PEACE RIVER
SITE C HYDRO PROJECT

RESERVOIR SHORELINE IMPACTS

METHODOLOGY AND CRITERIA

Prepared by

Klohn Crippen Berger Ltd. and SNC-Lavalin Inc.

For

B.C. Hydro

Report No. P05032A02-10-001
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Report No. P05032A02-10-001
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EXECUTIVE SUMMARY

The potential Site C hydroelectric project is one of several options being considered to help meet British Columbia's future electricity needs. Creation of the Site C reservoir would flood land and impact land use around the shoreline of the reservoir.

In 1978, studies were conducted to establish a safeline on private land around the proposed Site C reservoir. The safeline was defined as *"a conservatively located line beyond which the security of residents and their belongings can be reasonably assured"* and included the effects of sudden landslides and progressive, and relatively slow, shoreline erosion and the development of beaches. The safeline adopted by BC Hydro and used in the exhibits for the 1982 British Columbia Utilities Commission hearings incorporated existing natural landslides that would be unaffected by the reservoir.

Stage 2 Project Definition and Consultation for the Site C Project includes assessment of the impacts of the proposed Site C reservoir on the shoreline. Based on a literature review undertaken to determine current practice for assessing reservoir shoreline impacts, the reservoir shoreline impacts will be characterized by establishing several "reservoir impact lines" which are the boundaries beyond which lands adjacent to a reservoir are not expected to be affected by the creation, or normal operation, of the reservoir. The following reservoir impact lines will be established: Flooding Impact Line; Stability Impact Line; Erosion Impact Line; Groundwater Impact Line; and Landslide-Generated Wave Impact Line.

Establishing these five separate reservoir impact lines around the shoreline will enable stakeholders, including the public, First Nations, and regulatory agencies, to better understand the different physical processes involved and the resulting reservoir shoreline impacts. This understanding should help enable the development of land management practices around the reservoir shoreline during future stages of the project should it proceed.

This report describes each reservoir impact line and recommends the criteria and methodology to establish them.

The only available wind data for determining the Flooding Impact Line and Erosion Impact Line are from the Fort St John airport. Five stations have been installed in the valley near the proposed maximum normal reservoir level to measure wind and other weather data. Preliminary data indicate that winds are likely significantly lower in the valley than at the airport. The Erosion Impact Line is very sensitive to the energy of waves on the proposed reservoir. In-valley wind data must be collected over a sufficient period to allow correlation with the data from Fort St John airport before representative wave energies can be determined with any confidence. The stations were installed in March 2009 so that there will be sufficient data to assess impacts if the project proceeds to future stages.

Available geological information for the approximately 280 km proposed reservoir shoreline consists of: interpretations of geological sequences and slope stability from aerial photographs; a reconnaissance by boat to photograph and record the visible stratigraphy; information from holes drilled at known or potential landslide areas, Hudson's Hope, and Site C; available water well logs; and published information. A significant factor for establishing the Erosion Impact Line and the Stability Impact Line is the elevation of the contact between overburden and bedrock. This contact elevation was estimated during the boat reconnaissance using a GPS to establish the boat elevation, and hand held inclinometer and laser range finder. The accuracy of these measurements is likely in the order of ±10 m. More accurate determination of the contact elevation is required in those areas where: the top of the bedrock is obscured by vegetation or slide debris; the contact is close to the proposed maximum normal reservoir level; and existing buildings are potentially affected.

Erosion rates and beaching processes on reservoir shorelines in British Columbia similar to the proposed Site C reservoir shoreline need to be assessed to better define the erosion rates of the materials that will form the proposed Site C reservoir shoreline.

To reduce the uncertainty in the Landslide Generated Wave Impact Line more detailed investigations of the potential reservoir shoreline are required and site-specific analyses and/or numerical modeling should be conducted on the areas where the magnitudes or the consequences of landslide generated waves are potentially great, for example near existing potential large landslides.

The reservoir impact lines are still under development and will not be published until a subsequent stage of the project, if it proceeds, and then only after the major uncertainties described above have been reduced and potentially affected land owners have been consulted.

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1. INTRODUCTION

1.1 Background

The potential Site C hydroelectric project is one of several options being considered to help meet British Columbia's future electricity needs. The Site C project would be located about 7 km southwest of Fort St. John on the Peace River, just downstream of where the Moberly River enters the Peace River. As presently envisioned it would have a capacity of 900 MW and produce approximately 4,600 GW.h of electricity each year. The Site C reservoir would be 83 km long, have a surface area of approximately 9310 hectares and have a shoreline approximately 280 km long.

BC Hydro is undertaking a stage-by-stage approach to the evaluation of the Site C project as a potential resource option. At the end of each stage of review, BC Hydro will make a recommendation to government for a decision on whether to proceed to the next stage of project planning and development. This report has been prepared as part of the studies for Stage 2, Project Definition and Consultation.

1.2 Reservoir Shoreline Impacts

Creation of the Site C reservoir would flood land and impact land use around the shoreline of the reservoir. The reservoir shoreline impacts would include: flooding; stability and erosion of slopes; changes to groundwater levels; and increased potential for landslide generated waves.

In 1978, studies were conducted by Thurber Consultants Ltd, for BC Hydro to establish a "residential safeline", or simply "safeline" on private land around the proposed Site C reservoir. This safeline was defined as "a conservatively located line beyond which the security of residents and their belongings can be reasonably assured". The safeline was intended for residential and associated land use, and addressed safety from both:

- sudden landslides; and
- progressive, and relatively slow, shoreline erosion and the development of beaches.

The safeline did not address existing natural landslides that would be unaffected by the reservoir, however a "high bank" safeline was identified around a portion of the reservoir that incorporated existing natural landslides.

The safeline adopted by BC Hydro and used in the exhibits for the 1982 British Columbia Utilities Commission (BCUC) hearings enveloped the safeline recommended by Thurber Consultants (1978) and thus incorporated existing natural landslides that would be unaffected by the reservoir.

In 1978, Thurber Consultants did not carry out detailed studies to estimate the effect of the reservoir on non-residential land uses, such as wildlife habitat, heritage sites, agriculture, industry, forestry and recreation.

1.3 Land Acquisition and Rights

BC Hydro's land acquisition policy for the proposed Site C project, which was developed in 1989 and affirmed by BCUC the same year, included commitments by BC Hydro to:

- acquire only the minimal rights required for safe operation of the project;
- determine the extent of these rights on a site specific basis; and
- take land owner's preferences into account.

1.3.1 Private Property

BC Hydro controls building development around the majority of its existing reservoirs, including lands used for agricultural purposes, by means of registered statutory flowage rights of way. The standard statutory right of way agreement binds the property owner from developing the lands within the right of way. The standard agreement specifically prevents the construction of habitable buildings within a defined boundary, but allows for other compatible uses of the lands, such as farming, gardening, and minor unoccupied outbuildings. BC Hydro considers that this form of agreement satisfies BCUC requirements to minimize land acquisitions, by minimizing the outright fee simple purchase of land.

1.3.2 Crown Land

For Crown land, BC Hydro has historically not acquired any rights above the maximum normal reservoir level. Instead, BC Hydro has relied on a Land Reserve designation under the Land Act, which prevents alienation of Crown land within the reserved area. The reserve prevents any use of the Crown land for development; therefore future development of habitable buildings would not be possible.

1.4 Stage 2 Reservoir Shoreline Impacts Studies

The scope of work for the reservoir shoreline impacts studies undertaken during Stage 2 included:

- collecting and compiling available data;

- reviewing previous studies and investigations;
- reviewing the current state of practice for determining reservoir shoreline impacts; and
- recommending the approach, methodology and criteria for determining the reservoir shoreline impacts.

This report presents the results of the above work.

2. REVIEW OF CURRENT PRACTICE

BC Hydro Report No H2293, *Geotechnical Guidelines for Determining Slope Stability and Groundwater Impacts on Reservoir Shorelines for Land Use Purposes, Provisional Issue* (BC Hydro 1993) proposed changing from a "safeline" concept to a "reservoir impact line" concept. The term "reservoir impact line" means a "boundary beyond which lands adjacent to a reservoir are not expected to be affected by the creation, or normal operation, of the reservoir". The use of reservoir impact lines has two main benefits:

- they are concerned only with technical issues that determine the landward extent of the effects of reservoir shoreline processes; and
- they provide a standardized method of analysis for the entire reservoir shoreline, regardless of ownership.

After reservoir impact lines have been established, guidelines can be established to tailor uses of the land that lies between the reservoir and the impact lines.

International Commission on Large Dams (ICOLD)[1] Bulletin 124, *Reservoir Landslides: Investigation and Management, Guidelines and Case Histories,* (ICOLD 2002), adopted the reservoir impact line methodology verbatim from BC Hydro (1993). Reservoir impact line definitions from ICOLD (2002) are presented in Table 1.

The Canadian Dam Association's (CDA)[2], *Dam Safety Guidelines* (CDA 2007), includes several technical bulletins. The technical bulletin *Geotechnical Considerations for Dam Safety* does not directly address reservoir shoreline impacts. Reservoir shoreline slope stability is addressed, but only to the extent that a landslide could result in release of the reservoir. ICOLD (2002) is included in the CDA technical bulletin's bibliography and none of the references in the extensive bibliography supersedes ICOLD (2002). The CDA technical bulletin *Public Safety and Security Around Dams (draft for discussion)* addresses hazard assessments and the preparation of public safety plans. The section on hazard

[1]ICOLD is a non-governmental international organization that provides a forum for the exchange of knowledge and experience in dam engineering, with the objective of ensuring that dams are built safely, efficiently, economically, and without detrimental effects on the environment.

[2] The Canadian Dam Safety Association (CDSA) was founded in 1989 to advance the implementation of practice to ensure the safe operation of dams in Canada. In 1997, the CDSA amalgamated with the Canadian National Committee on Large Dams (CANCOLD), the Canadian branch of ICOLD, to form the Canadian Dam Association (CDA). Members of the CDA include dam owners, governing bodies, consultants, academics, contractors, and equipment manufacturers. The CDA Dam Safety Guidelines consist of principles that should be understood by dam owners, regulators, operators, etc.; and guidelines that outline processes and criteria for management of dam safety in accordance with the principles. The CDA Guidelines are generally accepted to represent the state of practice in dam safety in Canada.

assessments for reservoirs addresses floating debris and control measures for hazards such as signage, booms, buoys fencing and barricades. Slope stability, erosion and the other shoreline processes are not mentioned.

The earlier version of the CDA *Dam Safety Guidelines* (CDA 1999) addressed slope stability of the reservoir shoreline in more detail than CDA 2007, however, only the potential effect of reservoir shoreline slope stability on the safety of the dam was addressed.

