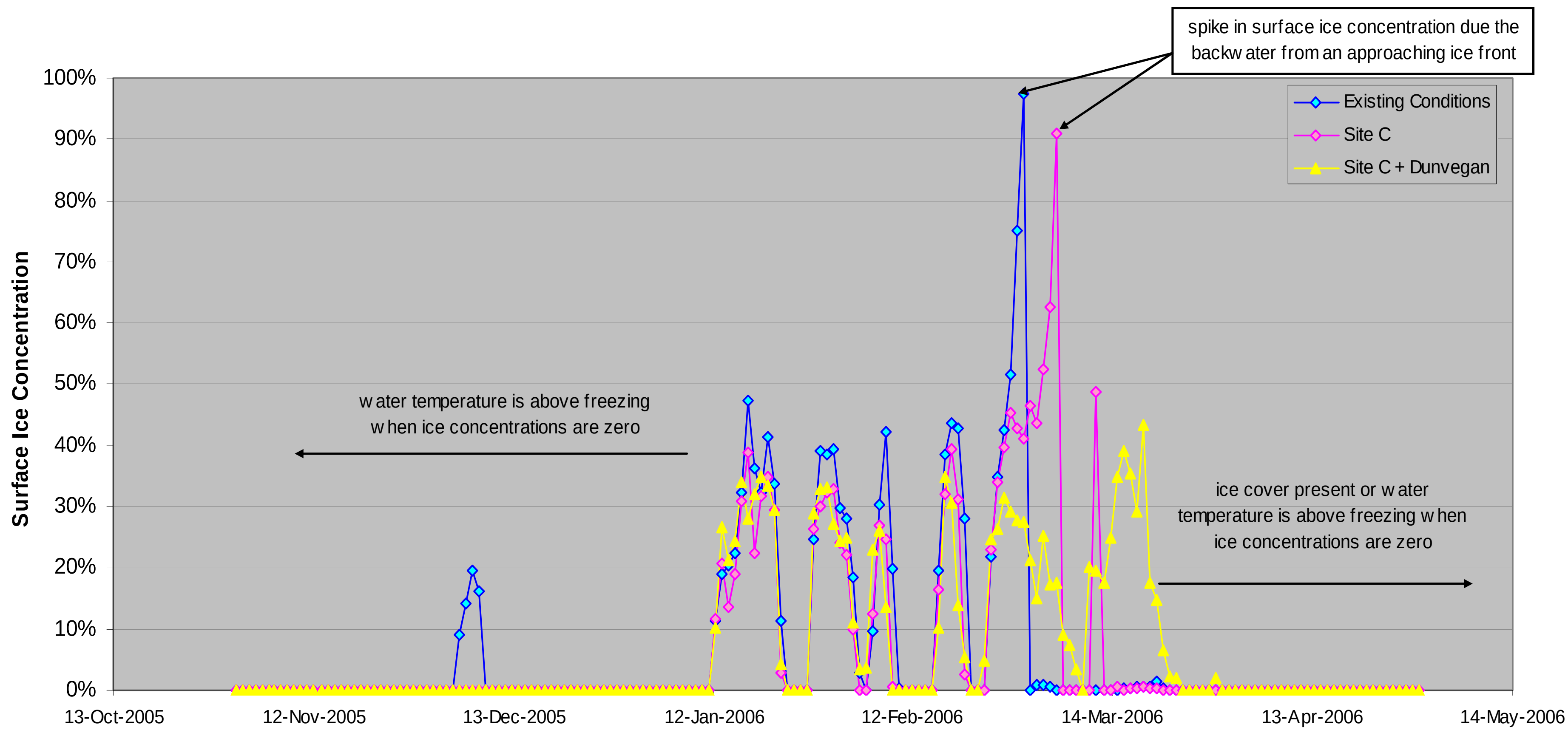

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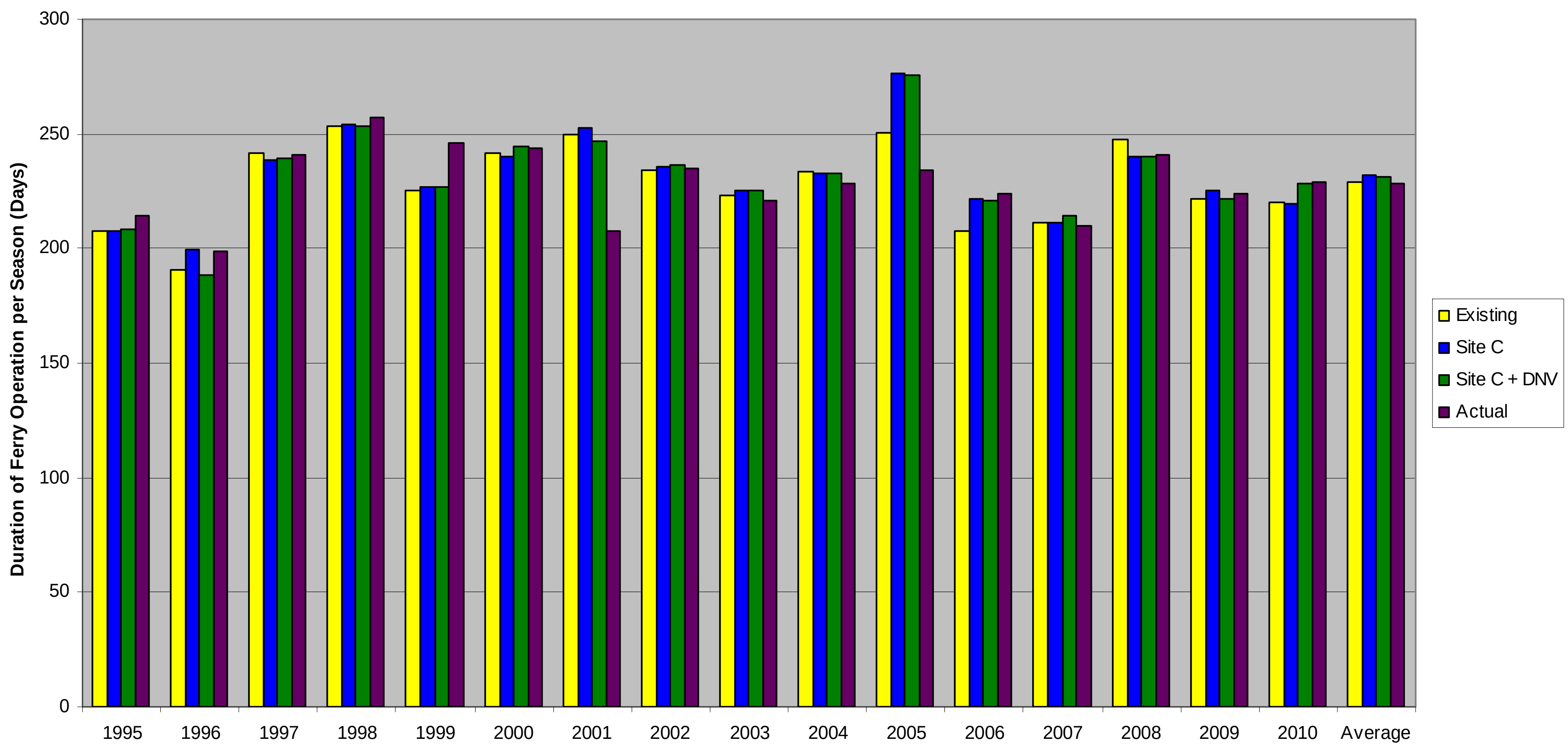
Figure 17 Simulated Surface Ice Concentrations at Shaftesbury for Existing Conditions and with the Project (2005-2006)



NOTES:
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2. "SITE C + DNV" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

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Figure 18 Simulated Total Duration of Shaftesbury Ferry Operation

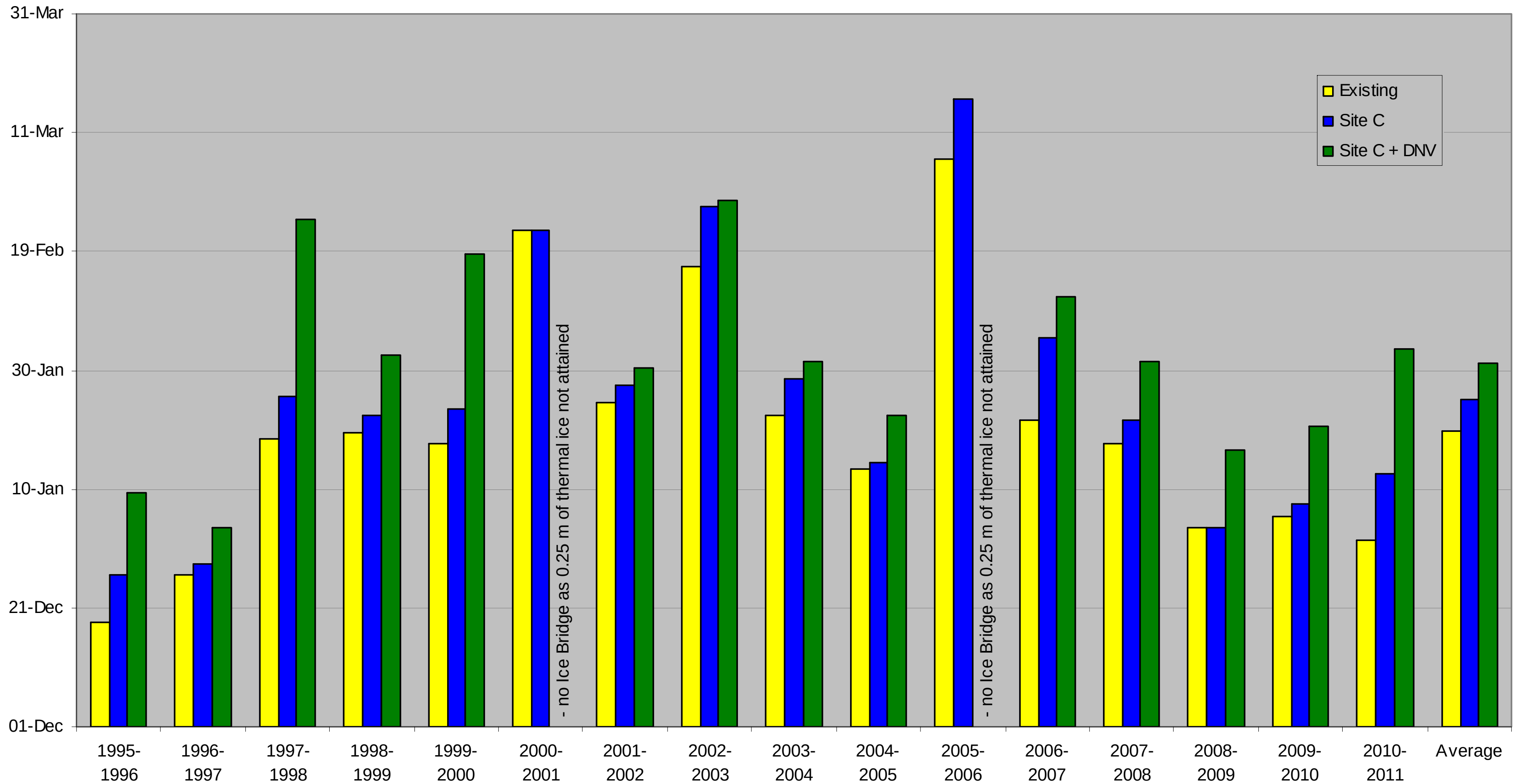

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Figure 19 Simulated Date of First Shaftesbury Ice Bridge Crossing