The following dam safety guidelines from BC and other jurisdictions were also reviewed:

- Alberta Environment, *Alberta Reservoir Lands Guidelines*, 2005;
- British Columbia Ministry of Environment, *Dam Safety Regulations*, 2000;
- Ontario Ministry of Natural Resources, Lands and Natural Heritage Branch, *Ontario Dam Safety Guidelines, Draft* 1999;
- United Kingdom Department for Environment, Food and Rural Affairs (UK DEFRA), *Reservoir Safety – Floods and Reservoir Safety Integration*, 2002;
- United States Federal Emergency Management Agency (US FEMA), *Federal Guidelines for Dam Safety,* 2004;
- US Army Corp of Engineers (USACE), *Hydrologic Engineering Requirements for Reservoirs Manual,* Real Estate and Right-of-Way Studies, 1997; and
- Washington State Department of Ecology, *Dam Safety Guidelines,* 2004.

Most of the above publications have very little or no information on reservoir shoreline impacts and any information that was found is consistent with BC Hydro (1993) and ICOLD (2002).

Table 1 Reservoir Impact Line Definitions from ICOLD (2002)

Impact Line	Definition	Comments
Flooding Impact Line	The boundary beyond which the land adjacent to a reservoir will not be inundated as a result of normal reservoir operations or flood events with a return period of more than 1/1,000 years.	Established through hydrological studies; defines land directly affected by flooding. Note: the 1/200 flood level plus 0.6 m is used by the provincial government as the criteria for habitation on flood plains.
Stability Impact Line	(i) Residential The boundary beyond which the land adjacent to a reservoir will not be subject to sudden landsliding due to reservoir action, to an annual probability of exceedance of 1/10,000. It will not be located specifically so that existing instabilities not affected by the reservoir impoundment will be on the reservoir side of the boundary; these should be noted where identified. Land subject to slow steady movements due to the reservoir may also be included on the reservoir side of the boundary as it could be useless for development. (ii) Non-Residential Similar to (i) but having a lesser degree of confidence due to a lower level of data. Required confidence will depend on land use.	Geotechnical boundary, for use in shoreline sectors with existing or proposed human habitation, to define areas where lives may be threatened. A 1/10,000 annual probability of exceedance is the limit of technical confidence with extremely extensive investigations. Different probability levels may be selected for specific projects. The effects of toe erosion and earthquakes upon stability are considered. Non-residential lines can be drawn for various uses such as forestry, industrial or recreational; lines for each use could correspond to different probability levels. If land use changes, lines should be reviewed to ensure the technical basis of the location is adequately justified by the available information.
Erosion Impact Line	The boundary beyond which the land adjacent to a reservoir will not regress due to progressive erosion caused by normal reservoir action. Normal reservoir action includes erosion due to storms; the return period will be determined for individual reservoirs. The boundary will not be located specifically to include the results of existing erosive processes not affected by reservoir impoundment; these should be noted where identified.	This erosion does not threaten life as the rate is generally slow. This geotechnical boundary delineates the net increase or decrease of areas subject to regression by erosion. Criteria should not be over conservative as the erosion process is not life threatening. Erosion can often be controlled by protective works; impact lines may be produced for the cases of protected and unprotected shoreline.
Groundwater Impact Line	The boundary beyond which the groundwater levels adjacent to a reservoir shoreline are not significantly affected by the presence of the reservoir.	The significance of groundwater changes upon both land use and groundwater use both presently and in the future need to be considered. The impacts of raised groundwater levels upon slope stability are included in the "Stability "Impact Line" and are not included here.
Landslide-Generated Wave Impact Line	The boundary beyond which waves produced by a landslide into a reservoir will not cause erosion or other damage. The probability of slide occurrence should be the same as that used for the "Stability Impact Line" for the slide area. For potential slides, not caused or influenced by the reservoir but whose impacts would be transmitted due to the presence of the reservoir, the probability of occurrence should be estimated on a case-by-case basis.	This line is only applicable to shoreline segments that would be impacted by a potential slide induced wave. To produce this line, estimates must be made of slide volume and velocity. Modeling may be required to determine wave height, attenuation and the resulting run up.

3. RECOMMENDED APPROACH

3.1 Proposed Reservoir Impact Lines

Based on the literature review summarized in Section 2, it is considered that the use of reservoir impact lines in accordance with ICOLD (2002) represents the current state-of-practice and this approach is recommended for determining the reservoir shoreline impacts of the Site C Project.

In accordance with ICOLD (2002) the reservoir shoreline impacts will be characterized by establishing the following reservoir impact lines:

- Flooding Impact Line;
- Stability Impact Line;
- Erosion Impact Line;
- Groundwater Impact Line; and
- Landslide-Generated Wave Impact Line.

Establishing the five separate reservoir impact lines around the shoreline will enable stakeholders, including the public, First Nations, and regulatory agencies, to better understand the different physical processes involved and the resulting reservoir shoreline impacts.

The literature review described in Section 2 did not find any references for projects that have used the ICOLD (2002) guidelines for determining reservoir impact lines, in Canada or elsewhere.

It was the intent of the ICOLD (2002) guidelines that the definitions of the reservoir impact lines should be modified for specific projects. Therefore, subsequent sections of this report propose definitions of each reservoir impact line, and the criteria and methodology that will be used for establishing the reservoir impact lines for the proposed Site C Project.

3.2 Reservoir Operation

The reservoir impact lines for the proposed Site C Project will be a function of reservoir operation. The following reservoir operating assumptions will be used for establishing the reservoir impact lines:

- during normal operation of the proposed Site C Project, the reservoir level will be controlled so that it does not exceed the maximum normal reservoir level of El. 461.8 m;
- normal operating range of 1.8 m, therefore the reservoir impact lines will be based on frequent fluctuations from El. 461.8 m to El. 460.0 m; and
- during an emergency in the BC Hydro system, such as the outage of a large generating facility, the Site C reservoir could be drawn down by up to 6 m, therefore the reservoir impact lines will take into account infrequent fluctuations from El. 461.8 m to El. 455.8 m.

An emergency reservoir operating level of El. 450 m has been established by BC Hydro. This is the lowest possible elevation at which the proposed Site C dam would be able to pass the flow capacity of the upstream power plants. This is not a level that the reservoir would be drawn down to for any normal operations or maintenance. The emergency operating level would be used for an unexpected dam safety emergency requiring drawdown of the reservoir. The probability of an event requiring such a drawdown is very low; therefore this reservoir level will not be used to establish the reservoir impact lines. However, since this could constitute a rapid drawdown which could have adverse affects on the slope stability of the reservoir shoreline, the effects of a drawdown on the reservoir slopes would have to be taken into account in preparation of the Emergency Preparedness Plan for the Project.

Drawdown to El. 450 m would expose by nearly 6 m steep banks that had been continuously saturated and buttressed by water for years. The likely consequences of such a drawdown should be known so that appropriate procedures, including monitoring, could be incorporated into the Emergency Preparedness Plan. Therefore, it is recommended that if the project proceeds to construction the Emergency Preparedness Plan for the project should include the procedures required to manage the risks associated with drawing the reservoir down to the emergency reservoir operating level.

3.3 Existing Natural Conditions

The purpose of establishing reservoir impact lines is to determine the effects of the reservoir on the adjacent land and land use. The effect of the reservoir is the difference between the existing natural conditions and the anticipated conditions after reservoir filling (i.e. post-project minus pre-project). Therefore, where applicable, a natural stability impact line and a natural erosion impact line will be established using the same methodology and criteria used to establish the reservoir impact lines.

3.4 Uncertainties

The methods used to establish reservoir impacts have inherent uncertainties that must be understood and taken into account when both establishing and using reservoir impact lines. Important uncertainties are described in the subsection for the applicable reservoir impact line.

In addition, some of the physical processes that cause the reservoir shoreline impacts are time dependent. For example, progressive shoreline erosion and beach development can continue for a very long time, if not indefinitely. Temporal aspects are also discussed in the subsection for the applicable reservoir impact line.

The uncertainties in predicting both the extent and rate of the reservoir shoreline impacts lead to the proposal to adopt an observational approach for periodically reviewing and updating the reservoir impact lines after the reservoir has been filled. A fundamental requirement of the observational approach is to establish the requirements for routine monitoring of the shoreline early in the planning process. Recommendations for monitoring specific impact lines are given in some of the following subsections. In addition, the routine monitoring could include:

- regular remote sensing of the entire reservoir shoreline and slopes, likely by airborne LiDAR[3];
- observations of slopes from air and water craft;
- semi-annual reading of instrumentation (slope indicators and piezometers) installed in reservoir slopes, and in some cases continual reading of in-place inclinometers, piezometers and GPS stations;
- annual inspections of active slopes; and
- interpretation of the data and compilation of annual reports.

The methodologies and criteria proposed in the following sections are considered suitable for establishing reservoir impact lines at a regional level only. Areas found to be especially prone to flooding, landslides, erosion, groundwater, and

[3] LIDAR (Light Detection and Ranging) is a remote sensing technology that measures the distance to the surface using laser pulses.

landslide-generated waves, and where the consequences are considered potentially high, will require further investigation and analysis so that the reservoir impact lines in those areas can be defined with more confidence during future stages of the project should it proceed.

If the project proceeds to future stages, it is recommended that the reservoir impact lines be reviewed, and possibly modified in light of any new information, methodologies, or criteria available at that time, especially just before reservoir filling, during reservoir filling and periodically thereafter.

3.5 Review

Independent external reviewers, who have been selected based on their experience and expertise in the evaluation of similar reservoir shoreline processes, will review and comment on the reservoir impact lines so that the lines are reasonable and consistent with the current state of practice.

4. FLOODING IMPACT LINE

4.1 Definition and Commentary

Definition: The boundary beyond which the land adjacent to the reservoir is not expected to be flooded as a result of the creation or normal operation of the reservoir.

Commentary: The Flooding Impact Line will be based on the maximum normal reservoir level with suitable allowances for floods and winds. Flood allowances will include any surcharge above the maximum normal reservoir level due to the passage of floods, and any gradient on the water surface due to flows through the reservoir, including the tributary arms. Wind allowances will include seiche[4], waves, and wave run-up[5].

4.2 Criteria

4.2.1 Flood Hazards

Creation of the reservoir will result in flood hazards along the shoreline in areas where there currently is no flood hazard.

4.2.1.1 Guidelines

The BC Ministry of Water, Land and Air Protection (BC MWLAP), Flood Hazard Area, Land Use Management Guidelines (2004) were written to help local governments, land-use managers and approving officers develop and implement land-use management plans. The guidelines provide the recommended minimum provincial requirements.

The BC MWLAP guidelines include:

- flood plain setbacks**,** to keep development away from areas of potential erosion and to avoid restricting the flow capacity of floodways; and
- flood construction levels**,** to keep living spaces, and areas used for the storage of damageable goods above flood levels.

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[4] Seiche is the increase in water level along a reservoir due to wind blowing along the reservoir. The water level downwind is higher than the water level upwind.
[5] Wave runup is the maximum vertical extent of wave uprush on a beach or structure above the still water level.

The “designated flood” and the “designated flood level” determine the flood plain setbacks and flood construction levels. The designated flood is the 200-year flood (the flood that has a statistical annual return period of once in 200 years) based on a frequency analysis of unregulated historic stream flows, or based on a regional analysis where there is inadequate stream flow data. The designated flood level is the observed, or calculated, water surface elevation for the designated flood. Appropriate freeboard is added to the designated flood level to determine the flood construction level. Although flood plain setbacks and flood construction levels are provided in the BC MWLAP guidelines for small lakes, ponds, swamps, marsh areas and some reservoirs, they state that specific flood plain setbacks and flood construction levels should be established for larger reservoirs.

The ICOLD (2002) definition of the Flooding Impact Line in Table 1 includes inundation from a flood with an annual return period of 1/1000 (essentially the 1000-year flood).

Because the 1000-year flood is a more conservative criterion than the designated flood used by BC MWLAP (2004), the 1000-year flood will be used to establish the Flooding Impact Line for the proposed Site C reservoir.

4.2.1.2 1000-Year Flood Flows

Klohn Crippen Integ[6] (1989) used a calibrated watershed model to estimate the standard project flood (SPF), which is defined by the US Army Corps of Engineers (USACE), as “the flood that can be expected from the most severe combination of meteorological and hydrologic conditions that are considered reasonably characteristic of the geographic region involved, excluding extremely rare combinations”. Based on recommendations by the USACE the SPF was derived assuming 100-year return period snowpack in the basin, a 100-year return period wet May and a three day storm with one half of the rainfall of the probable maximum precipitation commencing on 1 June. The peak inflow into the potential Site C reservoir was estimated to be 8410 m^3/s, corresponding to about one third of the probable maximum flood (PMF)[7].

[6] Klohn Crippen Consultants Ltd in Association with Shawinigan Integ operated under the name Klohn Crippen Integ.

[7] The Probable Maximum Flood (PMF) is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.

Klohn Crippen Consultants Ltd. and SNC-Lavalin Inc. (2003) estimated the following peak flood flows into the proposed Site C reservoir:

1. The 1000-year flood return period release from the W.A.C. Bennett Dam was estimated to be 8000 m^3/s based on an extrapolation of a BC Hydro flood frequency analysis, which estimated flows up to the 100-year flood; and
2. The 1000-year return period flood in the Halfway River was estimated to be 6400 m^3/s, based on a flood frequency analysis of the flows in the Halfway River recorded at Environment Canada, Water Survey of Canada (WSC) gauge 07FA008.

In 2009, as part of the Stage 2 engineering studies for the Site C Project, Klohn Crippen Consultants and SNC-Lavalin Inc. re-estimated the 1000-year return period flood as 6580 m^3/s in the Halfway River based on a flood frequency analysis of the flows at WSC gauge 07FA008, as additional gauge data were available.

Based on the above, the following peak flood flows will be used as the 1000-year flood flows for establishing the Flooding Impact Line for the proposed Site C reservoir:

- 8410 m^3/s discharge from Peace Canyon Dam;
- 6400 m^3/s in the Halfway River, with a concurrent 2000 m^3/s discharge from Peace Canyon Dam (equal to all units operating at full discharge); and
- flood flows in the other Peace River tributaries such as Cache Creek and the Moberly River, pro-rated from the Halfway River 1000-year flood flow based on their respective catchment areas.

4.2.1.3 Designated Flood Level

The current design of the spillway of the proposed Site C Project has six spillway gates, 16.2 m wide by 16.4 m high. The spillway has a crest elevation El 446.5 m, which is more than 15 m below the maximum normal reservoir level. The spillway has a discharge capacity of 11,700 m^3/s with all gates fully open and the reservoir at the maximum normal reservoir level (Klohn-Crippen Integ, 1990). Flooding would occur landward of the Flooding Impact Line only during floods that exceed the spillway capacity of 11,700 m^3/s with all the gates open and the reservoir at El. 461.8 m.

The peak spillway discharge during the PMF is estimated to be 17,500 m^3/s (Klohn-Crippen Integ, 1990). PMFs are estimated by deterministic methods and therefore are not associated with a probability. However, some publications have estimated annual return periods of such extreme floods to be in the order of 1/10,000 to 1/100,000. Based on the above, floods exceeding the spillway capacity at the maximum normal reservoir level would be extremely rare events, and the probability of exceeding the maximum normal reservoir level at the Site C dam is extremely low.

Therefore, the maximum normal reservoir level of El. 461.8 m will be used as the designated flood level at the Site C dam for establishing the Flooding Impact Line.

4.2.2 Wind

Since the BC MWLAP guidelines use the 200-year return period for the flood hazard criterion, the 200-year return period wind will be used to determine the wind allowances.

4.3 Methodology

4.3.1 Flood Allowances

The digital elevation model from the LiDAR survey will be used to set-up a numerical model of the reservoir and tributary arms using HEC-RAS[8] so that water surface profiles can be calculated for the passage of floods. Roughness parameters will be based on the assumption that the reservoir will be cleared and that all tree stumps will be cut to within 300 mm of the ground surface.

The water surface profile along the Peace River will be calculated using the 1000-year flood discharge from Peace Canyon Dam. Water surface profiles will be calculated along each tributary arm using the estimated 1000-year flood for that tributary. Water surface profiles will be calculated assuming the maximum normal reservoir level at the dam (El. 461.8 m).

4.3.2 Wind Allowances

The only available wind data for the prediction of seiche, wave heights and wave runup are from the Fort St John airport, which may not be representative of the winds that would exist in the valley after the reservoir has been filled. During

[8] The USACE HEC-RAS computer program is standard engineering software used to calculate steady state water surface profiles in channels.

Stage 2 five wind stations were installed in the valley upstream of Site C to collect wind data near the proposed maximum normal reservoir level. The Fort St John wind data will be used for establishing the Flooding Impact Line until sufficient wind data has been collected from these wind stations at which time the Flooding Impact Line should be updated. The lack of in-valley wind data results in uncertainty in the Flooding Impact Line established using the available data.

Wind allowances will be calculated using the 200-year maximum hourly wind speed values provided by Environment Canada (2008).

4.3.2.1 Seiche

Seiche will be calculated using the method given in Smith (1995), which is similar to the method given in ICOLD (1993).

The 200-year wind will be assumed to blow along the reservoir long enough to cause a seiche. As seiche can travel around bends, the open water (fetch) lengths used to calculate seiche will generally be taken as the straight line distance from the upstream limit to the location where the seiche height is calculated. Due to the significant change in direction of the reservoir downstream of the Halfway River transfer effects around the reservoir bend downstream of the Halfway River would likely be minimal, therefore the seiche will be calculated separately for the reaches upstream and downstream of the bend. The reaches used for calculation of seiche will be Peace Canyon to the Halfway River bend and the Halfway River bend to Site C for the remainder.

Seiche will be calculated at the locations selected for the calculation of wave allowances described in Section 4.3.2.2. The seiche at each location will be calculated separately and then added to the seiche calculated at the upstream location to give the combined seiche, i.e. the seiche calculated for location 2 will be added to the seiche calculated for location 1, then the seiche calculated for location 3 will be added to the combined seiche from locations 1 and 2, and so on downstream to Site C.

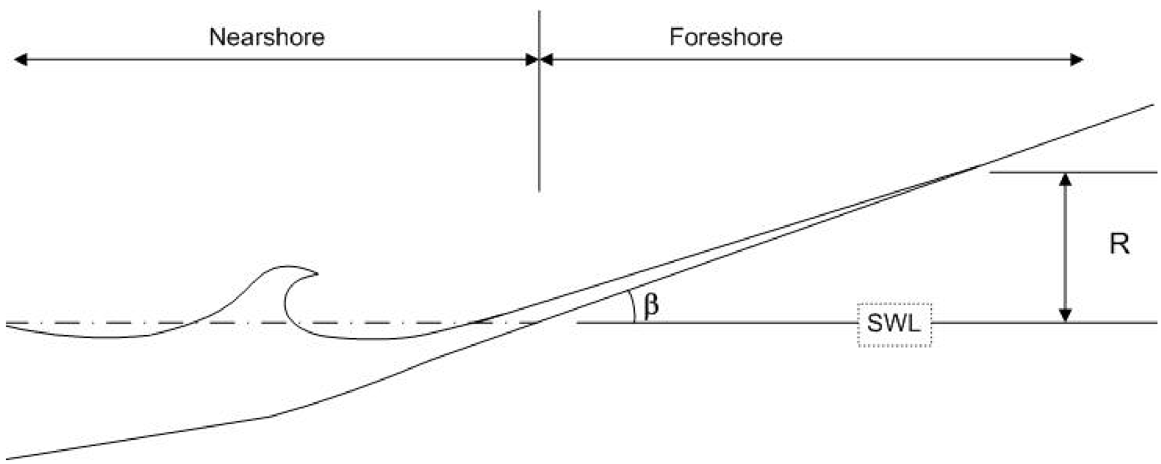
4.3.2.2 Wave Allowances

Wave heights and wave runups will be calculated using the method given in Smith (1995), which is similar to the method given in ICOLD (1993).

The locations for calculation of wave heights and wave runup will be selected to maximize the straight, unobstructed, open water fetch lengths.

Wave runup is a function of the foreshore slope as depicted in Figure 1 and is determined from a chart that has been derived empirically.

Figure 1
Wave Runup Definition
(SWL is still water level)



4.3.3 Plotting the Flooding Impact Line

The methodology described in Sections 4.3.1 and 4.3.2 provide elevations which are added to provide the elevation of the Flooding Impact Line at discrete locations along the reservoir, i.e. Flooding Impact Line elevations = water surface elevation for the 1000-year flood (from the water surface profile) + seiche + wave runup as shown on Figure 2. This assumes that the 200-year wind is coincident with the peak of the 1000-year flood, which may result in a longer return period (i.e. greater than 1000 years). However, as strong winds are likely to be associated with the large storms that produce a 1000-year flood it is considered reasonable to combine the wind and flood.