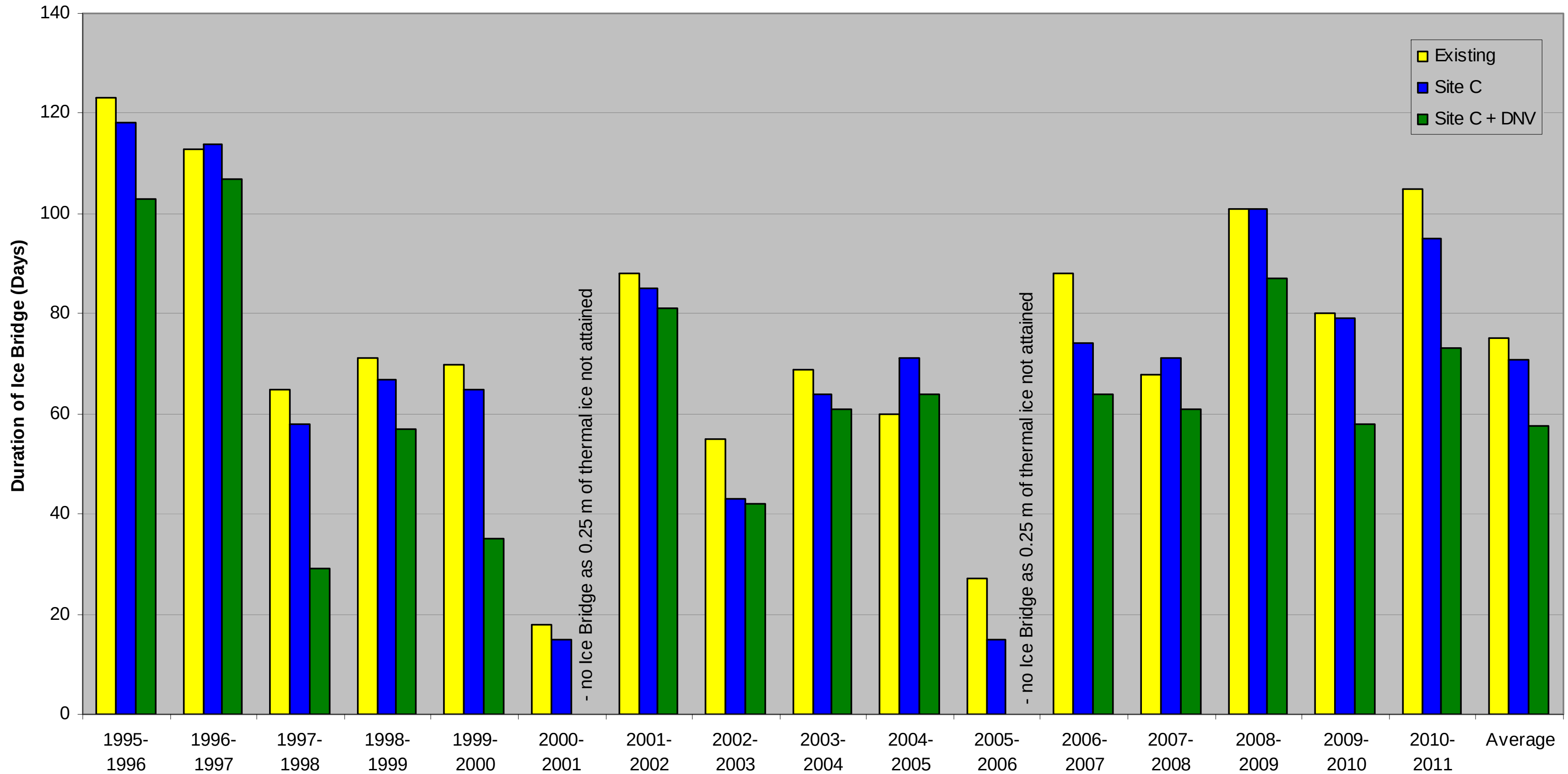

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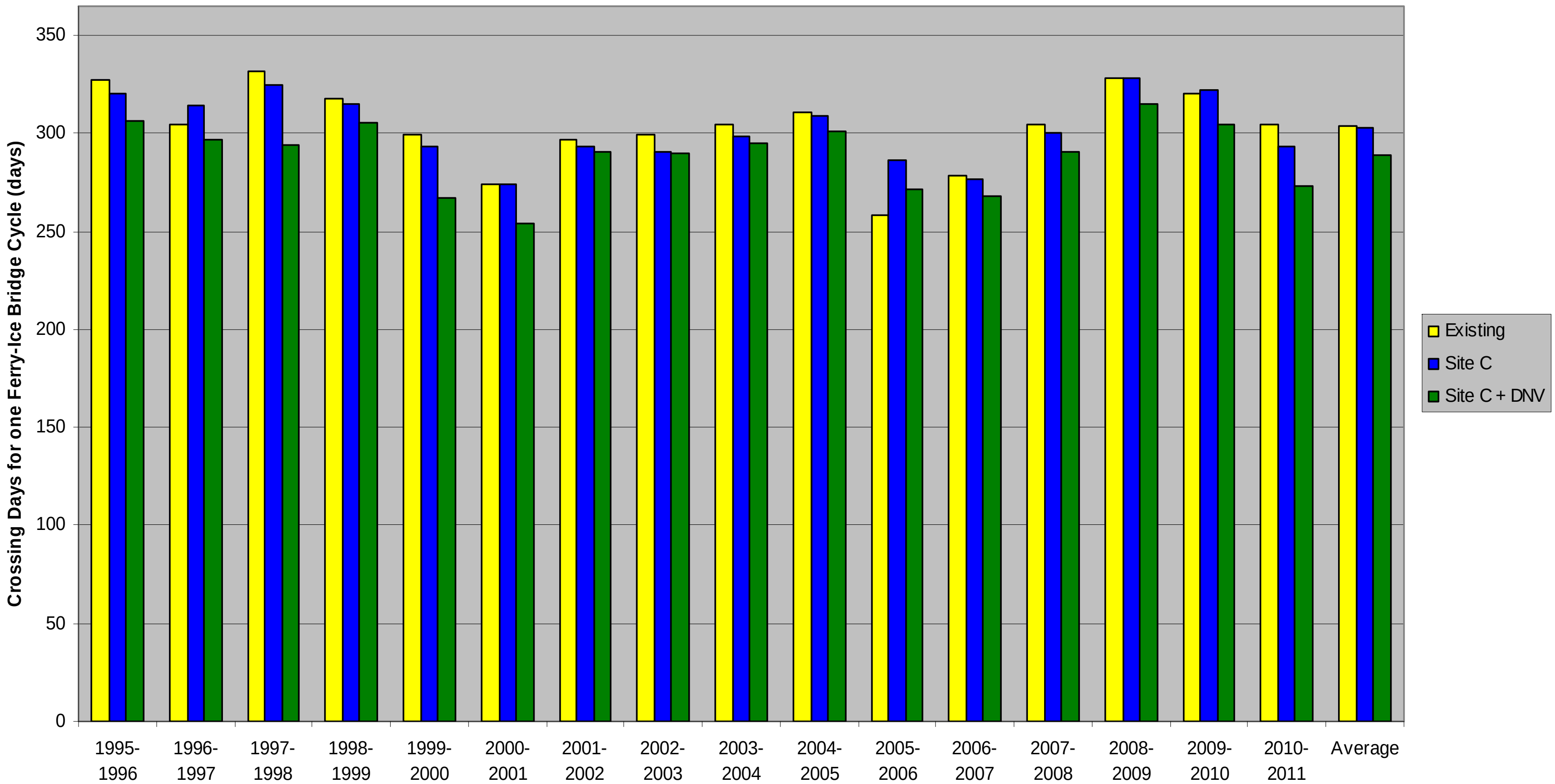
Figure 20 Simulated Duration of Shaftesbury Ice Bridge Crossing



NOTES:
1. PERIOD IS CALCULATED FROM JUNE 1 TO MAY 31.
2. "SITE C" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
3. "SITE C + DNV" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

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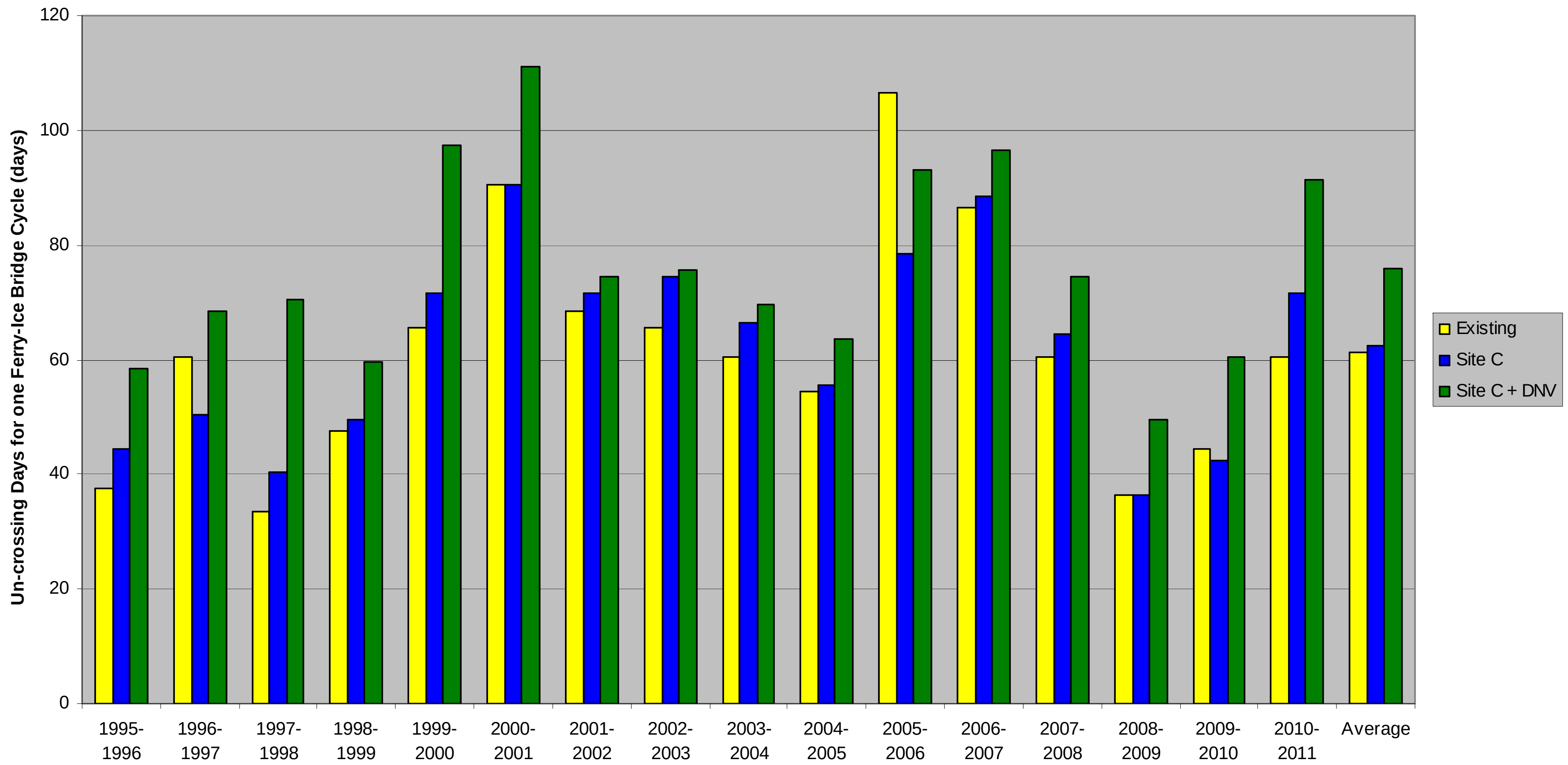
Figure 21 Simulated Annual Total Crossing Days at Shaftesbury



NOTES:
1. PERIOD IS CALCULATED FROM JUNE 1 TO MAY 31.
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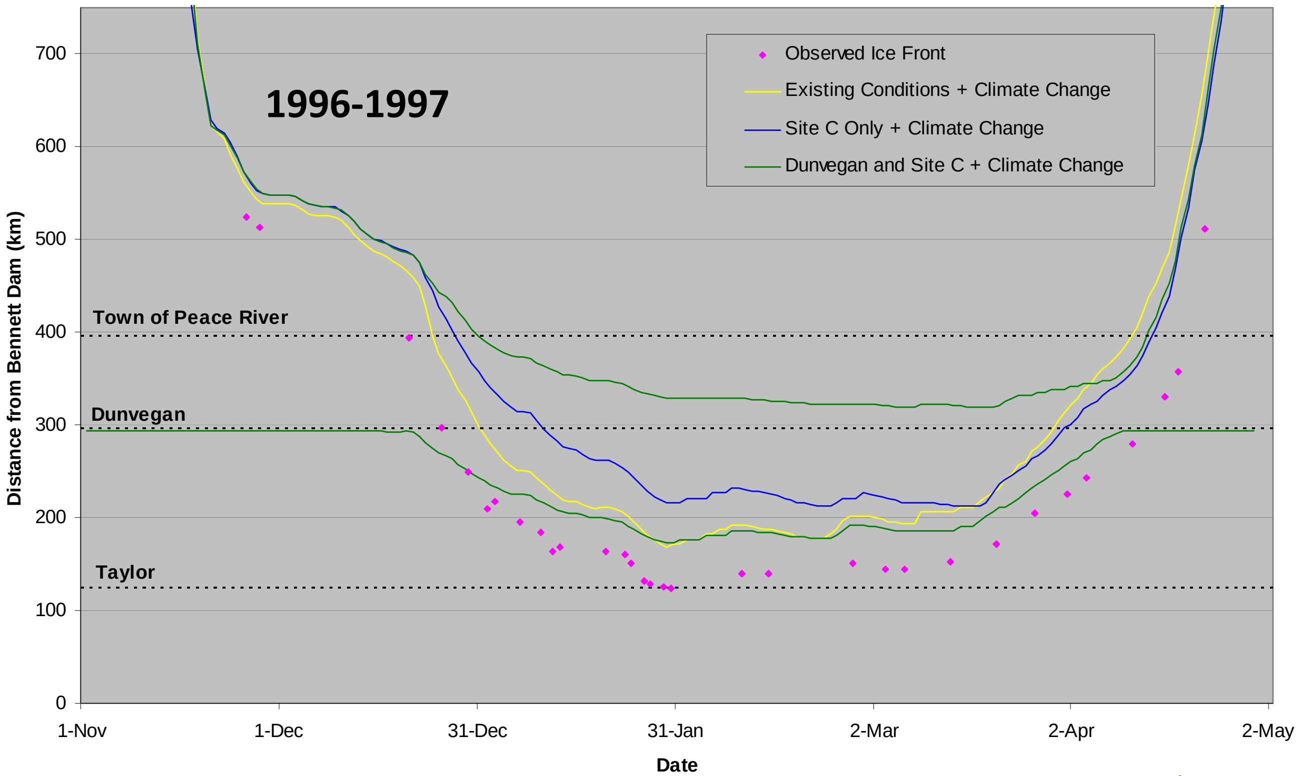
Figure 22 Simulated Annual Total Un-Crossable Days at Shaftesbury