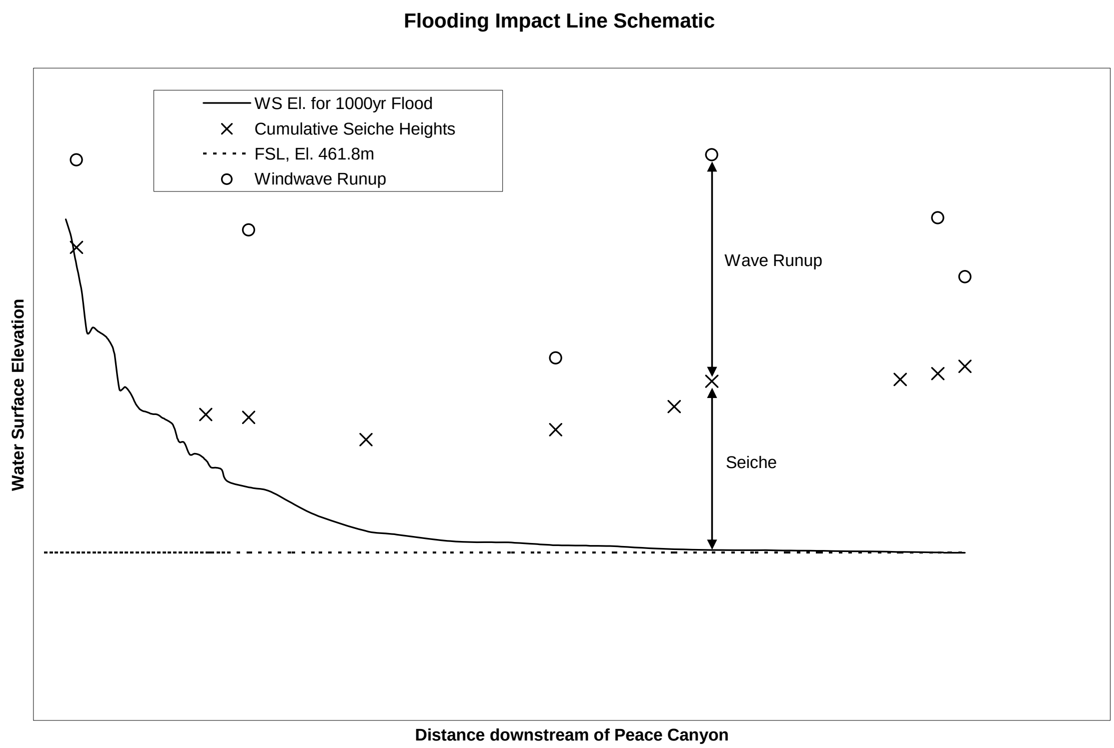
The Flooding Impact Line will be plotted on topographic mapping produced during Stage 2 from aerial photography and aerial LiDAR survey using the calculated elevations. The mapping has a quoted accuracy of about ±0.3 m vertical, which results in uncertainty in the location of the Flooding Impact Line on the topographic mapping. This uncertainty is a function of the accuracy of the mapping, and the slope of the land at the elevation of the Flooding Impact Line – the flatter the slope, the greater the uncertainty. For example on a slope of 10H:1V the accuracy of the Flooding Impact Line will be ±3 m horizontal due to the mapping accuracy.

The Flooding Impact Line would move landwards with time after reservoir filling due to progressive shoreline erosion and beach development, which change the topography and the location of the shoreline. Also, the existing slope of the ground at the maximum normal reservoir level will be used to calculate the wave runup. However, as beaches form, the foreshore slope will change and therefore the wave runup will change.

As part of the Stage 2 studies, changes to the Flooding Impact Line with time due to progressive shoreline erosion and beach development will not be considered.

As discussed in Section 6, there is considerable uncertainty in both the rate of erosion and potential stable beach angles, all of which results in uncertainty in the location of the Flooding Impact Line.

Figure 2



4.4 Recommendations

If the project proceeds further, it is recommended that:

- the Flooding Impact Line should be reviewed and updated using wind data from the climate stations that are being installed in the valley at about reservoir level as part of the Stage 2 studies, to reduce the uncertainty resulting from using Fort St John airport wind data to estimate seiche, wave heights and wave runup;
- differential GPS, more accurate aerial LiDAR survey and/or traditional ground survey methods should be used to more accurately define the location of the Flooding Impact Line in plan, specifically in relatively flat lying areas and in populated areas, to reduce the uncertainty resulting from the accuracy of the LiDAR survey obtained in Stage 2; and
- the landward progression of the Flooding Impact Line due to progressive shoreline erosion and beach development should be estimated using the updated Erosion Impact Lines established during subsequent stages as recommended in Section 6.4.

Since the available period of record from the new climate stations will be short it will be necessary to correlate wind data from the new stations with the long term records from the Fort St John airport.

If the Site C dam is constructed, it is recommended that, in addition to the general requirements for periodic updating of the impact lines given in Section 3.4, the Flooding Impact Line should be reviewed, and adjusted if required after:

- clearing of the reservoir;
- first filling to the maximum normal reservoir level;
- after large floods; and
- five to ten years of normal operation to account for progressive shoreline erosion and beach development using the updated Erosion Impact Lines established after reservoir filling as recommended in Section 6.4.

5. STABILITY IMPACT LINE

5.1 Definition and Commentary

Definition: The boundary beyond which the land adjacent to the reservoir is not expected to be affected by landslides resulting from the creation, or normal operation, of the reservoir.

Commentary: The banks of the Peace River and its tributaries are prone to naturally occurring slumping and landslides, and therefore a natural stability line will be established to identify existing naturally unstable areas. While establishing the Stability Impact Line, existing naturally unstable areas, which will not be affected by the reservoir, will be noted, but such areas will not necessarily be included on the reservoir side of the Stability Impact Line. Existing naturally unstable areas that will be affected by the reservoir will be incorporated into the Stability Impact Line.

5.2 Natural Instability and the Affects of Reservoir Filling

The banks along the Peace River have experienced a long history of natural instability in the process of river valley development with approximately 30 km of the reservoir shoreline comprising of the debris of landslides that occurred over the last 10,000 years, with the remainder of the reservoir shoreline consisting of undisturbed bedrock or undisturbed overburden. A considerable number of papers and reports have been written about the stability of slopes in the Peace River valley.

For the purpose of this report:

- “small” landslides are those with volumes less than 75,000 m^3;
- “large” landslides are those with volumes between 75,000 m^3 and 750,000 m^3; and
- “very large” landslides are those with volumes greater than 750,000 m^3.

In the area of the proposed reservoir, landslides in overburden are far more common than landslides in bedrock. Overburden landslides are predominantly small slumps and flows that originate in the glaciolacustrine[9] silts and clays that overly the bedrock.

However some large and very large overburden slides have occurred, most notably the 14 million m^3 Attachie slide which occurred in 1973.

A few large and very large bedrock landslides have also occurred in the Peace River valley, the largest of which is the Cache Creek slide with a volume of about 70 million m^3. The available historic records and the age of vegetation on the Cache Creek slide debris indicate that the last major movement of the slide debris may have occurred in the early 1900s.

All rapid bedrock landslides with volumes greater than 10 million m^3 are associated with a thick capping of Dunvegan sandstone, and sliding occurs near the contact between that formation and the underlying Shaftesbury shale.

Slope instability in both bedrock and overburden are frequently associated with clay layers. A series of bedrock landslides, between the proposed Site C dam site and Tea Creek, are associated with a layer of white clay in the shale.

Reservoir filling will increase the groundwater levels in the bedrock and overburden slopes adjacent to the reservoir, and add a buttressing water load to the slopes. Depending on the geology at a specific site, the combination of these effects will either decrease or increase the stability of the slope.

Filling the proposed Site C reservoir is expected to have the following effects:

1. Relatively small overburden sloughs and slides are expected to be triggered by both reservoir filling and subsequent normal operations where the overburden near the maximum normal reservoir level is predominantly sand and gravel, and where the reservoir level is typically <15 m above the bedrock contact. The resulting instability is expected to be small and occur soon after reservoir filling.

2. Pore pressures are expected to increase along clay seams in the shale bedrock below the maximum normal reservoir level. Increased pore water pressures will lower the frictional resistance to sliding, which is expected to result in slow readjustments in existing slides, such as in the Tea Creek area, and possibly some movement in intact slopes.

[9] Sediments deposited into lakes that have come from glaciers are called glaciolacustrine deposits.

3. The reservoir is expected to have no affect on bedrock slides that could originate along the contact of the Dunvegan and Shaftesbury formations because these contacts are well above the maximum normal reservoir level.

4. The reservoir is expected to have little, if any, effect on large overburden slides, because these are predominately located above the reservoir level.

5.3 Criteria

The ICOLD (2002) guidelines subdivide the Stability Impact Line into residential and non-residential areas. ICOLD (2002) defines the Stability Impact Line for residential areas as the boundary beyond which the land will not be subject to sudden landsliding due to reservoir action, to an annual probability of exceedance of 1/10,000, and comments that such a line is a:

> "Geotechnical boundary, for use in shoreline sectors with existing or proposed human habitation, to define areas where lives may be threatened. A 1/10,000 annual probability of exceedance is the limit of technical confidence with extremely extensive investigations. Different probability levels may be selected for specific projects."

Very extensive investigations, in-situ measurement of groundwater levels, strength testing and analysis would be required to establish the limits of landslides with such low probabilities of occurrence. It is not practical to investigate the entire 280 km reservoir shoreline and perform the analyses required to establish the Stability Impact Line on a probabilistic basis. Instead, it is proposed to establish the Stability Impact Line by predicting the future performance of the shoreline slopes based on the historic performance of slopes in the Peace River valley.

Future development of habitable buildings close to the Stability Impact Line is possible, therefore the uncertainty in the location of the Stability Impact Line will have to be taken into account when determining the acquisition of land and rights and the land management practices around the reservoir shoreline.

After reservoir filling, the majority of the shoreline slopes would slowly flatten as small sloughs and slides of material move down the slope and into the reservoir, until the slope eventually reaches a stable angle. Monitoring the behaviour of these slopes and periodically updating the Stability Impact Line based on their actual performance would provide a sufficient margin to allow for the uncertainty in establishing the Stability Impact Line, i.e. there will be sufficient time to take the necessary actions to avoid a sudden slide from endangering any habitable buildings.

However, in a few areas where fast, large slides have occurred in the past such as at Attachie, or where such slides are considered possible, an additional setback may be required to allow for the uncertainty in establishing the Stability Impact Line. Such areas will be identified and establishment of a Geotechnical Review Line on the landward side of the Stability Impact Line will be recommended to allow for the uncertainties. This additional setback would allow for the installation of instrumentation for slope monitoring behind the Stability Impact Line. Data from this instrumentation would be used in the periodic review and updating the reservoir impact lines after the reservoir has been filled.

The distance between the Stability Impact Line and the Geotechnical Review Line would be a BC Hydro management decision in consultation with stakeholders and will not be considered in the Stability Impact Line, which is intended to solely communicate the anticipated effects of reservoir on slope stability.

5.4 Methodology

5.4.1 General

The purpose of the Stability Impact Line is to allow better understanding of the effects of the reservoir. Because there are many existing naturally unstable areas in the river valley, it is proposed to establish a natural stability line in addition to the Stability Impact Line. The effect of the reservoir will be the difference between the two lines. It is proposed to establish both impact lines using the same methodology and criteria.

The methodology will include the following steps:

1. Map the bedrock, surficial materials, and geomorphic processes around the reservoir shoreline using air photos and observations from a river based reconnaissance, supplemented by a review of existing geological mapping, geological sections, drill hole data, laboratory test data and literature.

2. Identify and characterize existing natural landslides and unstable areas using air photos and, if feasible, satellite imagery, supplemented by information contained in existing reports.

3. Divide the reservoir shoreline into a number of representative reaches with similar:

   - topography;
   - geology;
   - material properties;
   - geomorphic processes; and
   - groundwater conditions,

   and prepare a geological model for each representative reach.

4. Estimate the furthest distance from the reservoir shoreline where a landslide backscarp could extend (the break line) for each representative reach. The break line will be based on observations of existing natural landslides in similar terrain and geology and information in literature on the stability of the Peace River valley.

5. Use the results of steps 1-4, to establish the natural stability line and the Stability Impact Line as the lines that envelope all break lines for potential slope failures.

Considerable judgment will be required for establishing both the natural stability line and the Stability Impact Line.

The Stability Impact Line will be based on the existing topography, which will change as a result of shoreline erosion and beach development. To the extent possible, the effects of these shoreline changes will be taken into account in developing the Stability Impact Line.

As described above, a geological model will be prepared for each representative reach. At El. 461.8 m, the proposed Site C reservoir would have a shoreline approximately 280 km long. Dividing a shoreline of this length into representative reaches inevitably involves some simplification and approximation, and therefore introduces uncertainty.

For example, locating clay layers can be very important to preparing the geological models. A thin clay layer in the overburden or bedrock can have a significant affect on slope stability as it represents a weaker layer that can also impede drainage in overburden but may promote drainage in the shale bedrock.

On the other hand, some clay layers occur at defined elevations over extensive areas, and can be incorporated into the geological models with some certainty.

5.4.2 Examples

Application of the methodology is illustrated in Figures 3 and 4.

Figure 3 shows a location where the natural slope has a height of about 200 m and consists of glaciolacustrine silts and clays (tan colour) overlying shale bedrock (grey cross hatching). A horizontal clay layer (magenta line) is located in the shale near the bottom of the slope. Based on observations of existing slopes in the Peace River valley upstream of Site C, the flattest slope found in glaciolacustrine silts and clays approximates 4H:1V and the flattest slope found in shale bedrock with a horizontal clay layer also approximates 4H:1V.

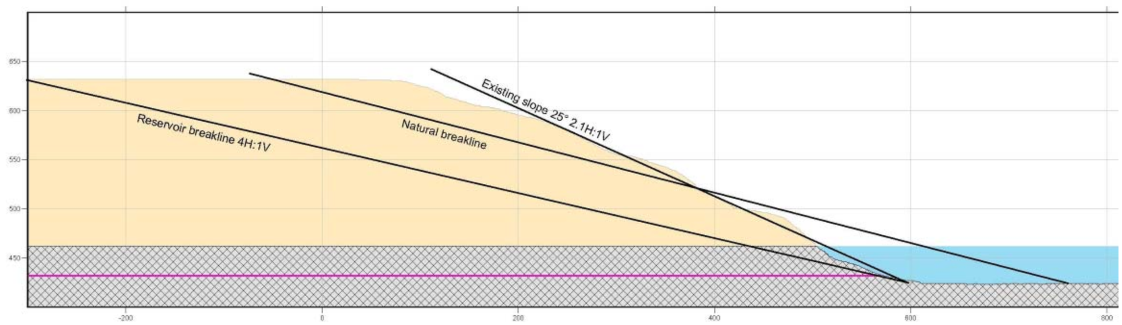
The river valley has been formed since the end of the most recent ice age about 10,000 years ago by the Peace River eroding down through the plateau. The 4H:1V slopes observed in the glaciolacustrine materials and shale bedrock (with a clay layer) are the flattest slopes found in these materials in the valley. Therefore, 4H:1V slopes are used to establish the break lines in these materials.

The majority of the slides occurring in the Peace River valley are small and slow. Successive small slides gradually flatten the valley slopes as material moves from the upper parts of the slopes and accumulates on the lower parts of the slopes. This process continues until the slope becomes stable and consists of intact material on the upper part of the slope and slide debris on the lower part. Based on the age and condition of the slopes, it is considered that this process of slope flattening by small slides in the glaciolacustrine material is likely to take millennia to reach a long term stable slope.

If the slide debris on the lower part of the slope is carried away by river or reservoir flow rather than accumulating on the lower part of the slope, the ultimate break line would be further landward. For the purposes of establishing the break lines for the natural stability line and the Stability Impact Line it will be assumed that all slide debris is gradually carried away from the lower part of the slope by flow so that the toe of the long term stable slope would be located at the edge of the river bank in the case of the natural break line and at the toe of the existing slope for the Stability Impact Line. This assumption is significant as it likely exaggerates the difference between the natural stability line and the Stability Impact Line since the velocities in the reservoir will be much lower than in the river and therefore less erosive. The main reservoir process removing material from the slope would be wave erosion as discussed in Section 6, which would occur from the shoreline rather than the toe of the slope.

Figure 3 shows the natural break line, established as the location where a line at 4H:1V drawn from the edge of the current river bank daylights on the plateau above the slope, and the break line for the Stability Impact Line, which is established as the location where a line at 4H:1V drawn from the edge of the toe of the slope daylights on the plateau above the slope. The difference between the natural break line and the Stability Impact Line is the impact of the reservoir. However, it is important to realize that this does not imply that the slopes at this location will slide to a 4H:1V slope when the reservoir is filled.

Figure 3
Sample location with bank approximately 200 m high
with clay layer in shale



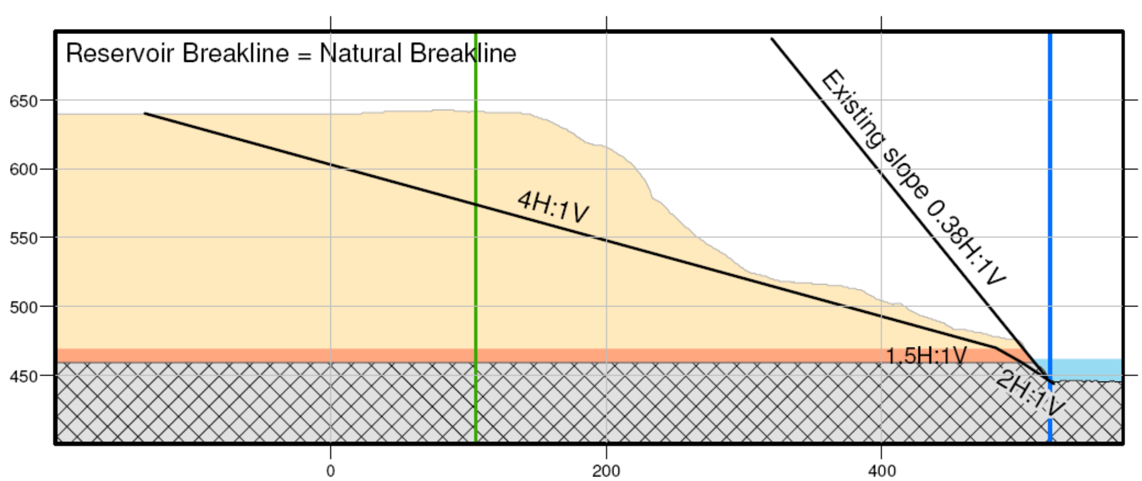
As shown in Figure 3 the existing natural slope in the glaciolacustrine materials at this location is about 2.1H:1V, which is considerably steeper than the 4H:1V slope used to establish the break lines. In addition, the reservoir level is below the top of the shale so the groundwater conditions in the glaciolacustrine materials will be unaffected by filling the reservoir. Therefore, the reservoir will have no impact on the stability of the glaciolacustrine materials other than possibly the removal by currents in the reservoir or by wave action of any slide debris that would otherwise accumulate on the lower part of the slope. Thus the only affect of the reservoir on the slope in the glaciolacustrine materials will be for the top of the slope to eventually move further landward than it would under natural conditions.

As shown in Figure 3 the slope in the shale is flatter than the general slope angle and there is a small amount of slide debris at the toe of the slope. Filling of the reservoir will flood the end of the clay layer and eventually change the groundwater conditions in the shale. Increasing groundwater levels could cause slow movements in the shale with some individual blocks of shale moving down and outwards on the clay layer. If the Site C Project is constructed, the response of the slope to reservoir filling and increasing groundwater levels in the slope would be monitored so that the Stability Impact Line could be updated based on actual slope performance.

Figure 4 shows a location where the natural slope has a height of about 200 m and consists of glaciolacustrine silts and clays (tan colour) overlying shale bedrock (grey cross hatching). A gravel layer (orange band) is located between the shale and the glaciolacustrine materials. Based on observations of existing slopes in the Peace River valley upstream of Site C, the flattest slope found in shale bedrock without a horizontal clay layer approximates 2H:1V.

Figure 4 shows the natural break line, which is established as the location where a line at 2H:1V through the shale, 1.5H:1V through the gravel and 4H:1V through the glaciolacustrine materials drawn from the edge of the river bank daylights on the plateau above the slope, and the break line for the Stability Impact Line, which is established as the location where a line at 2H:1V through the shale, 1.5H:1V through the gravel and 4H:1V through the glaciolacustrine materials drawn from the edge of the toe of the slope daylights on the plateau above the slope. At this location there is no difference between the natural break line and the reservoir break line as the river is located near the toe of the slope.

Figure 4
Sample location with bank approximately 200 m high
with no clay layer in shale



The reservoir level is below the top of the gravel so the groundwater conditions in the glaciolacustrine materials will be unaffected by filling the reservoir. Therefore, the reservoir will have no impact on the stability of the glaciolacustrine materials.