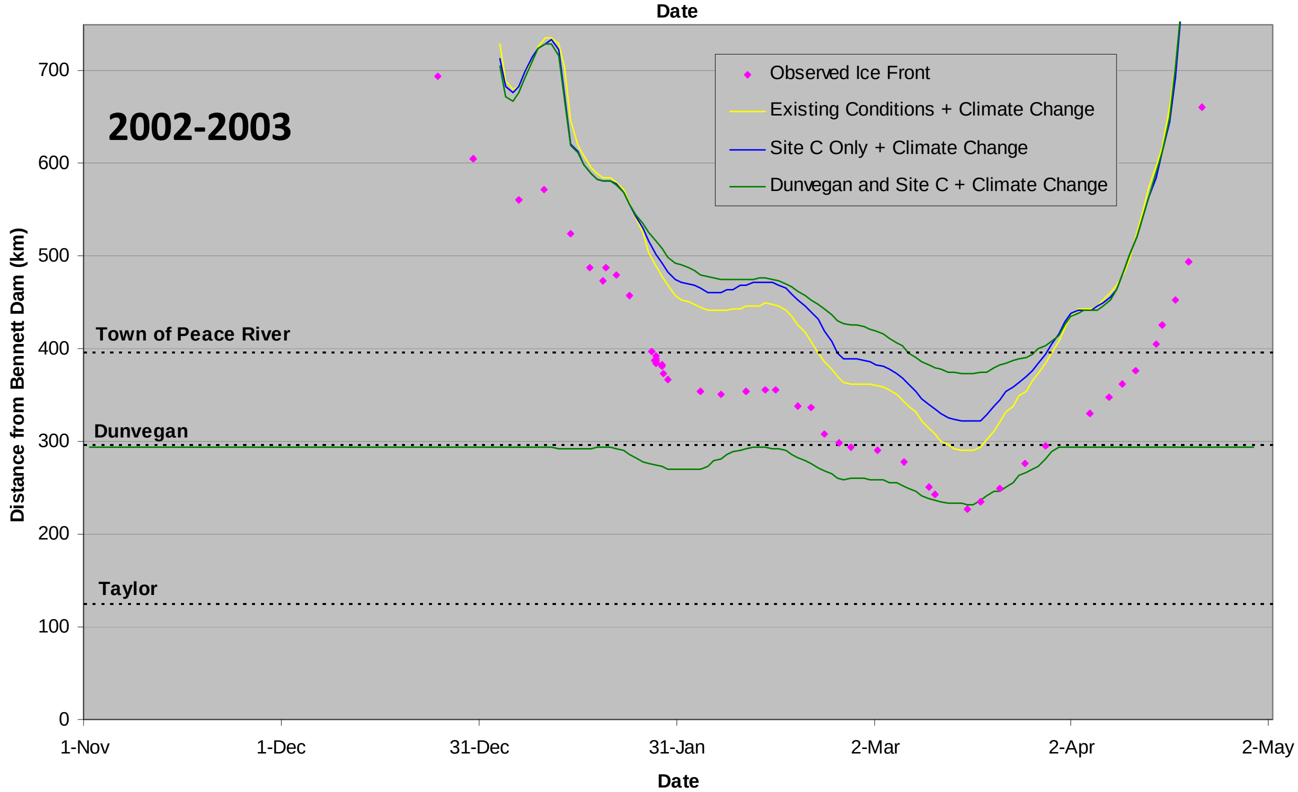


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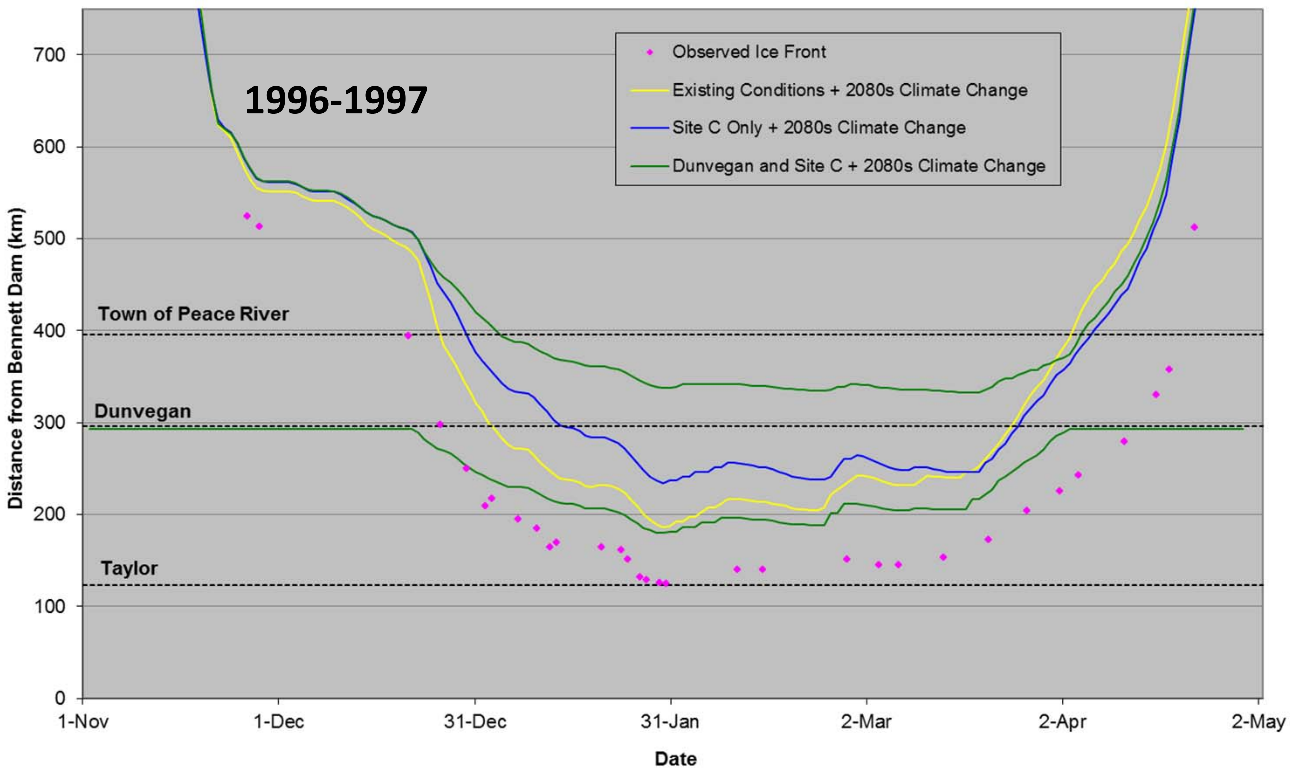
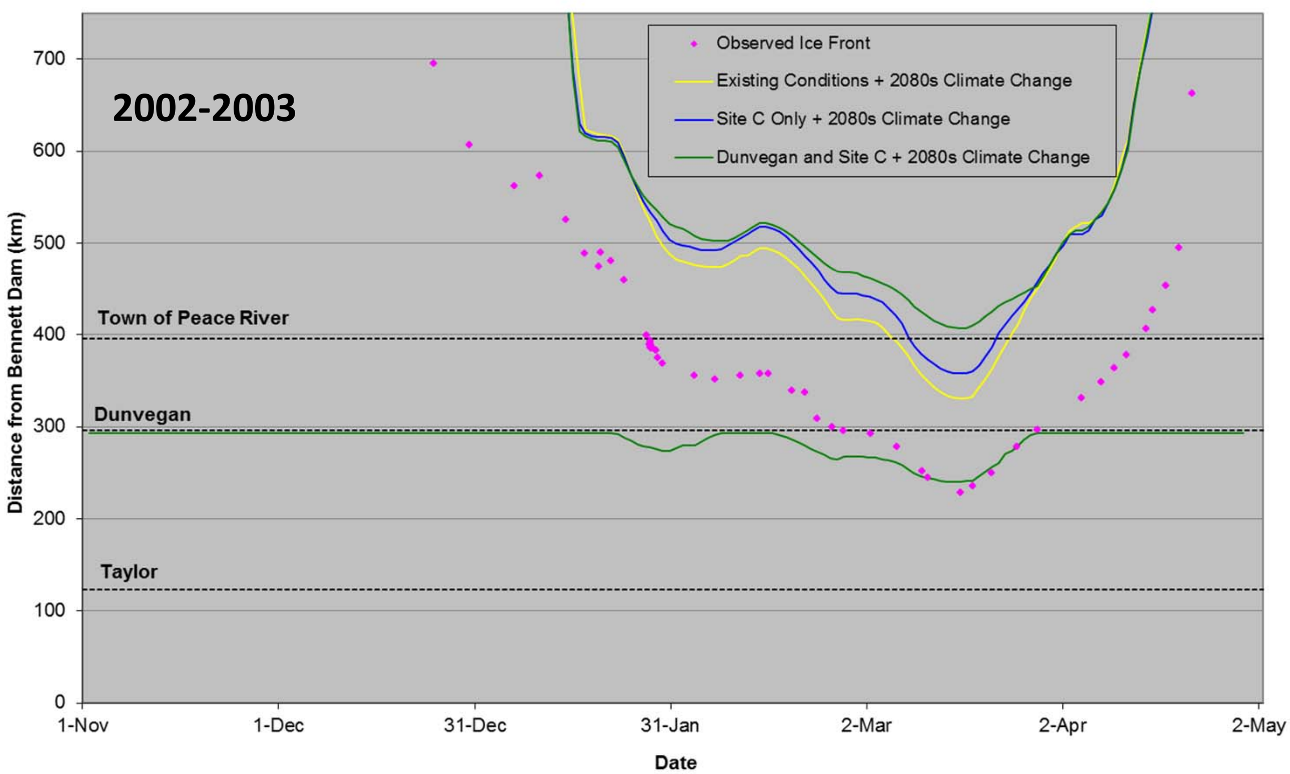
Figure 23 Simulated and Observed Ice Front Progression under a 2050s Climate Scenario (1996-1997 and 2002-2003)





NOTES:

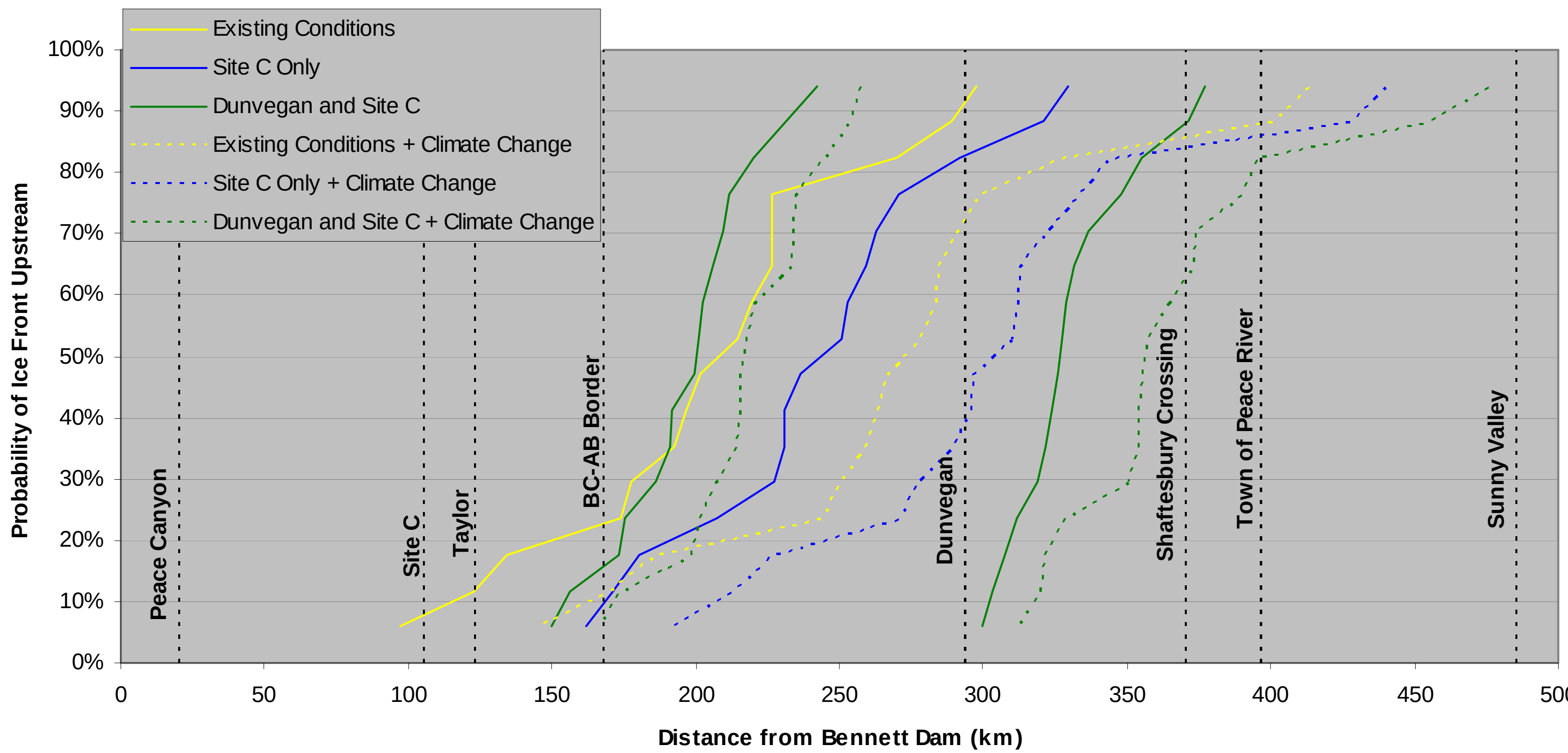
1. "SITE C ONLY" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
2. "DUNVEGAN AND SITE C" REFERS TO THE MODEL SCENARIO WITH THE PROJECT AND THE PROPOSED DUNVEGAN PROJECT.

Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification

BC hydro

SITE C CLEAN ENERGY PROJECT

Figure 24 Simulated and Observed Ice Front Progression under a 2080s Climate Scenario (1996-1997 and 2002-2003)



NOTES:
1. "SITE C ONLY" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
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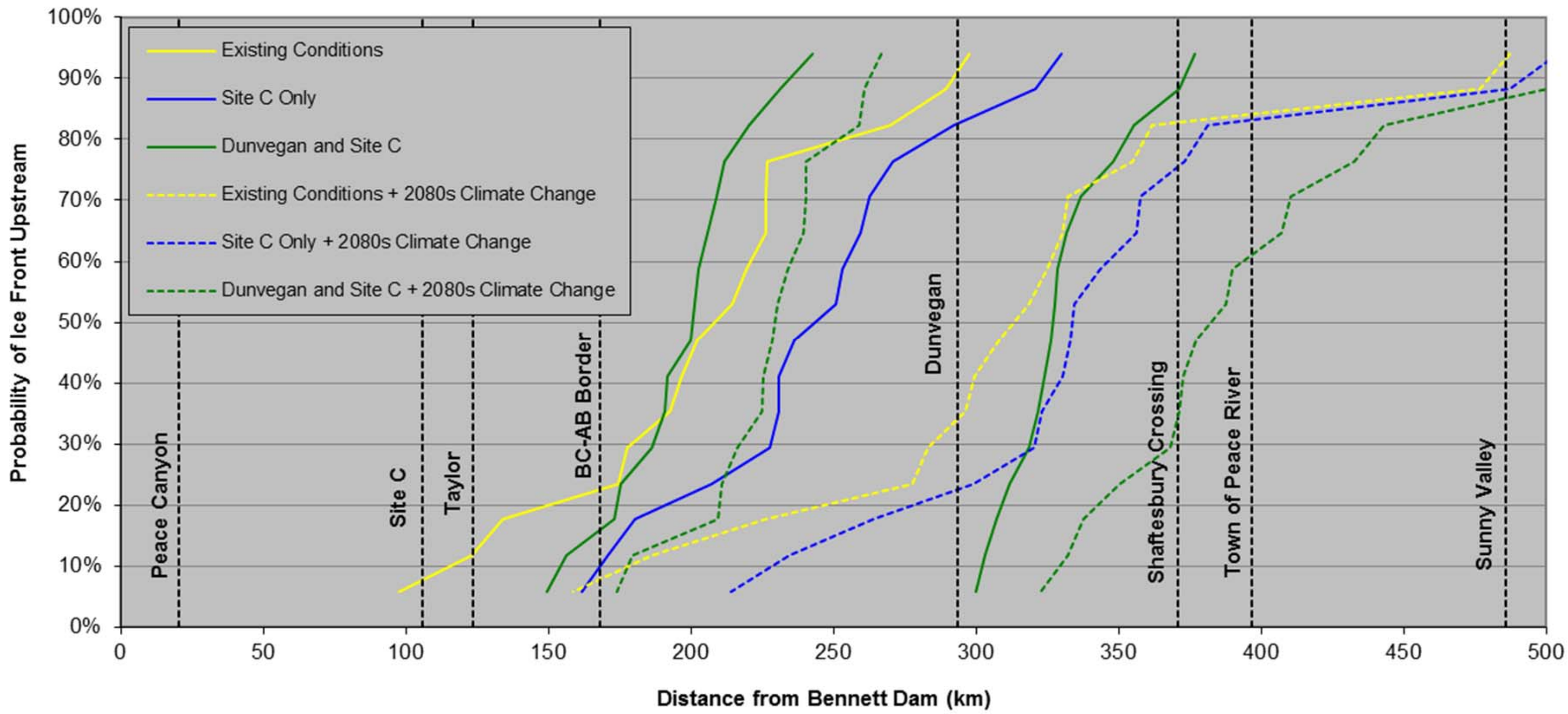
Construction of the Site C Clean Energy Project is subject to required regulatory approvals including environmental certification

BC hydro

SITE C CLEAN ENERGY PROJECT

Figure 25 Simulated Probabilities of Maximum Upstream Extent of Ice Cover for Baseline Climate and 2050s Climate Scenario



NOTES:

1. "SITE C ONLY" REFERS TO THE MODEL SCENARIO WITH THE PROJECT.
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SITE C CLEAN ENERGY PROJECT

Figure 26 Simulated Probabilities of Maximum Upstream Extent of Ice Cover for Baseline Climate and 2080s Climate Scenario

APPENDIX A

Operations during Freeze-up and Break-up

The following is a summary of the most up to date procedures from the latest Alberta – British Columbia Joint Task Force on Peace River Ice Manual, 4th Edition (2010) as well as from monitoring procedures that support Joint Task Force decisions and operations. The procedures are continuously being evaluated and updated to better balance the risk of ice jam related flooding with hydropower optimization. They could change in the future but for the purpose of the Downstream Ice Regime Technical Data Report, it was assumed that the procedures would be the same if the Project is built.

A1. Operations during Freeze-up at the Town of Peace River

The progression of the ice front downstream of the Town of Peace River is monitored by a combination of ground-based observers, aerial reconnaissance flights, satellite images, water level gauge and web cameras. Information on ice front location, water levels, ice thicknesses, ice cover types (consolidated or juxtaposed) are collected and frazil ice pan thickness and suspended frazil ice are also measured. Resources from Alberta Environment and BC Hydro are used for this monitoring. The Town of Peace River also have observers when freeze-up or break-up are occurring close to Town.

Using the ice front observation as guidance, the CRISSP model is used by BC Hydro to forecast the arrival of the ice front at a point downstream of the Town of Peace River (km 411). This location is called the “rendezvous point”; a location where the “control flow” and the ice front are targeted to meet. When the forecast shows that the arrival of the ice front is due to arrive at this point in two days, “control flow” is implemented at the Peace Canyon generating facility. This allows time for the control flow to reach the Town just before the ice front arrives so that a stable ice cover forms at the appropriate level at the Town. While this operational protocol works well in most of the years, aberrations occur every now and then. During the freeze-up in January-February 2012, the ice stalled just downstream of km 411, which made it difficult to forecast the timing of control flow. In that year the Joint Task Force operators assumed a “rendezvous point” of km 401 with three days travel time instead two. However, for the purposes of the current study, a rendezvous point at km 411 with an advance of 2 days was used to evaluate the influence of the Project on control flow durations.

Control flow is a more or less steady medium to high discharge (considering the annual range of operational flow releases) that promotes a freeze-up water level that is (i) not too high so as to compromise the freeboard that guards against overtopping of the Town of Peace River dykes due to secondary consolidations and (ii) not too low to prevent flows from being increased later in the winter as the need for hydropower increases. The latter could result in secondary consolidations if the flow increases coincided with adverse ice conditions. Since the 2005-2006 ice season, the control flow has been set at 1600 m^3/s at the Town of Peace River. This flow includes local tributary inflows. Depending on year to year variability, local inflows can be between 100 and 275 m^3/s, requiring a discharge out of

Peace Canyon of between 1325 to and 1500 m^3/s. (For comparison, full plant discharge is 1982 m^3/s.) While on control flow, 4 hours of peaking or anti-peaking is permitted to help meet daily peak electricity loads, with the remaining 20 hours of the day being held constant. The daily peaking flows of 4 hours attenuates sufficiently by the time the flows reach the ice front so as to not disrupt the ice cover. The daily average discharge has to meet the control flow target.

The 1600 m^3/s control flow is to help target a freeze-up elevation at the Town of Peace River of 315.0 m elevation at the Water Survey of Canada gauge. If the freeze-up produces an elevation greater than 315.5 m the Joint Task Force considers recommending measures to bring the level down below 315.5 m and preferably down to 315.0 m in order to provide sufficient freeboard below the dykes to contain a secondary consolidation. The dyke elevation in the vicinity of the Water Survey of Canada gauge is at 320.5 m.

Various factors influence the actions the Joint Task Force will recommend and are not in the scope of this report but they would be based on things like the weather forecast, the distance that the ice front is upstream of the town, the likelihood of having another consolidation occurring after a secondary consolidation has already occurred. Historically, the Joint Task Force has recommended reducing flows (2005) and increasing flows (2008). The latter action may seem counter intuitive but increasing flows flushes out frazil ice that can reduce water levels in the long term more so than decreasing flows. This was a successful operation in 2008.

Control flow at freeze-up remains in place until the ice cover is deemed stable enough to resume normal operations at the Peace Canyon Dam. This is determined by measuring the thermal ice thickness between a point just upstream of the Town of Peace River (McLeod Cairn – km 387) and Dunvegan Bridge (km 296). The thermal ice has to reach 0.4 m in thickness over a length of at least 10 km in this reach for BC Hydro to come off control flow (Jasek, 2006). Normally, one would expect the thermal ice to be thicker at the downstream end of the reach since that ice has had more time to grow. However, this is not always the case as variations in snow fall on the ice cover due to the timing of ice cover formation as well as spatial variability can cause thicker thermal ice further upstream. When a thermal ice thickness of 0.4 m is reached, BC Hydro can ramp up to the required discharge value at a maximum daily average rate of 150 $m^3/s/day$.

In addition to ground based monitoring at freeze-up, the Town of Peace River staff also have to shut storm sewer outlet gates to prevent the river from backing-up into the storm sewer system, which could cause overland flooding if high freeze-up water levels are unusually high. With the storm gates closed all winter, runoff from any mid-winter snowmelt or rain events has to be pumped out from of the storm drains and into the river in order to prevent surface water drainage problems and adversely high groundwater levels in the community.

Operations during Break-up at the Town of Peace River

If the snowpack in the lower Smoky River basin is above normal and the Peace River ice front is upstream of the Town, the Joint Task Force carries out intensive monitoring of the Peace and Smoky Rivers. As warm weather in April occurs, daily aerial observations are conducted on both rivers and other tributaries. A pre-break-up level of 314.0 m is used as an alert level for monitoring of unregulated inflows and Peace Canyon releases. If the discharge at the Town is greater than 2000 m^3/s, the Joint Task Force then forecasts total flows for up to 3 days in advance. If these flows are forecast to exceed the theoretical discharge of 3200 m^3/s that could overtop the dyke under ice jam conditions (Andres 1996), the Joint Task Force would then recommend that the Peace Canyon releases be reduced in order to reduce the possibility of the 3200 m^3/s being exceeded. Historically, there were instances where Peace Canyon discharge has been backed down to minimum (about 300 m^3/s) for several days in order to meet this criterion.

It is possible that the 3200 m^3/s limit could still be exceeded with Peace Canyon releases down to minimum. Due to the flashy nature of the Smoky River, and the travel time for flow changes to arrive at the Town of Peace River from Peace Canyon, operations at break-up can be challenging. However, Alberta Environment has recently developed a run-off model for the Smoky Basin that can be used as a predictive tool. This forecast tool was not available for the 2007 break-up where the 3200 m^3/s criterion and possible flooding was narrowly averted (Jasek, et al. 2007). As of this writing Alberta Environment continues to make improvements to the Smoky River run-off model.

The Town of Peace River also have observers monitoring the break-up on the Peace River close to Town as well as at the mouths of the Smoky and Heart rivers that have the potential to cause local spring break-up flooding independent of break-up on the Peace River.

APPENDIX B

CRISSP Calibration

Introduction - History of Numerical River Ice Modelling on the Peace River

Prior to the present ice study, a great deal of river ice modelling work has been undertaken for the Peace River. This work has been largely driven by the Dunvegan Hydro Project proposed by Glacier Power Ltd. (since purchased by TransAlta Corporation). In 2002, BC Hydro used the RICE model (River Ice - the predecessor to CRISSP) to ascertain the influence on the ice regime of a proposed run-of-river Hydro Project near Dunvegan, about 100 km upstream of the Town of Peace River. Glacier Power Ltd. retained Trillium Engineering and Hydrographics Inc. to apply the TRICEP (TRillium Engineering ICE model of the Peace River) model to answer many of the same questions being addressed herein. Due to knowledge gaps in the Peace River ice regime specifically, and the state of knowledge of river ice modelling in general, additional studies were recommended after the 2002 Dunvegan Project hearing.

Subsequently, a study group with members from BC Hydro, Alberta Environment and Glacier Power Ltd. undertook a two-year field study to fill in knowledge gaps (Trillium Engineering and Hydrographics Inc., 2004). Near the end of the completion of this study, Trillium merged with Northwest Hydraulics Consultants Ltd. Once the fundamental data was gathered, Glacier Power Ltd. contracted Dr. Shen, Clarkson University to develop a Peace River Ice (PRICE) model to simulate the influence of the Dunvegan Project on the ice regime of the Peace River. Experts from BC Hydro and Alberta Environment partook in this endeavour as well. The CRISSP model was not available for two more years but essentially the PRICE model contained the same computational engine as CRISSP.

Once CRISSP was completed in 2006, BC Hydro ran its own calibration and simulations to model the influence of Dunvegan. The same cross sections were used as in the PRICE model since extensive work was carried out by NHC (with technical input from BC Hydro) to develop this simplified yet practical and sufficiently accurate geometry.

The starting point for the CRISSP model calibration was the calibrated parameters used in the PRICE model. However, there were some slight differences between the two models and so some of the calibration coefficients were adjusted so the results from the CRISSP model provided a better fit to the field data. Once the CRISSP model was calibrated the results were close to those produced by the PRICE model.

In 2008 the Dunvegan Project received environmental approval, largely because the major stakeholders were comfortable with the predictions of the river ice modelling that was undertaken. It was also helpful that both PRICE and CRISSP showed similar results. Since 2006, the CRISSP model has been used operationally with very good success. Operational usage provided opportunities to make additional improvements in the calibration and these have been incorporated into this study.

The University of Alberta has also conducted numerical simulations of ice processes on the Peace River. These were carried out using their RIVER1D model described in two documents - Andrishak and Hicks (2008) who simulated the ice regime on the Peace River to assess the influence of climate change on the ice cover duration and She, et al. (2012) who simulated the 1982 freeze-up and secondary consolidation.

CRISSP Calibration

As mentioned above, the CRISSP model was originally calibrated for the Peace River in 2006 and has been used operationally since then with minor improvements to the calibration along the way. The cross sections and starting calibration coefficients were those established in the PRICE model developed by Andres and Healy (2006) for the assessment of changes related to the proposed Dunvegan Hydro Project. When these were incorporated into CRISSP, the ice cover advanced too quickly and the freeze-up water levels were too low, because the total ice cover thickness was too thin. This suggested that the two models were slightly different and further calibration was needed.

The single most important output variable that required accurate prediction was the ice front position, as many socio-economic and environmental questions are related to the timing of freeze-up and break-up and the duration of the ice cover. There are many input variables that affect the progression and recession of the ice cover. These can be classified into three groups:

1) Heat transfer at the air-water interface:

- affects the simulation of the water temperature
- affects how much ice is generated and the ice discharge at the ice front, thus affects the rate of ice front progression.