5.5 Recommendations

It is recommended that the feasibility of using remote sensing technologies, such as PSInSAR™ (a technology for ground deformation monitoring, using satellite-borne radar imaging) and air-borne LiDAR, should be investigated as a means of locating areas of natural instability that may not have been previously identified and for long term monitoring of the reservoir slopes if the Site C Project is constructed.

If the project proceeds further, it is recommended that:

- more detailed investigations of the slopes of the reservoir shoreline be undertaken especially close to existing residential development; and
- a slope monitoring program around the potential reservoir shoreline be established using remote sensing, with permanent GPS stations and in place inclinometers in areas where large landslides have occurred in the past or in locations where potential large slides are identified.

If the Site C dam is constructed, it is recommended that the performance of the slopes of the reservoir shoreline be monitored before and after reservoir filling, and the Stability Impact Line be reviewed, and adjusted if required, to account for the actual performance of the slopes.

6. EROSION IMPACT LINE

6.1 Definition and Commentary

Definition: The boundary beyond which the land adjacent to the reservoir is not expected to be affected by progressive shoreline erosion and beach development as a result of the creation, or normal operation, of the reservoir.

Commentary: Progressive shoreline erosion and beach development does not typically have an immediate effect on property or threaten human life; however, sudden, relatively small, localized slope failures due to undercutting of the bank can be expected.

Shoreline erosion is an ongoing process so the Erosion Impact Line should be predicted for several time intervals to demonstrate the expected progressive nature of shoreline erosion.

In some cases it may be possible to use protective works to control or limit shoreline erosion.

The banks of the Peace River and its tributaries are naturally being eroded by river flows. A natural erosion line will therefore be established along the reaches where natural erosion is significant, particularly at the upstream end of the reservoir and on the tributaries where the reservoir depth will be shallow. While establishing the Erosion Impact Line, existing natural erosion that will not be affected by the reservoir will be noted but such areas will not necessarily be included on the reservoir side of the Erosion Impact Line. Areas of existing natural erosion, that will be affected by the reservoir, will be incorporated into the Erosion Impact Line.

6.2 Criteria

Erosion of the reservoir shoreline would be caused by wind generated waves and long shore currents. Since this is a continual process, average annual wind data will be used to estimate the progressive shoreline erosion and beach development. Sensitivity analyses will be done to determine the effects of unusual wind storms.

6.3 Methodology

After reservoir filling, bank erosion due to undercutting and the movement of material downstream by the Peace River and its tributaries will cease; but long-term progressive shoreline erosion and beach development will begin within the normal operating range of the reservoir.

Based on a literature review, the method proposed by Penner (2000) is considered to represent the current state of practice for predicting progressive shoreline erosion, slope regression and beach development around reservoirs, and will be used to establish the Erosion Impact Line.

According to Penner, shoreline erosion is caused by several interacting processes: wave erosion of the bluff toe; beach flattening and down-cutting by current and wave action; mass-wasting of the shoreline bluff from weathering, periodic failures of the bluff; removal of failed bluff slope debris by wave action; and offshore and alongshore transport of eroded sediment. For modeling purposes shoreline erosion is visualized in three stages of evolution as shown in Figure 5, which is taken from Penner (1993) and shows nearshore and beach slope angles typical for erosion in fine grained glacial lake sediment around the Great lakes and Lake Winnipeg:

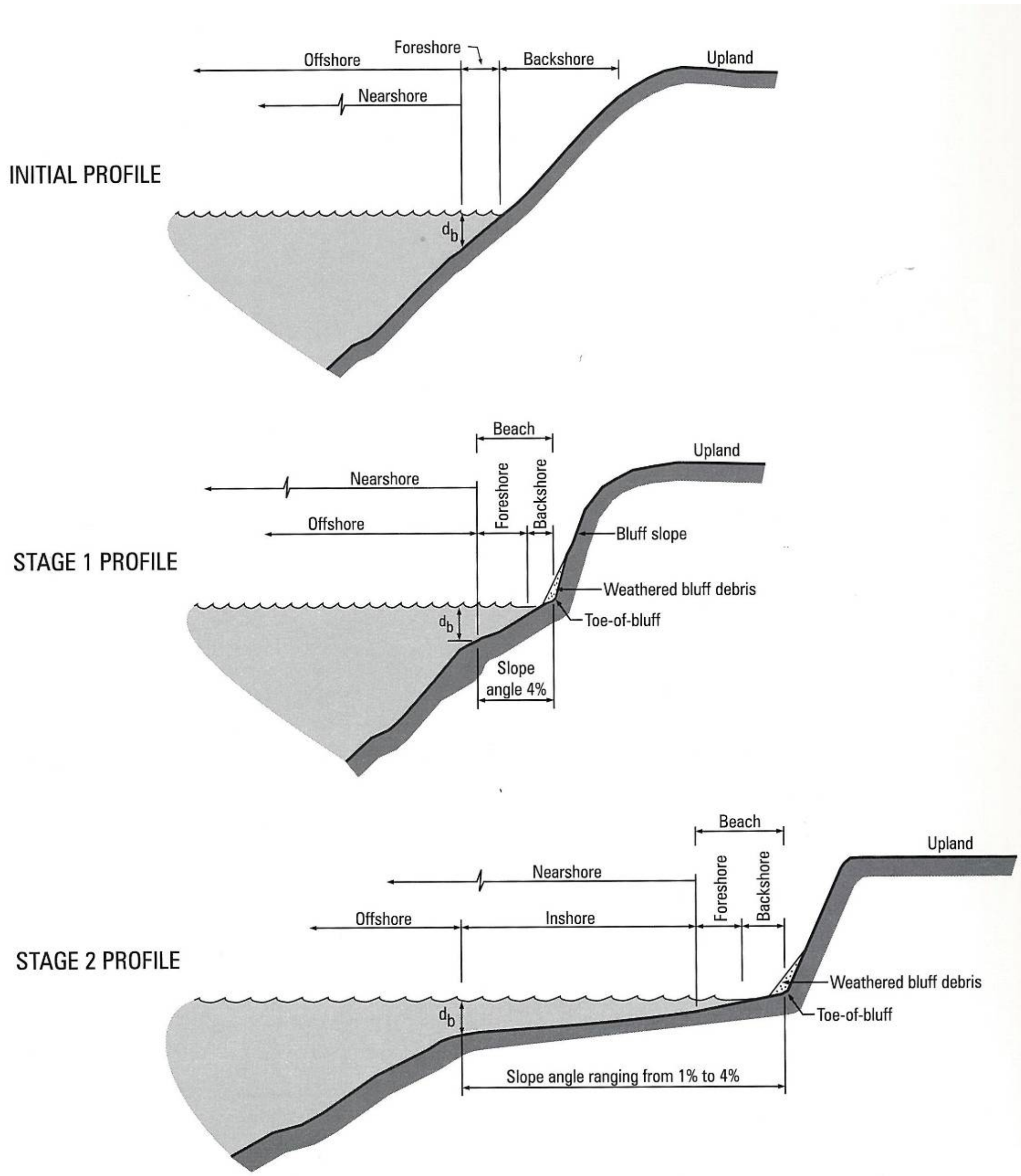
1. The initial stage occurs when waves wash and erode previously un-flooded slopes around a new reservoir. A narrow beach slope forms, backed by an adjoining bluff face. During this early stage, erosion of the bluff toe and bluff mass wasting dominate the shoreline erosion process.

2. As erosion continues, the beach slope widens and the bluff face gets higher. The height of the evolving bluff depends on the topography of the pre-erosion shoreline zone. Beach erosion becomes increasingly important, although erosion of the bluff toe and bluff mass wasting are still significant.

3. With continued erosion, the beach slope widens and flattens and beach down-cutting begins to dominate the erosion process. Bluff mass wasting continues, but is largely independent of wave erosion effects except for removal of bluff debris by wave action.

Figure 5

Shoreline Evolution



Penner developed a numerical model for predicting erosion rates on lakes and reservoirs by: synthesis of data in published papers and reports; measurements of historical erosion rates; and field studies of three reservoirs in the Prairies.

The model predicts volumetric rates of erosion (m^3/yr per metre of shoreline) based on a linear relationship between the erodibility coefficient of the geological material being eroded and the annual wave energy. It is important to note that this method estimates the volume of material eroded per year, therefore the landward progression of a high bluff will be slower than a low bluff, as the higher bluff will produce more material to be transported away.

Prerequisites for predicting the post-erosion shoreline profile are the beach slope and bluff slope angles that will form.

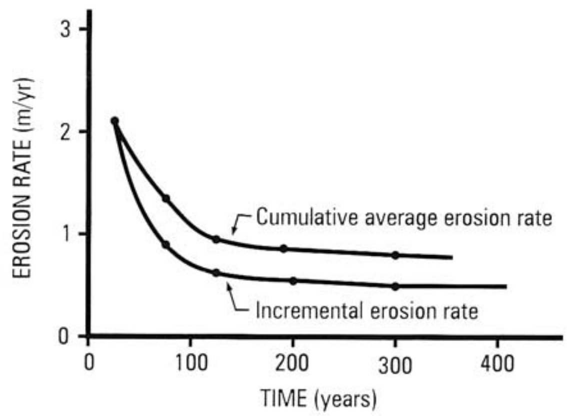
The impact of storms on long-term erosion rates is accounted for by incorporating the full range of historical wind velocities and durations into the wave energy calculations. However, short term erosion rates due to storms, although temporary, may exceed long-term average rates predicted by the model. Similarly, short-term erosion rates between storms may be much lower than long-term average rates.

The Erosion Impact Line will be established using the geology of the same representative reaches of reservoir shoreline used to establish the Stability Impact Line. Erodibility coefficients will be based on an evaluation of existing river bank erosion and slope recession rates measured from ortho-rectified historical air photos; experience on other reservoirs and lakes, including Williston Reservoir and Moberly Lake; and on judgment. The beach and bluff slope angles will be based on observations from natural lakes and reservoirs. The Erosion Impact Line will be predicted for several time intervals up to 100 years, to demonstrate the expected progressive nature of shoreline erosion.

Figure 6, which is taken from Penner (1993), shows how the estimated erosion rate decreases with time as the beach evolves. The erosion rates shown in Figure 6 were calculated for Wuskwatim Lake in Northern Manitoba and are shown in this report to illustrate how erosion rates change with time. The actual rates at Site C will depend on wind energy, the erodibility of the various materials forming the shoreline, and the topography.

Figure 6

Declining Erosion Rates with Time



Because the bluff of the regressing shoreline becomes unstable as beaching progresses and the bluff is undercut, the Stability Impact Line will be established to encompass the Erosion Impact Line.

As described in Section 4.2.2, the only available wind data for the prediction of erosion are from the Fort St John airport, which may not be representative of the winds that would exist in the valley after the reservoir has been filled. During Stage 2, five wind stations were installed in the valley upstream of Site C to collect wind data near the proposed maximum normal reservoir level. The Fort St John wind data will be used for establishing the Erosion Impact Line until more sufficient wind data has been collected from these wind stations at which time the Erosion Impact Line should be updated. The lack of in-valley wind data results in uncertainty in the Erosion Impact Line established using the available data.

There are different methods that can be used to reduce the rate of or halt progressive shoreline erosion and beach formation. As part of the Stage 2 studies, the Erosion Impact Line will not consider such methods, other than at Hudson's Hope.

6.4 Recommendations

If the project proceeds to the next stage, it is recommended that:

- additional information should be obtained on erosion rates and beaching processes on reservoir shorelines in British Columbia that are similar to the proposed Site C reservoir, to better define the erosion rates of the materials that will form the shoreline of the proposed Site C reservoir;

- field investigations should be carried out to better define the geological conditions along those portions of the proposed shoreline which are covered with colluvium or vegetation to better define the thicknesses of the materials;
- the Erosion Impact Line should be reviewed and updated using wind data from the climate stations that are being installed in the Peace River valley as part of the Stage 2 studies; and
- consideration should be given to selecting locations where shoreline erosion can be monitored should the Site C dam be constructed.

If the Site C dam is constructed, it is recommended that, in addition to the general requirements for periodic updating of the impact lines given in Section 3.4:

- shoreline erosion monitoring baselines should be established prior to reservoir filling; and
- the Erosion Impact Line should be reviewed, and adjusted as required, based on actual erosion, erosion processes, and erosion rates measured at the baseline locations.

7. GROUNDWATER IMPACT LINE

7.1 Definition and Commentary

Definition: The boundary beyond which groundwater levels in the land adjacent to the reservoir are not expected to be affected by the creation, or normal operation, of the reservoir.

Commentary: Groundwater Impact Line will identify areas where groundwater levels will be increased by the reservoir so that potential effects on water well supply, habitable buildings (e.g. basement flooding and septic systems), natural vegetation and agriculture can be indentified.

The Groundwater Impact Line will not address effects of raised groundwater levels on slope stability, which will be included in the Stability Impact Line.

7.2 Criteria

Groundwater recharge from the surface will be determined from the average annual precipitation at Fort St John.

7.3 Methodology

The Groundwater Impact Line will identify the areas where the groundwater levels are expected to increase due to filling of the reservoir so that the impacts on water well supply, flooding of low lying areas, natural vegetation, agriculture, basements and septic systems can be identified.

Klohn Crippen Consultants Ltd. (2005) conducted a conceptual, desk-top groundwater study of the proposed Site C reservoir area. The report documented water supply wells within 3 km of the Peace River, and estimated potential changes in groundwater quantity and quality as a result of filling the reservoir to elevation 464.1 m[10].

The Klohn Crippen Consultants Ltd. (2005) study has some limitations:

- it did not fully investigate the effects of the reservoir on the water supply wells for Fort St. John; and

[10] It is not known why the terms of reference for the 2005 study used the reservoir elevation of 464.1 m rather than 461.8 m.

- the effect of flooding any contaminated sites on groundwater conditions was considered beyond the scope of the study and not pursued.

Regional groundwater flow in the overburden and bedrock adjacent to the Peace River is three dimensional in nature and will be modeled using FEFLOW®. This software package is a three dimensional finite element program capable of modeling fracture flow, time-varying boundary conditions and material parameters, saturated and unsaturated flow. It will be used to prepare a regional numerical model which will be used to estimate the steady-state, pre-project, groundwater flow, and the lateral extent of groundwater effects of reservoir filling.

The data to develop the numerical model will include:

- surface topography derived from the project digital elevation model, developed from the LiDAR survey;
- geologic data used for the Stability Impact Lines and the Erosion Impact Lines
- GIS information on land uses; and
- information available through the BC Ministry of Environment, Groundwater Section.

The ground surface and the surface of each regionally significant stratum (e.g. glaciolacustrine deposits, basal gravel, and shale bedrock) will be modeled. These surfaces will be based on the geological mapping of the river valley, supplemented by other available geological data (e.g. water well logs).

The model will be calibrated to pre-project conditions and used to simulate the results of groundwater changes due to filling of the reservoir. Piezometric maps will be produced to indicate the extent of the anticipated regional groundwater impacts.

Key sensitivities in numerical model parameters will be identified and recommendations will be provided for future work and site groundwater investigations to reduce modeling uncertainty.

Changes in groundwater chemistry attributable to changes in groundwater levels will not be considered in Stage 2, but the numerical model could be used in future stages to estimate such changes, and the effects of groundwater changes on contaminated sites.

7.4 Recommendations

If the project proceeds further, it is recommended that where required, the numerical model and the Groundwater Impact Line should be updated to predict any ground water quality impacts from contaminated sites.

If the potential Site C dam is constructed, it is recommended that, in addition to the general requirements for periodic updating of the impact lines given in Section 3.4:

- monitoring of some of the groundwater wells that could be impacted by the reservoir should commence sufficiently in advance of reservoir filling to provide baselines for groundwater level and quality;
- groundwater monitoring wells should be installed sufficiently in advance of reservoir filling to provide baselines for groundwater level and quality, if required to supplement the monitoring of existing groundwater wells in some areas;
- the monitoring wells should be monitored during reservoir filling and for several years after reservoir filling; and
- the results of the monitoring should be used to update the numerical model and Groundwater Impact Line.

8. LANDSLIDE-GENERATED WAVE IMPACT LINE

8.1 Definition and Commentary

Definition: The boundary beyond which the land adjacent to the reservoir is not expected to be affected by waves generated by a landslide into the reservoir.

Commentary: It is proposed that landslides considered for the Landslide-Generated Wave Impact Line will include both:

- those that result from the creation, and normal operation of, the reservoir; and
- existing naturally unstable areas, that may not be affected by the reservoir, but whose effects could be increased by the presence of the reservoir.

In the latter case, it is proposed that the Landslide-Generated Wave Impact Line will include only the area affected by the landslide-generated wave but not the slide area itself. As noted in Section 5, existing naturally unstable areas that are not affected by the reservoir will not be included within the Stability Impact Line.

8.2 Criteria

In areas where large slides have occurred in the past and where potential large slides have been identified, slide volumes and velocities identified in previous studies will be used to estimate the waves that could be generated by those landslides.

A hypothetical slide of 75,000 m^3 with a velocity of 3 m/s will be used to estimate the landslide generated waves in all other parts of the shoreline.

8.3 Methodology

In the early 1980s, two 1:400 scale physical hydraulic models were used to investigate the nature and magnitude of waves that could be generated by potential landslides entering the proposed Site C reservoir.

The Western Canada Hydraulic Laboratories Ltd. (1981) model simulated 6 km of the reservoir upstream of the proposed dam site, and 3 km of the Moberly arm of the reservoir. The model was used to investigate waves generated by potential landslides in the Tea Creek area and in the Moberly River valley. The model testing was focused on determining the landslide-generated wave run-up on the proposed dam and the freeboard required to prevent overtopping of the dam.

The Northwest Hydraulic Consultants Ltd. (1983) model simulated a 22 km long section of the reservoir and was used to investigate waves generated by potential landslides on the south bank, in the vicinity of the 1973 Attachie slide, and the slopes opposite Bear Flat. The model testing was focused on determining the landslide-generated wave run-up directly across the valley, on the north bank of the reservoir, and the potential effects on Highway 29 and proposed recreation areas.

The Landslide Generated Wave Impact Line for the reservoir shoreline in the vicinity of the proposed Site C dam, at Bear Flat and at the Halfway River will be based on the landslide-generated wave data from the 1981 and 1983 physical hydraulic model tests.

The Landslide Generated Wave Impact Line for the remainder of the reservoir shoreline will be based on published empirical methods for estimating landslide-generated wave heights.

Table 2 summarizes a number of methods to predict landslide-generated wave heights. These methods require the landslide and reservoir characteristics to be simplified, and provide order of magnitude estimates of the wave heights generated and propagated by the simplified landslide.

Table 2 Empirical Methods for Estimating Landslide-Generated Wave Heights

Source	Basis	Key Variables
Huber and Hager (1997), Huber (1997) and Huber (1982)	Physical model studies	Relative slide mass, still water depth
Pugh and Chiang (1986)	Morrow Point Dam physical model study results	Slide Froude number, relative distance, displacement parameter
Noda (1970)	Analytical, comparison to experimental and actual data	Slide Froude number
Slingerland and Voight (1979)	Physical model studies at USACE Waterways Experimental Station	Dimensionless slide kinetic energy (slide volume, Froude number)
Kamphuis and Bowering (1970)	Experiment	Slide volume/unit width, slide Froude number
Northwest Hydraulics (1983a)	Review of landslide-generated wave estimates	Slide dimensions, slide Froude number, slide position with time once in the water

Both the Western Canada Hydraulic Laboratories (1981) and the Northwest Hydraulic Consultants (1983) hydraulic model studies demonstrated that the landslide-generated wave heights increase with landslide velocity. For example at Bear Flat, increasing the peak landslide velocity from 7 m/s to 27 m/s increased the maximum recorded wave height from 1 m to 10 m. However, some of the empirical methods listed in Table 2 do not explicitly consider landslide velocity (e.g. Huber and Hager (1997) and Pugh and Chiang (1986)).

Tannant (1984) undertook a comparison of the maximum wave heights, obtained from several theoretical and empirical methods, with the maximum wave heights obtained from the above referenced 1981 and 1983 hydraulic model studies. The theoretical and empirical methods compared were the modified Bakhmeteff method (described in Northwest Hydraulics (1983), Slingerland and Voight (1979), and Kamphuis and Bowering (1970)). As part of locating the Landslide-

Generated Wave Impact Line, Tannant's comparison will be expanded to include the other empirical methods listed in Table 2.

According to Huber and Hager (1997) landslide-generated wave run-up height depends on:

- wave height;
- wave length;
- wave speed;
- water depth; and
- run-up slope angle.

The methods proposed by Huber and Hager (1997), Dean and Dalrymple (2006), USACE (2003), Synolakis (1987) and Gedik (2004) will be used for estimating wave run-up on the shoreline of the reservoir.

Waves generated by a landslide attenuate as they travel up and down a lake or a reservoir. The methods proposed by Huber and Hager (1997), Dean and Dalrymple (2006) and Kranzer and Keller (1959) will be used for estimating wave attenuation.

When a wave traveling along a lake or reservoir reaches a shallow area, for example a flooded terrace, the wave height can be amplified. Amplification will be estimated based on Dean and Dalrymple (2006), USACE (2003) and d'Angremond et. al. (1996).