2) Ice cover characteristics, including porosity of the incoming floes, the resulting porosity of the ice cover after the floes arrive, and the geotechnical constants that describe how the granular material (frazil pans and slush) behave as a floating granular material:

- affects the thickness of the ice cover and therefore the rate of ice front progression
- affects water level increases at freeze-up

3) The hydraulic roughness of the ice cover:

- affects how much downstream friction force from the water is applied to the underside of the ice cover (higher roughness increases this force which results in a thicker the ice cover and therefore reduces the rate of ice front progression)
- higher ice roughnesses reduce flow velocities and increase the depth of flow under the ice cover in addition to thickening the ice cover (the two influences combine to increase the freeze-up water level)

The complex interdependence of a multitude of variables made the calibration of the model a challenge requiring several iterations. Four winters were used for the calibration, including the three most recent for which the most comprehensive dataset was available (2002-2003, 2003-2004, 2004-2005) and a cold winter 1995-1996. Winter 2002-2003 was used the most extensively. Additional runs were performed for the other winters to confirm and fine tune the calibration based on the 2002-2003 runs.

A list the more important and relevant parameters are described below.

B1. Heat Transfer at the Air-Water Interface

Since a complete set of meteorological parameters for the Peace River are not available, the "linear approximation" option for surface heat exchange was used in CRISSP to simulate the heat transfer at the water surface. This option or approach is quite common in most river ice simulations and accounts for the majority of the physical processes. The most common form of linear approximation considers the heat transfer as the sum of two components: a convective component that is proportional to the difference between the water and air temperature and a temperature independent component that represents short wave solar radiation,

$$\text{Total Heat Exchange} = hwa\,(Tw - Ta) - RN$$

> where Tw is the water temperature, Ta is the air temperature and RN is the net short wave radiation computed from considerations of latitude, cloud cover conditions, and the albedo of ice and water. The only variable that needs to be calibrated for specific regional conditions is the heat transfer coefficient hwa ($W/m^2/^oC$). More details about the modelling of the heat exchange can be found in Shen (2005).

Measured water temperatures in the Peace River were used to calibrate the heat transfer coefficient. There are two features of the observed water temperatures that one should try to reproduce in the model. The simulated water temperatures should follow the observed temperatures in response to warm and cold periods and there should be an approximately equal number of observed data points above and below of the simulated water temperatures (over all fit). The model should also be able to simulate reasonably well the location and timing of the zero-degree isotherm (when and where the water temperature reaches the freezing point). The latter condition is perhaps more important to satisfy as it determines when ice production starts and ceases which determines when the ice fronts advances and stalls, and when recession of the ice cover starts and stops.

Results from both PRICE and CRISSP indicated that a range of heat transfer coefficients could satisfy either the overall fit to the water temperature data and the zero-degree isotherm. The PRICE and CRISSP results showed that choosing a higher heat transfer coefficient at the high end of the range would produce a better overall fit to measured water temperatures, but a poorer prediction of the zero-degree isotherm. Choosing a lower heat transfer coefficient would better simulate the location of the zero-degree isotherm. Andres and Healy (2006) selected a heat transfer coefficient of 20 $W/m^2/^oC$ as a compromise.

However, a heat transfer coefficient of 17 W/m^2/^{o}C was selected herein after many calibration runs because a higher priority was placed on properly simulating the timing of the zero-degree isotherm, which in turn would produce a better simulation of the ice front. The downside to this approach was that simulated water temperatures in the fall were slightly higher than measured. However, as there were no ice processes taking place when the water was relatively warm, this was not a big issue for simulating the ice regime. In the spring, the heat transfer coefficient has little influence on the water temperature as the solar radiation plays the dominant roll in the recession of the ice cover.

There could be several reasons why both the overall fit and the timing of the zero-degree isotherm cannot be simulated accurately with one heat transfer coefficient. The first that comes to mind is the selection of the cross-sections whose shapes are then break-up optimized to best represent ice cover formation within the active portion of the main channel. If the amount of ice generated by the model and that which arrives at the ice front is simulated accurately, this helps to ensure accuracy of the predicted ice front progression. However, the optimized cross sections are slightly narrower and deeper than the actual river. Therefore to simulate the cooling of the water correctly a higher heat transfer coefficient is needed since the surface area is slightly smaller.

Another factor is the potential for the dampening of water temperature fluctuation by the river bed. In both models the heat exchange between the bed and the water is neglected; essentially, the river is behaving such as if it is flowing over an insulated boundary. In reality, the bed of the river is responding to the changing water temperature. When the river is cooling down the bed is warmer than the river water and is releasing heat into the river. When the river is warming up the bed is cooler than the river and heat is being withdrawn from the river. This may account for the fact that measured temperature fluctuations in the river are smaller than those simulated no matter what heat transfer coefficient is chosen. This is separate from the geothermal heat flux that has been considered to be negligible in river ice processes.

Another uncertainty is the tributary water temperature. There are no consistent water temperature measurements of tributaries available and it is assumed in the model that the tributary water temperatures enter the Peace River at the ambient water temperature of the Peace River. This assumption is valid over most of the year except for early fall and late spring when the tributary inflows are greater and the tributary temperatures could deviate from the main stem water temperatures. However, since most of the ice processes occur in late fall, winter and early spring this assumption does not adversely affect the prediction of changes to the ice regime to a large degree.

B2. Hydraulic Roughness of the River Bed

Since the PRICE cross sections were first obtained from NHC, some minor modifications have been made to the geometry as well as the bed roughnesses. As experience was gained with forecasting the arrival of the ice front at the Town of Peace River for operational purposes, it was noted that there was a slight bias towards an earlier simulated arrival of the ice front at the Town of Peace River. It was apparent that model produced slight discontinuities in ice discharge at locations where the bed roughness and/or the bed slope changed abruptly. An updated version of the model addressed this problem to some degree but the breaks in bed slope and sudden changes in bed roughnesses still had to be smoothed to get rid of the remainder of the discrepancy. This improved the accuracy of computing the ice front arrival at the Town of Peace River while not affecting the accuracy of the ice front arrival at other locations. In the PRICE model the bed roughness varied from 0.019 to 0.034, and was varied on a reach by reach basis to better reflect open water levels at gauging sites. A constant bed roughness of 0.03 was chosen in CRISSP because it was decided that it was more important to reproduce the ice front timing then the accuracy of open water levels.

B3. Hydraulic Roughness of the Ice Cover

A large amount of winter water level and ice thickness data has been collected since the 2002-2003 winter. River stage data from two of these winters were used to calibrate the roughness of the underside of the ice cover. A total of 7 water level stations between Dunvegan (km 295.6) and the Town of Peace River (km 396.7) for the 2002-2003 winter, and a total of 13 stations between Dunvegan (km 295.6) and the McCracken Flats (km 522.2) for the 2003-2004 winter were used in the calibration. However, as the ice formation (and subsequent ice thickness) has a stochastic and unpredictable component, the calibration cannot be expected to give accurate results every year. The CRISSP model has two separate ice roughness parameters: one describing conditions at the start of freeze-up when roughness is typically higher, and a second ice roughness for the late spring after the underside of the ice cover has been smoothed over the winter. In early winter Manning ice roughness coefficients ranged from 0.031 to 0.078 and late winter roughness coefficients ranged from 0.011 to 0.042 with one extreme value near one gauge of 0.003. Although a small portion of these values may be considered outside of the normal range expected, the large variability was necessary to compensate for local river geometry variability not accounted for by the approximate cross sections as well as for noise introduced by the stochastic nature (year to year variability) of the river ice freeze-up process.

B4. Ice Cover Characteristics

For the calculation of total ice cover thickness using the wide-jam equation (Uzuner and Kennedy, 1976), several variables that describe ice cover characteristics need to be prescribed. The ice internal frictions angle, the lateral thrust coefficient and the porosity of the ice cover can all be combined by an equation (Andres and Healy, 2006) to determine the ice jam coefficient □, which is ultimately the parameter that determines the total ice cover thickness of a consolidated ice cover.

The ice internal friction angle of 43^o was chosen herein. This is about the middle value between 40^o and 45^o that can be found in the literature. The default value in CRISSP of 0.342 for the lateral thrust coefficient was used. The porosity of the ice accumulation immediately after it forms is determined implicitly in CRISSP and it depends on the porosity of the slush under the solid crusts of the ice pans (specified as 0.67 – determined from PRTIGM* calibration) as well as the thermal ice thickness (crust thickness) of the ice pans (calculated by CRISSP).

* (Peace River Thermal Ice Growth Model – Jasek (2006) describes the calibration)

Thus the porosity of the ice cover can vary in space and time depending on the thicknesses of the ice pan crusts and the thickness of slush underneath the crusts of the ice pans that are arriving at the leading edge of the ice cover. A typical example on the Peace River would be ice pans with total thicknesses of 0.60 m and ice crusts of 0.12 m. If such ice pans make up an ice cover at a particular location and time, the combined porosity there would be about 0.46. In this example and from the ice jam parameters specified above, the ice jam coefficient □ would be about equal to 0.9. The jams on the Peace River were assumed to be cohesionless, as this has been the general practice in ice jam studies.

B5. Undercover frazil slush erosion, transport and deposition

Initial runs of the CRISSP model had allowed for the transport of frazil slush underneath the ice cover (an option that can be deactivated if desired). Essentially, this would allow slush to be eroded from the higher velocity areas and deposited in lower velocity areas with the amount of transport being limited by the transport capacity criteria (Shen, 2005). However, this caused simulated water levels to deviate from those observed. Slush was being deposited in certain locations causing the water level to increase slowly for several weeks after initial ice cover formation. This does not happen in reality; the water levels tend to drop slowly over the course of the winter as the frazil slush is redistributed from high velocity areas (in the main channel) to low velocity areas (under the border ice and into side channels). This is a two-dimensional process and is impossible to simulate with a 1D model. Therefore, for the simulations using CRISSP 1D in this study the frazil erosion and deposition options were turned off in the model and the reduction in water level due to redistribution of frazil was simulated empirically by adopting a time-dependent decaying Manning ice roughness coefficient (Shen, 2005).

In previous studies using the PRICE model, Andres and Healy (2006) simulated the deposition of suspended frazil under the ice cover. This approach was taken because there would be a potential for the Dunvegan project to increase the proportion of suspended ice to surface ice floes and the thinking was that this suspended ice would be deposited under the ice cover shortly after its formation, thereby increasing its thickness. This would then have the potential to increase freeze-up levels at the Town of Peace River. The modelling showed that this increase was only 0.2 m on average and a conservative value of 0.5 m was recommended. However, data collected by BC Hydro using an upward looking sonar instrument (Jasek and Marko, 2007, 2008) showed that most of the suspended ice comes out of suspension prior to reaching the ice front in the slow moving backwater reach just upstream of the ice front where the turbulence necessary to keep the ice in suspension is substantially less. The CRISSP model also indicated that most of the ice was coming out of suspension in this reach. Given these two independent sources of information, the assumption in this study was that an extra thickness due to increased suspended frazil ice would not occur as a result of the Dunvegan project. The Project would have even less of an influence on the ratio of suspended ice to surface ice floes since it is upstream of Dunvegan. Therefore neglecting the deposition of extra slush underneath the ice cover for the Project scenario is reasonable.

B6. Ice Cover Consolidation and Juxtaposition

Section 2.2 described the conditions under which a juxtaposed or a consolidated ice cover forms. A juxtaposed ice cover tends to form where the river slope is milder, the discharge lower than normal, and/or when the air temperatures are lower than normal. A consolidated ice cover tends to form in steeper reaches of the river and during mildly cold, average or above average air temperatures. Because a juxtaposed ice cover is only a single layer ice floe thick, it advances upstream much more rapidly than a consolidated ice cover. Historically, the change in river slope at the Notikewin River at km 565 was taken as the dividing line between a consolidated ice cover regime upstream of this point and a juxtaposed ice cover regime downstream of this location. Indeed there does appear to be a change in slope from 0.0002 m/m to 0.0001 m/m at this location (Figure 2). However, it is difficult to determine if this change in slope is as abrupt and is located precisely at this location since elevation points are limited to every few 10s or even 100s of kilometres along the Peace River. It could also be that the change in slope is more gradual and/or occurs at a slightly different location then shown in Figure 2.

As the starting point for calibration of the CRISSP model, km 565 was selected as the point downstream of which a juxtaposed ice cover always forms. As expected, this led to more rapid ice front progression downstream of this location. However, when the simulated ice fronts were compared to observed ones, it suggested that the point that demarcates the consolidated and juxtaposed reaches should be a little further downstream. The examination of river top widths on 1:50,000 scale maps indicated that Peace River gets somewhat wider at about km 625. This could be an indication that this is the location where the slope gets milder. This location was then selected as the dividing point between a consolidated and juxtaposed ice cover. This resulted in a better prediction of the ice front advance rates in this reach. An attempt was made to select a particular Froude number that would allow the model to decide at what point an ice cover was juxtaposed and when it was consolidated. However, a single value would not work for all years probably due to the effect of air temperature. It was more accurate to force the model to juxtapose the ice cover downstream of km 625 and consolidate it upstream of km 625.

It was evident from the observed ice front data that a juxtaposed ice cover could occasionally occur upstream of km 625, but only under extremely cold air temperatures, colder than about -35 ^{o}C. In those years the model was forced to juxtapose for short durations in those reaches when the air temperature was below this value. This produced a better match of the simulated and observed ice front locations. These short durations of juxtaposed ice cover were also incorporated in simulating short durations of juxtaposed ice cover for the Project and Dunvegan Project simulations as the timing of the extreme cold weather was independent of these projects.

CRISSP 1D has no method of accurately predicting secondary consolidations. Neither where and when they occur, nor where they stop or stall. Although calibration constants can be chosen such that the ice cover would collapse when a certain downstream directed loading on ice cover occurs, the resulting consolidations are chaotic and do not coincide precisely enough with those that occur in nature (which are also chaotic) and it is much more difficult to predict the overall ice cover advancement accurately. Since the observed ice front data contain instances of some secondary consolidations, the calibration includes some degree or an average amount of secondary consolidation.

B7. Heat Exchange Coefficient between Water and Ice

The exchange of heat between the water and the bottom of the ice cover is an important consideration when calculating the recession of the ice front in the spring. In CRISSP the heat transfer rate between the water and the ice is function of the mean velocity at the cross section to the power of 0.8 divided by average depth under the ice cover to the power of 0.2. A calibration constant times this ratio give the heat transfer in W/m^2/^{o}C .CRISSP also provides for a different constant depending if the water is above zero (1400) or at zero or supercooled (1000) to account for findings in the field by Shen (2005). Initially, these constants were tested in CRISSP but the recession of the ice front was highly irregular. The ice cover would thin out to infinitesimal amounts for 10s of kilometres and then suddenly disappear causing the ice front to recede 10s of kilometres in just one 30 minute time step. This does not happen in nature.

Field observations by the author and others indicate that the ice front does thin to a certain degree due to melting along its underside. However, once it is too thin to resist the hydraulic forces it collapses and forms a short reach of fragmented ice upstream of the ice front. Typically, these small “mechanical” ice front retreats are only a few hundred meters in length and occur every few minutes to hours. In order to obtain a more realistically smooth recession rate, the constant for heat exchange between water above zero and ice was increased from 1,400 to 10,000 – essentially eliminating the melting of the ice underside. This did not change the average recession rate over many hundred kilometres but just smoothed it out to reflect what happens in nature. Rather than thinning the ice cover for long reaches downstream of the ice front it melted the ice at the upstream end more quickly for shorter reaches. This change amounted to the same amount of energy going into melting the ice cover but it was more concentrated at the ice front.

B8. Thermal Ice Cover Thickness

The thermal ice thicknesses were simulated with the PRTIGM outside of the CRISSP model due to advantage described in Section 4.4.1. Calibration of the equations describing the growth of thermal ice on the Peace River is in Jasek (2006). The growth of thermal ice occurs after the after the ice cover forms so the fact that it is being simulated outside of CRISSP does not lead to inaccurate predictions of other parameters like ice front progression and ice related water levels, the latter being a function of the total ice thickness and not the thermal ice thickness.

APPENDIX C

Simulated Ice Front Plots

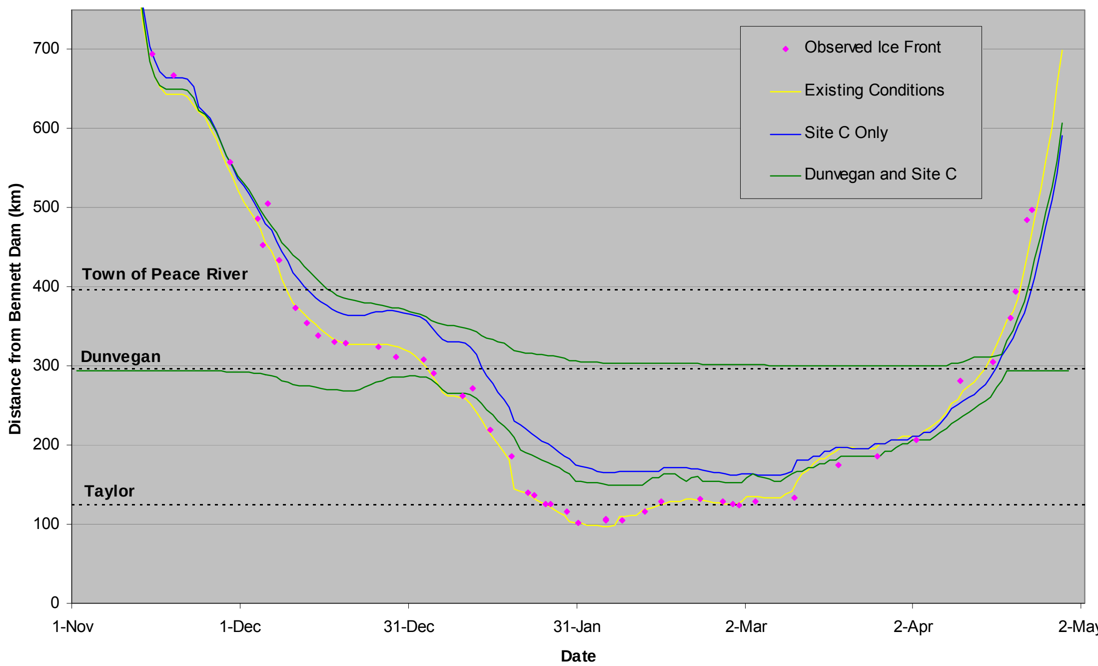

Figure C1. Simulated ice fronts for 1995 – 1996 winter.

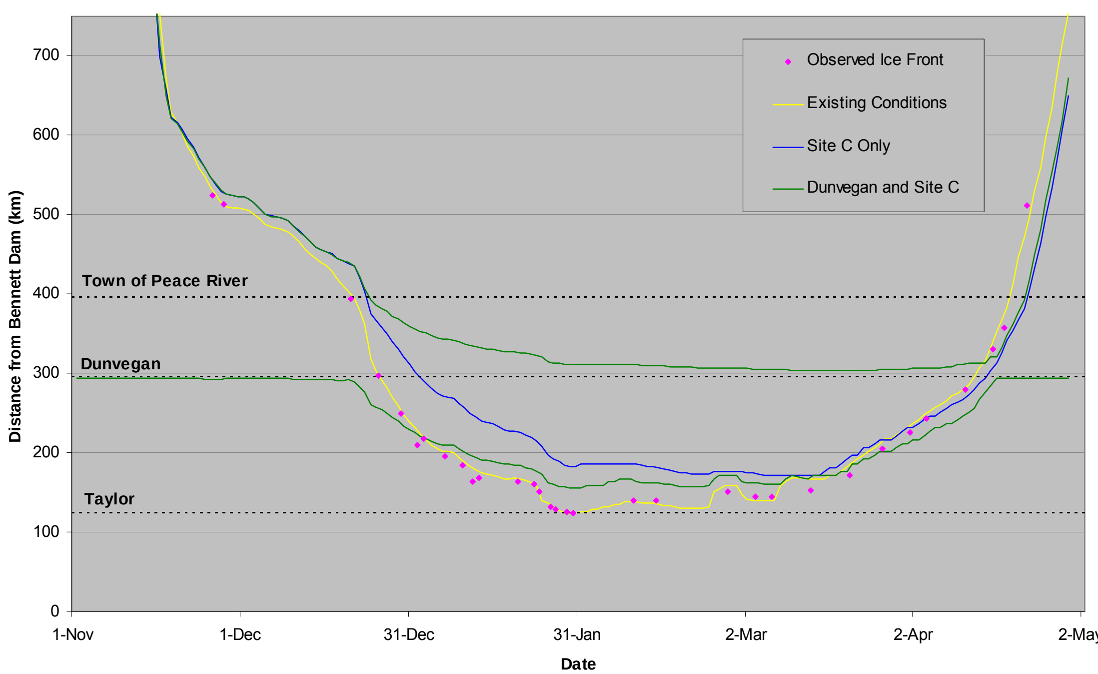

Figure C2 Simulated ice fronts for 1996 – 1997 winter.

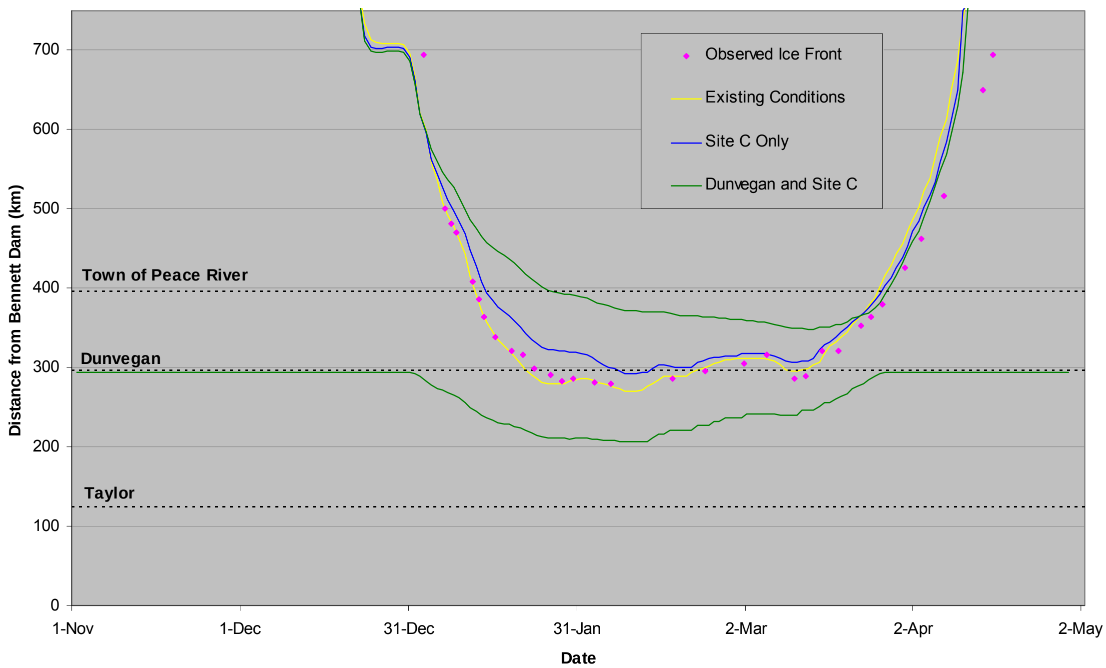

Figure C3. Simulated ice fronts for 1997 – 1998 winter.

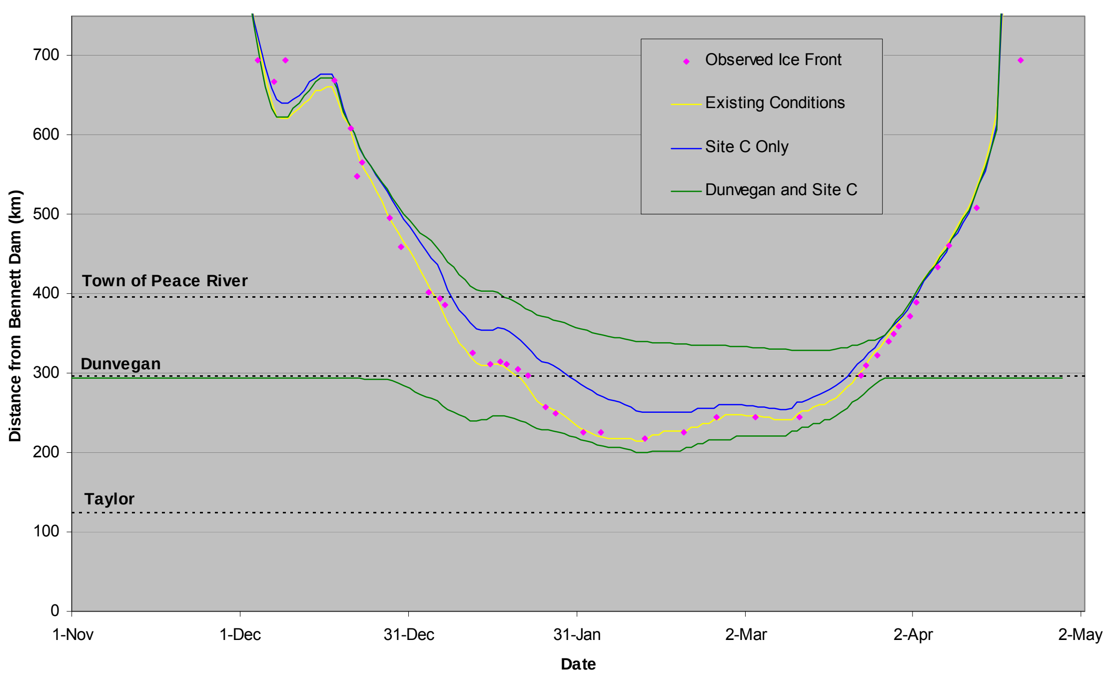

Figure C4. Simulated ice fronts for 1998 – 1999 winter.

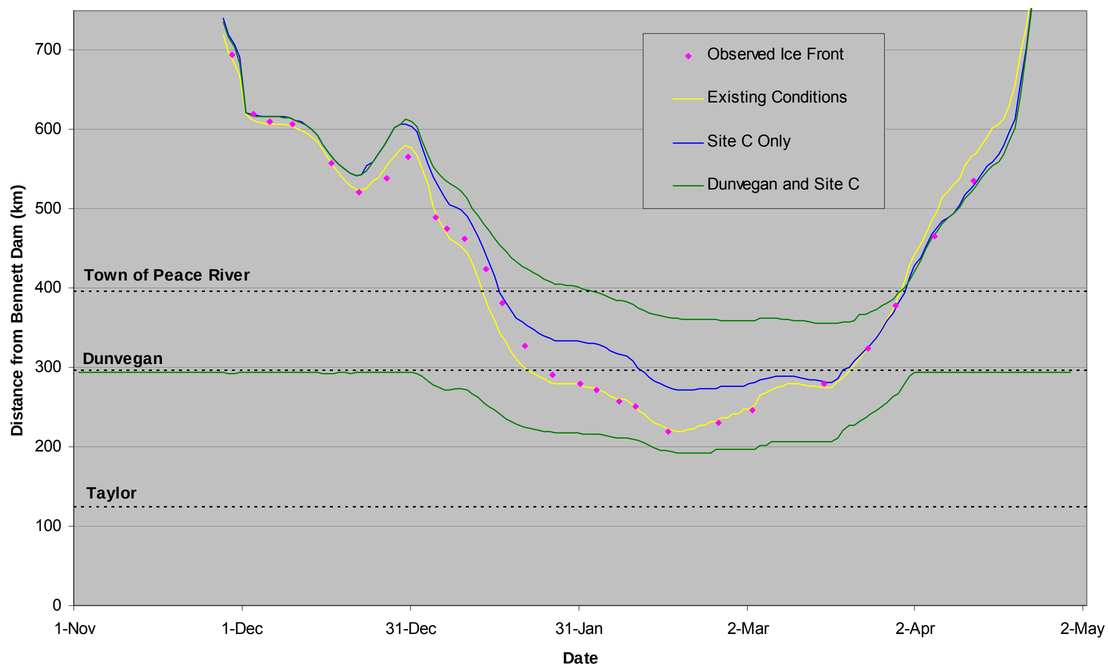

Figure C5. Simulated ice fronts for 1999 – 2000 winter.