Weighting factors will be applied to the estimates of wave height, run-up, attenuation and amplification based on:

- a comparison between the empirical methods and the above referenced 1981 and 1983 hydraulic model studies;
- the applicability of each method given the configuration of the postulated slide;
- the published limitations of each method; and
- judgment.

The results of all methods will be tabulated to illustrate the uncertainty in the estimates.

8.4 Pertinent Case Histories

Slide generated waves have been observed in many reservoirs and natural bodies of water around the world. These precedents will be compared to the calculated results for Site C to confirm the reasonableness of the calculations.

8.5 Recommendations

If the project proceeds further, it is recommended that:

- more detailed site-specific analyses and/or numerical modeling should be carried out on the areas where the magnitudes or the consequences of landslide generated waves are potentially great, for example near existing potential large landslides.

If the Site C dam is constructed, it is recommended that, in addition to the general requirements for periodic updating of the impact lines given in Section 3.4:

- consideration should be given to using physical hydraulic models to better predict the Landslide-Generated Wave Impact Line in areas where the magnitudes or consequences of landslide generated waves are potentially great, for example near existing known potential large landslides; and
- the Landslide Generated Wave Impact Line should be reviewed, and adjusted if required, five years after first flooding or normal operation of the reservoir, if any additional information on potential large landslides becomes available.

9. REFERENCES

Alberta Environment (2005). *Alberta Reservoir Lands Guidelines,* Alberta Environment, Edmonton.

Association of Professional Engineers and Geoscientists of British Columbia (2008), *Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia*.

BCBC (BC Building Code) (1998), *BC Building Code 1998*, BC Ministry of Municipal Affairs.

BCBC (BC Building Code) (2006), *BC Building Code 2006*,. Office of Housing and Construction Standards, BC Ministry of Forests and Range Minister Responsible for Housing Government of British Columbia.

BC Hydro (1981), *Peace River Site C, Report on Reservoir Slopes*, Report No. H1361.

BC Hydro (1985), *Peace River Development, Site C Project Hydraulic Design Memorandum*, Report No. H1836.

BC Hydro (1993), *Geotechnical Guidelines for Determining Slope Stability and Groundwater Impacts on Reservoir Shorelines for Land use Purposes*, Provisional Issue, Report No. H2293.

BC Ministry of Environment, Lands and Parks Water Management Branch (2000), *Dam Safety Guidelines.*

BC Ministry of Transportation (BC MOT) (1993), *Subdivision Policy and Procedures Manual*.

BC Ministry of Transportation (BC MOT) 2005, *Guide to Rural Subdivision Approvals*, Sections 2.3.1.06 and 2.3.1.07.

BC Ministry of Water, Land and Air Protection (2004), *Flood Hazard Area Land Use Management Guidelines.*

BC Resource Inventory Committee (RIC) (1996). *Terrain Stability Mapping in British Columbia: a review and suggested methods for landslide hazard and risk mapping* (Draft)..

Berger T.B. (1973), *Reasons for judgment for the Honourable Mr Justice Berger on the matter of the Land Registry Act – and on application for approval of a proposed subdivision by Cleveland Holdings Ltd*, Supreme Court of British Columbia.

BGC Engineering Inc (2006), *Berkley Landslide Risk Management Phase 1 Risk Assessment*, Report to the District of North Vancouver.

Canadian Dam Association (CDA) (1999), *Dam Safety Guidelines 1999*, Edmonton, AB

Canadian Dam Association (CDA) (2007), *Dam Safety Guidelines 2007*, Edmonton, AB.

Cave P.W. (1992a, revised 1993), *Hazard acceptability thresholds for development approvals by local governments*, in Proceedings of Geological Hazards Workshop, BC Geological Survey Branch, Open File 1992-15, p 15-26.

d'Angremond, K., J. W. van der Meer, and R. J. de Jong (1996), *Wave transmission at low-crested structures*, ASCE, Proceedings of the 25th ICCE, Orlando, USA. pp 2418-2427.

Dean, R. G. and R. A. Dalrymple (2006), *Water Wave Mechanics for Engineers and Scientists*, Prentice Hall, Inc.

Dercole, F. (2008), Landslide Risk Management in the District of North Vancouver, in Proceedings of the Canadian Geotechnical Conference, GeoEdmonton 2008, pp 1048-1049

Environment Canada (2008), GRP122 – Extreme Value Analysis performed on Fort St. John A climate station data (Climate ID: 1183000), September.

Fell, R., Ho, K.K.S., Lacasse, S., and E. Leroi, (2005). *A Framework for Landslide Risk Assessment and Management*, in Proceedings of the International Conference on Landslide Risk Management. Hungr, Fell, Couture and Eberhardt (eds.), Balkema,, pp3-26.

Gedik, N., Irtem, E. and S. Kabdasli (2004). *Laboratory Investigation on Tsunami Run-Up*,Ocean Engineering, vol 32, no 5-6, pp 513-528.

Huber, A., W. H. Hager (1997), *Forecasting Impulse Waves in Reservoirs*, in Proceeding of 19th International Congress on Large Dams, Florence, 1997

Huber, A. (1997), *Quantifying impulse wave effects in reservoirs*, in Proceedings 19th International Congress on Large Dams, Florence, 1997.

Huber, A. (1982), Impulse Waves in Swiss Lakes as a Result of Rock Avalanches and Bank Slides - Experimental Results for the Prediction of the Characteristic Numbers of These Waves, in Proceedings of 14th International Congress on Large Dams, Rio de Janeiro 1982.

Hungr, O. (1997), *Some Methods of Landslide Hazard Intensity Mapping*, in Proceedings of the International Workshop on *Landslide Risk Assessment.* Cruden and Fell (eds), Balkema, pp 215-226.

ICOLD (1993), *Embankment Dams Upstream Slope Protection*. Bulletin 91

ICOLD (2002), *Reservoir Landslides: Investigation and Management, Guidelines and Case Histories*. Bulletin 124.

Imrie, A. and D. Moore (1997), *BC Hydro's Approach to Evaluating Reservoir Slope Stability from a Risk Perspectiv*", in Proceedings of the International Workshop on Landslide Risk Assessment. Cruden and Fell (eds), Balkema, pp 197-206.

Kamphuis, J.W. and R.J. Bowering (1970), *Impulse Waves Generated by Landslides*, in Proceedings of the 12th Coastal Engineering Conference, ASCE, pp 575 - 588.

Klohn-Crippen Integ (1989), *"Preparatory Engineering Activities for Peace River Site C, Spillway Design Floods, Task CH30"*, Report No. KC23.

Klohn-Crippen Integ. (1990), *Preparatory Engineering Activities for Peace River Site C, Preliminary Layout of the Right Bank Structures, Task CH70,* Report No. KC50.

Klohn Crippen Consultants Ltd. and SNC-Lavalin Inc. (2003), "*Peace Cascade Development, Prefeasibility Study for a Cascade of Low Consequence Structures as an Alternative to Site C*".

Klohn Crippen Consultants Ltd. (2005), *Peace River Ground Water Study,* Report for Triton Environmental Consultants Ltd.

Krazner, H. C. and J. B. Keller (1959), *Water Waves Produced by Explosions*, Journal of Applied Physics, vol 30, pp 398-407.

Leroi, E., Bonnard, Ch., Fell, R., and R. McInnes (2005), *Risk Assessment and Management*, in Proceedings of the International Conference on Landslide Risk Management. Hungr, Fell, Couture and Eberhardt (eds.), Balkema,pp 159-198.

National Building Code of Canada (NBCC) (1995), *National Building Code of Canada 1995,* National Research Council of Canada.

National Building Code of Canada (NBCC) (2005), *National Building Code of Canada 2005,* National Research Council of Canada.

Noda, (1970), *Water Waves Generated by Landslides*, ASCE, Journal of the Waterways, Harbors and Coastal Engineering Division, WW4, pp. 835-855.

Northwest Hydraulic Consultants Ltd. (1983), *Peace River Site C Project, Model of Landslide Waves at Attachie and Bear Flat Areas,* Northwest Hydraulic Consultants Ltd., (1983a), *Review of Landslide Generated Wave Analysis*.

Ontario Ministry of Natural Resources (1999), *Ontario Dam Safety Guidelines, DRAFT,* Lands and Natural Heritage Branch.

Penner, L. A., R.G. Boals (2000). *A Numerical Model for Predicting Shore Erosion Impacts Around Lakes and Reservoirs,* Canadian Dam Association, pp 75 – 84

Penner, L. A., (1993). *Shore Erosion and Slumping on Western Canadian Lakes and Reservoirs, A Methodology for Estimating Future Bank Recession Rates,* Environment Canada, Monitoring Operations Division.

Pugh, Cliffor A, and Wen-Li Chiang (1986), *Landslide-Generated Wave Studies,* Water Forum

Slingerland, R.L. and B. Voight (1979), Predictive Models of Landslide-Generated Water Waves, in Rockslides and Avalanches, Vol 2, B. Voight, editor, Elsevier.

Smith, CD. (1995), *Hydraulic Structures*. University of Saskatchewan.

Synolakis, C.E. (1987), *The Runup of Solitary Waves*. Journal of Fluid Mechanics, vol 185, pp 523-545.

Tannant, D. (1984), *An Assessment of Hydraulic Modelling as a Method of Prediction of Landslide-Generated Wave Heights on a Proposed Reservoir in Northeastern British Columbia*", Thesis, Department of Civil Engineering, University of British Columbia.

Thurber Consultants Ltd. (1978). *Site C Reservoir Shoreline Stability Assessment*, Report to BC Hydro, Report No. 15-2-62.

UK Department for Environment, Food and Rural Affairs (UK DEFRA) (2002). *Reservoir Safety – Floods and Reservoir Safety Integration*, Surrey.

US Army Corps of Engineers (USACE) (1997). *Hydrologic Engineering Requirements for Reservoirs*, Engineering Manual EM1110-2-1420, p 18-1 – 18-4, Washington, DC.

US Army Corps of Engineers (USACE) (2003). *Coastal Engineering Manual*..

US Federal Emergency Measures Agency (FEMA) (2004). *Federal Guidelines for Dam Safety: Emergency Action Planning for Dam Owners*, FEMA 64, Washington, DC.

Visher, D.L. (1986). *Rockfall-induced waves in reservoirs*, Journal of International Water Power & Dam Construction, Vol ??, No ??, pp ??.

Washington State Department of Ecology (2004), *Dam Safety Guidelines*.

Western Canada Hydraulic Laboratories Ltd. (1981), *Site C Project, Landslide Generated Wave Study, Moberly and Tea Creek Slides*.