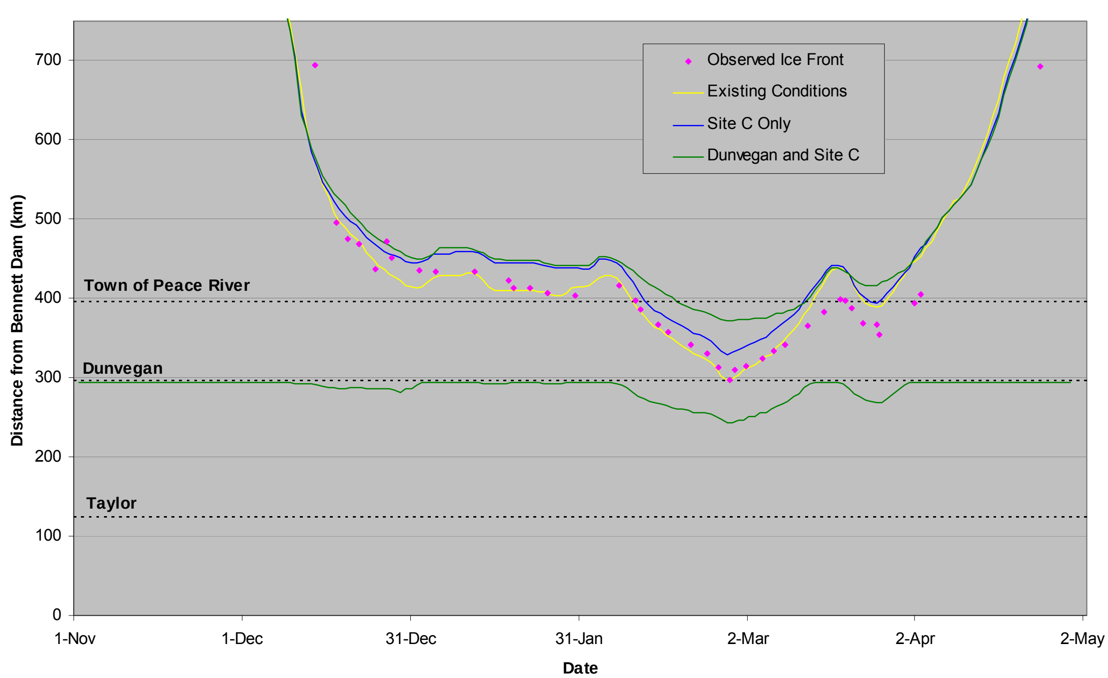

Figure C6. Simulated ice fronts for 2000 – 2001 winter.

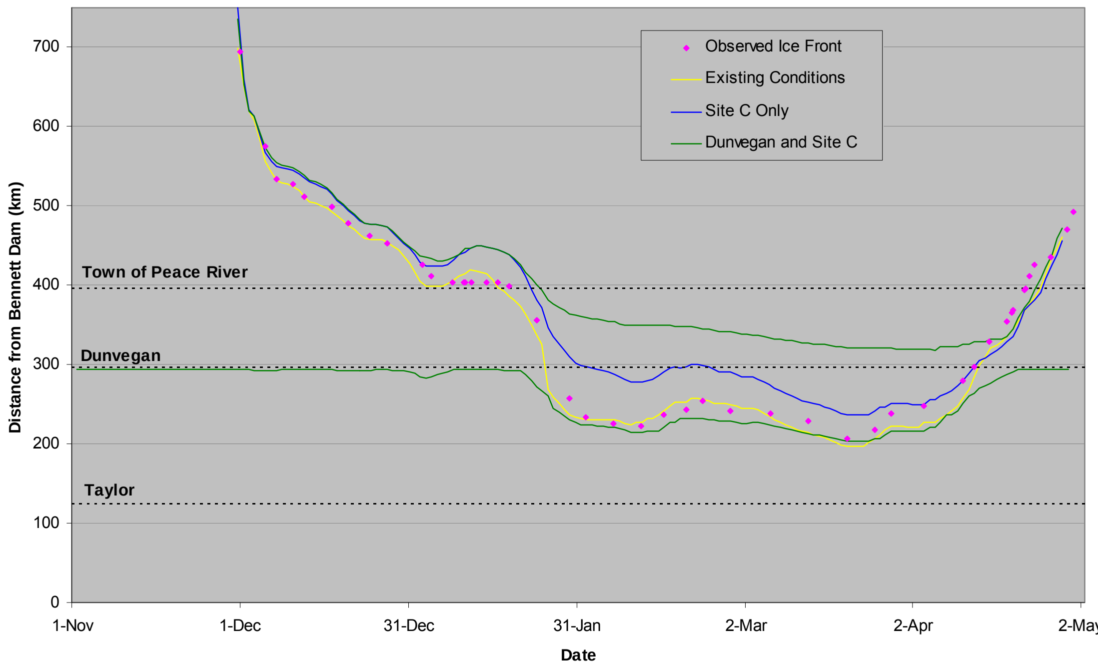

Figure C7. Simulated ice fronts for 2001 – 2002 winter.

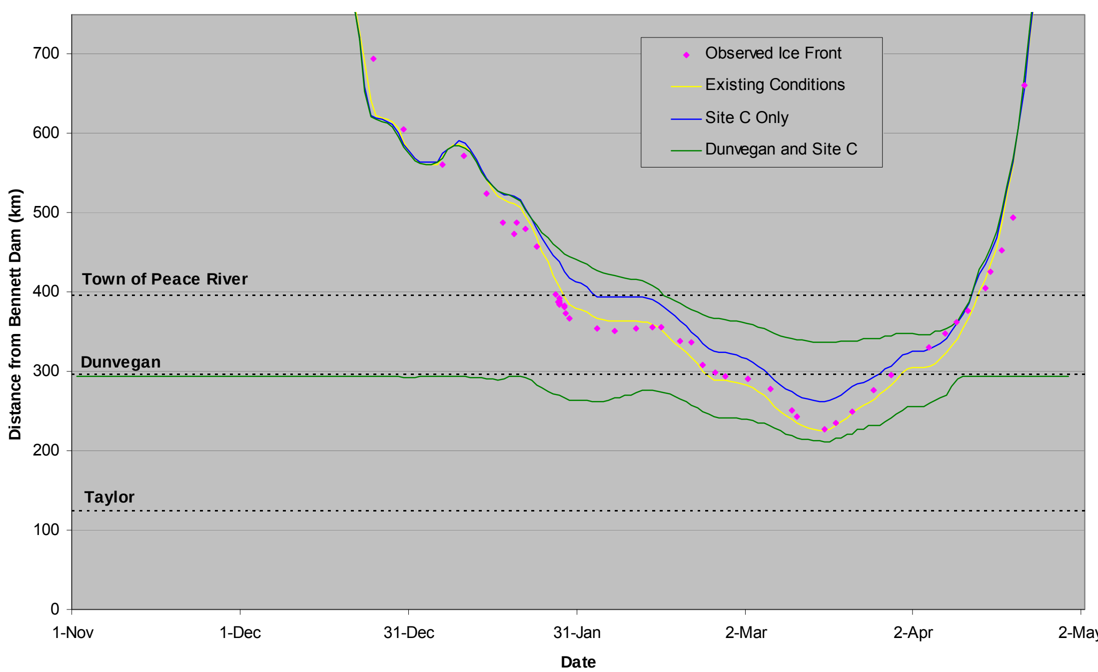

Figure C8. Simulated ice fronts for 2002 – 2003 winter.

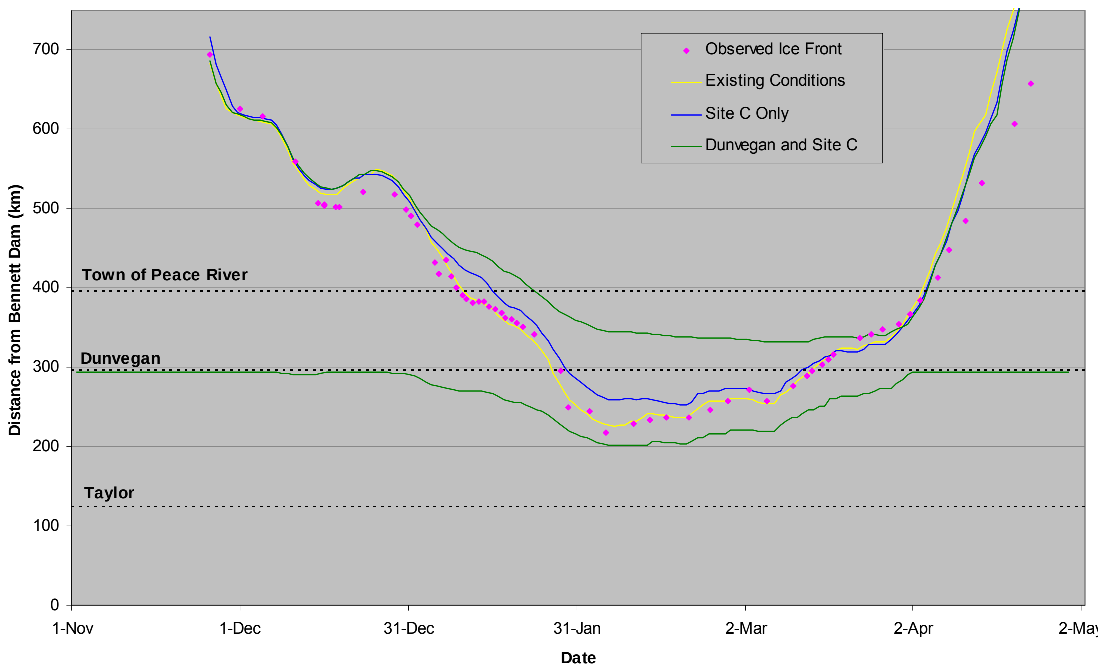

Figure C9. Simulated ice fronts for 2003 – 2004 winter.

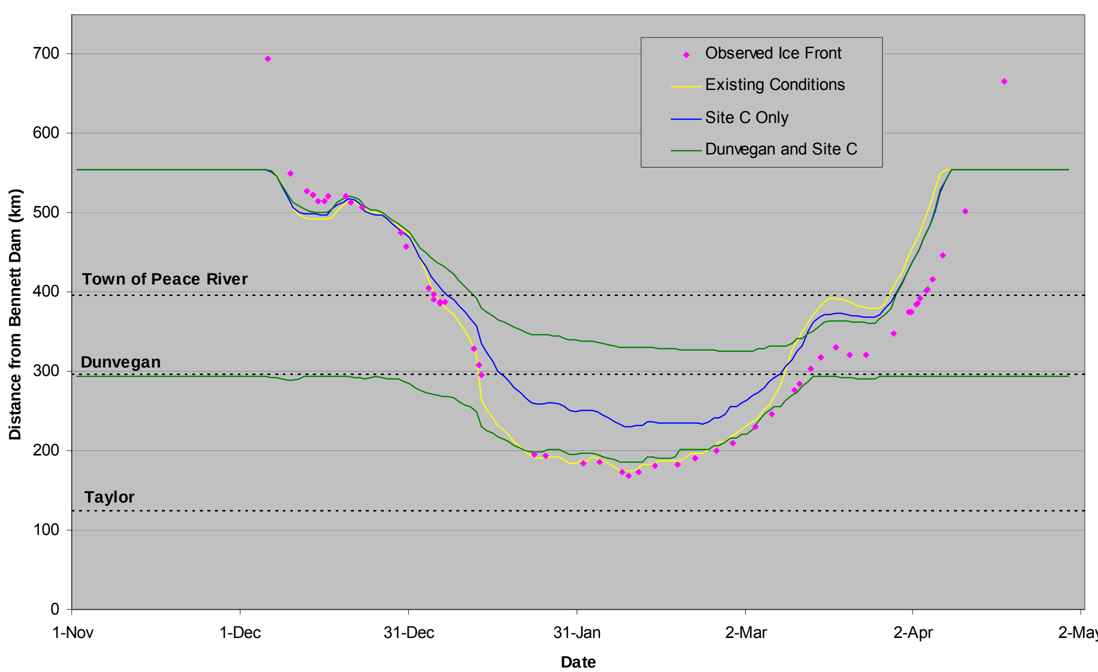

Figure C10. Simulated ice fronts for 2004 – 2005 winter.

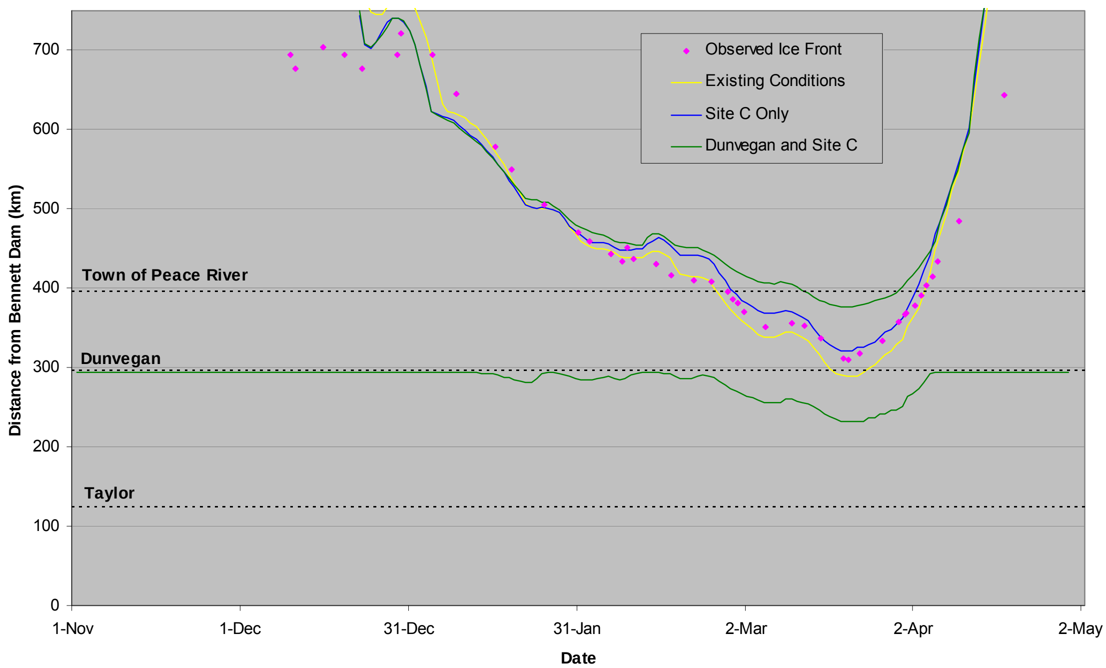

Figure C11. Simulated ice fronts for 2005 – 2006 winter.

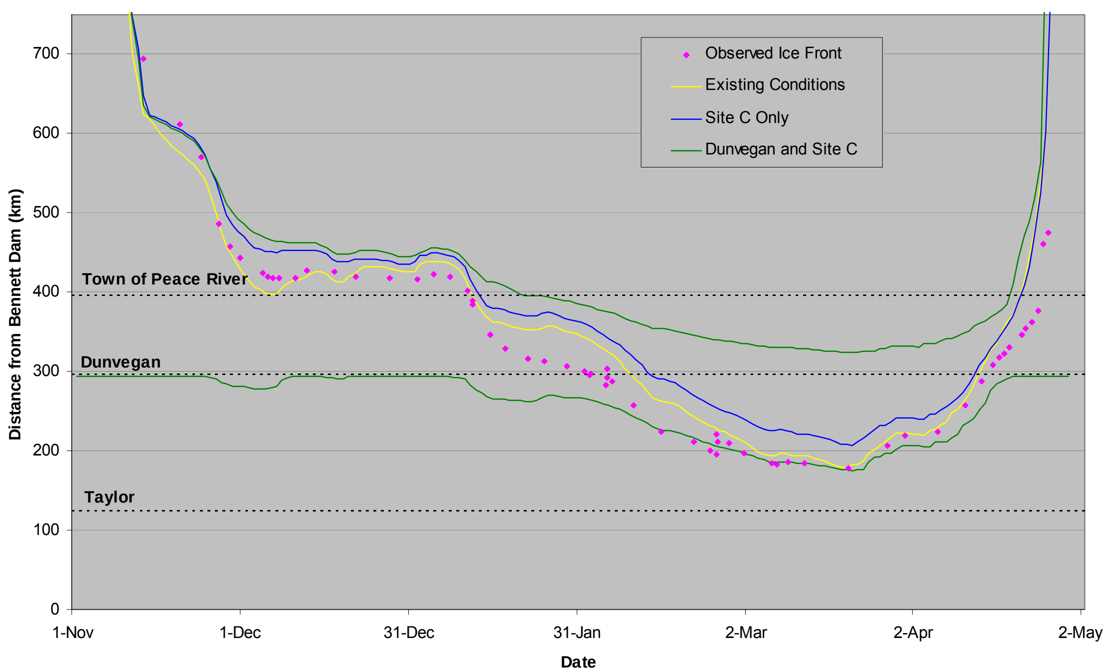

Figure C12. Simulated ice fronts for 2006 – 2007 winter.

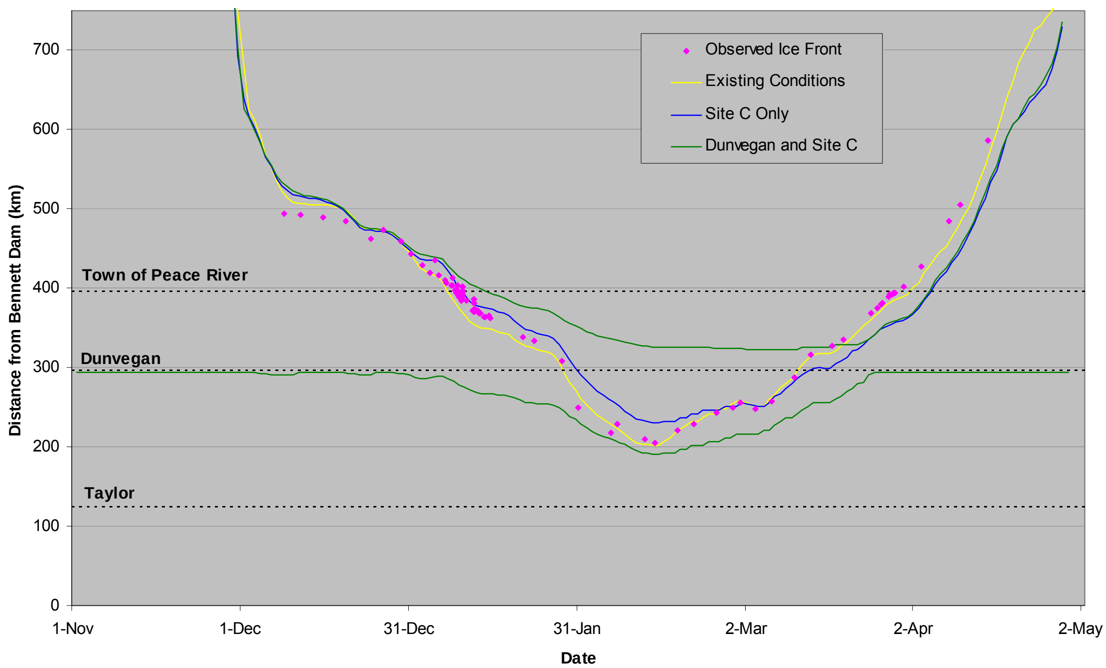

Figure C13. Simulated ice fronts for 2007 – 2008 winter.

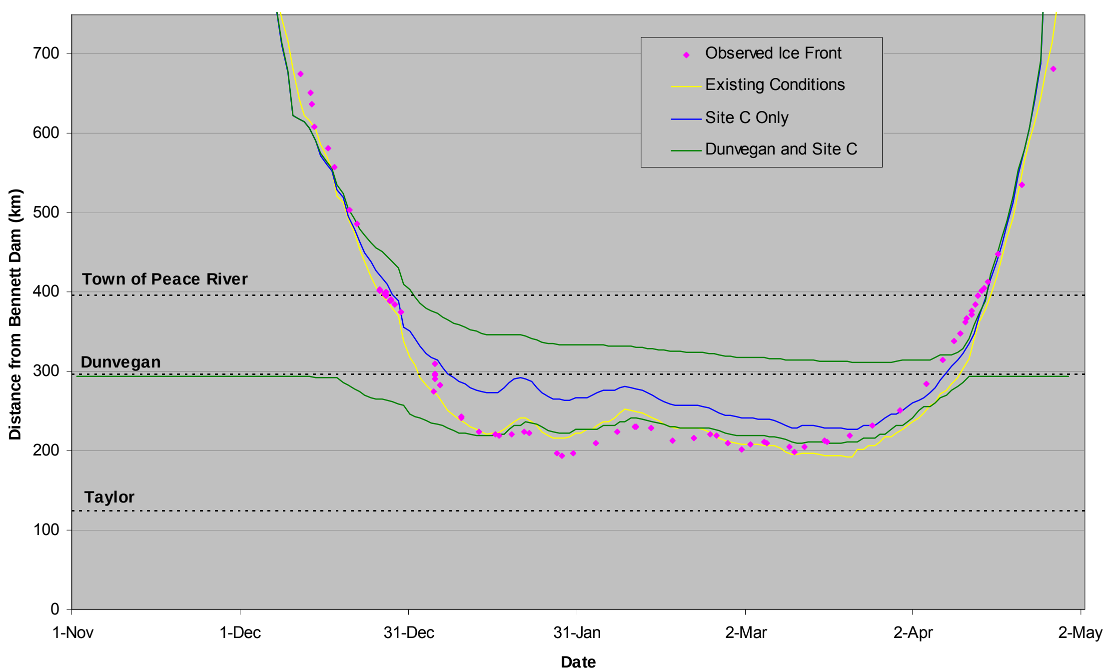

Figure C14. Simulated ice fronts for 2008 – 2009 winter.

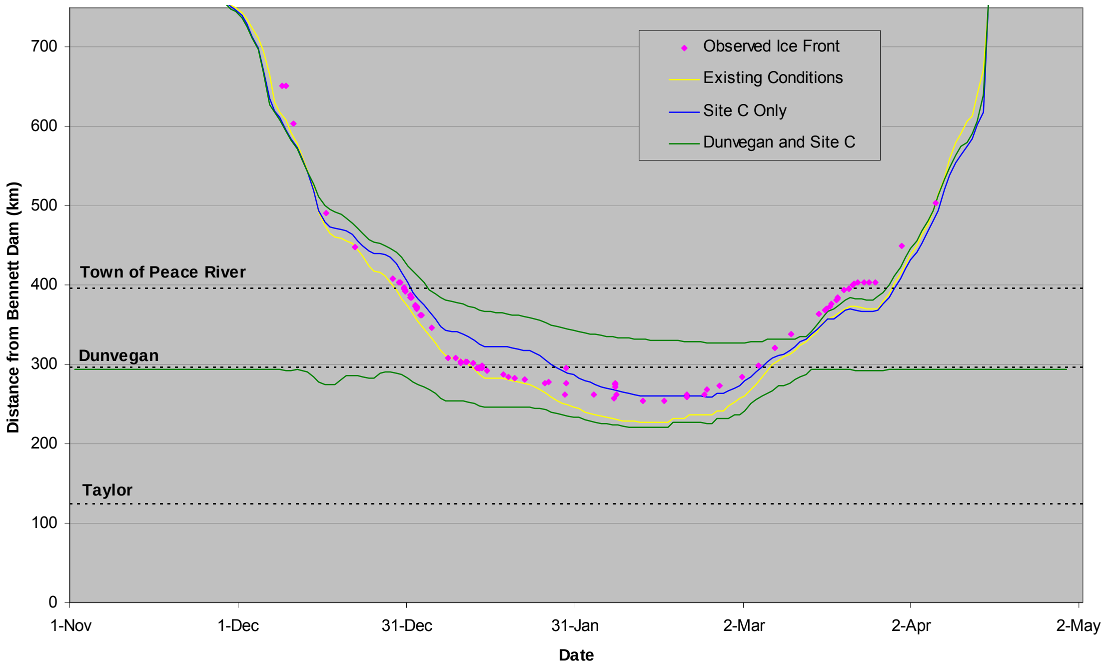

Figure C15. Simulated ice fronts for 2009 – 2010 winter.

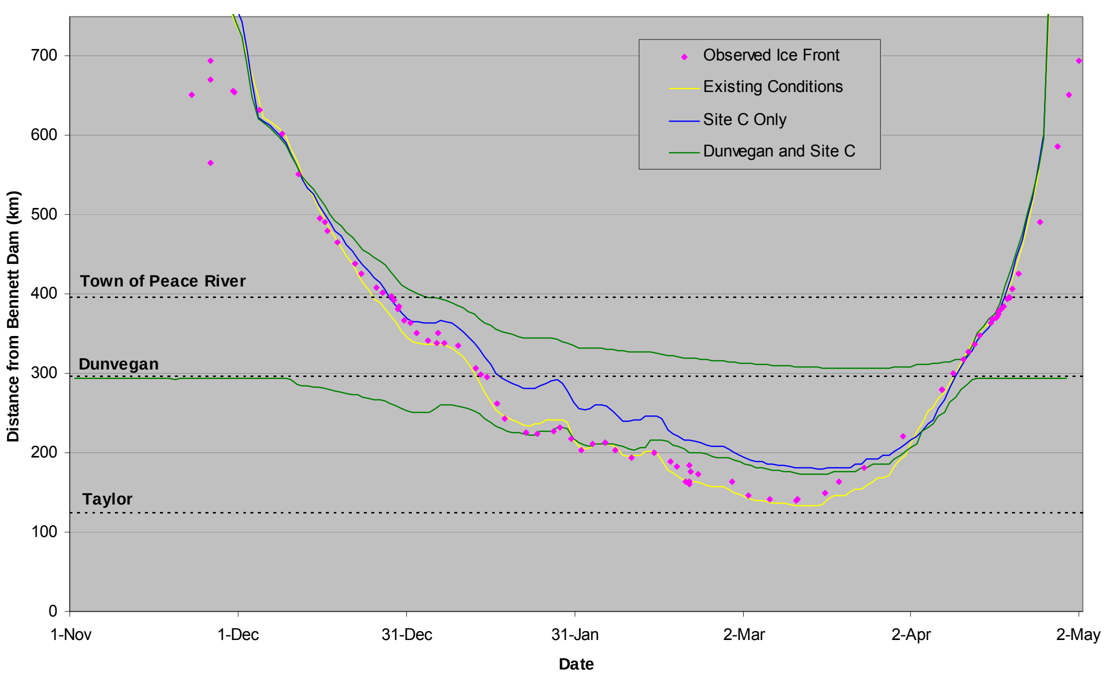

Figure C16. Simulated ice fronts for 2010 – 2011 winter.