Preliminary reservoir impact lines for the Site C Clean Energy Project

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The Site C Clean Energy Project is a planned third dam and hydroelectric generating station on the Peace River in northeast British Columbia, Canada. The Site C dam would be an earthfill dam with a height of approximately 60 m and would create a reservoir that would be approximately 83 km long. A detailed assessment was undertaken to characterize the potential for groundwater changes, flooding, shoreline erosion, slope instability and landslide-generated waves resulting from the impoundment and operation of the reservoir. The results of this assessment were used to generate preliminary reservoir impact lines that delineate areas of potential hazard. Four preliminary impact lines have been prepared in accordance with guidance provided by the International Commission on Large Dams: a Flood Impact Line, an Erosion Impact Line, a Stability Impact Line, and a Landslide-Generated Wave Impact Line. The reservoir impact lines are linked to recommendations for site-specific analysis, land use, and monitoring. They were intended to support the environmental assessment and the management of risks to public safety, land use and infrastructure. The objectives of this paper are threefold. First, this paper provides definitions for the Flood, Erosion, Stability, and Landslide-Generated Wave impact lines. Second, it describes how preliminary reservoir impact lines were developed for a new hydroelectric project in a geological environment comprising marine clay shales and a complex sequence of fluvial and glaciolacustrine sediments. Third, it illustrates how, when combined with emerging hazard and risk tolerance criteria, impact lines can be used to help communicate and manage geohazard risks around existing and proposed new hydroelectric reservoirs, and potentially along river, lake and marine shorelines.

RÉSUMÉ
Le Projet d'Énergie Propre du Site C prévoit la construction d'un troisième barrage et d'une centrale hydroélectrique sur la rivière Peace dans le nord-est de la Colombie-Britannique, au Canada. Le barrage du Site C serait un barrage en terre d'une hauteur d'environ 60 m et créerait un réservoir d'environ 83 km de long. Une évaluation détaillée a été réalisée pour caractériser les changements potentiels au niveau de l'eau souterraine, des inondations, de l'érosion des berges, des instabilités de pente et des vagues générées par des glissements de terrain résultant de la création et de l'exploitation du réservoir. Les résultats ont été utilisés pour générer des lignes d'impact préliminaires du réservoir qui délimitent les zones de danger potentiel. Quatre lignes d'impact préliminaires ont été préparées conformément aux indications fournies par la Commission Internationale des Grands Barrages: une ligne d'impact des inondations, une ligne d'impact de l'érosion, une ligne d'impact de stabilité et une ligne d'impact de vague générée par un glissement de terrain. Ces lignes d'impact du réservoir mènent à des recommandations par rapport à l'analyse d'un site spécifique, à l'utilisation du territoire et à la surveillance. Elles visent à favoriser l'évaluation environnementale et la gestion des risques pour la sécurité publique et celle de l'infrastructure. Les objectifs de cet article sont de trois ordres. Tout d'abord, cet article fournit des définitions pour les quatre types de lignes d'impact. Deuxièmement, il décrit comment les lignes d'impact préliminaires du réservoir furent développées pour un nouveau projet de centrale hydroélectrique dans un environnement géologique composé de schistes argileux marins et d'une séquence complexe de sédiments fluviaux et glaciolacustres. Troisièmement, il illustre comment, lorsqu'elles sont combinées avec des critères de tolérance de dangers et de risques émergants, les lignes d'impact peuvent être utilisées pour aider à communiquer et à gérer les risques liés aux dangers géologiques à proximité des réservoirs hydroélectriques existants et futurs et aussi potentiellement le long des rivages de rivières, de lacs et côtiers.

1 INTRODUCTION

The Site C Clean Energy Project (the Project) is a planned third dam and hydroelectric generating station near Fort St John on the Peace River in northeast British Columbia (Figure 1). The Site C dam would be an earthfill dam approximately 1,050 m in length, with a height of approximately 60 m above the riverbed. It would create a reservoir that would be approximately 83 km long and, on average, two to three times the width of the current river.

Highway 29 is situated on the north bank of Peace River between Hudson's Hope and Fort St John. The reservoir would inundate four sections of the current highway alignment at the location of tributary stream crossings, including (from west to east) Lynx Creek, Farrell Creek, Halfway River, and Cache Creek. BC Hydro has prepared definition-level designs to re-align these highway sections by using a combination of elevated causeways and bridge structures. Additional adjustments to the highway alignment are planned at Dry Creek and east of Farrell Creek in order to upgrade drainage structures and to avoid areas prone to reservoir shoreline erosion.

A detailed geotechnical assessment was undertaken to characterize the potential for groundwater changes, flooding, shoreline erosion, slope instability and landslide-generated waves resulting from the impoundment and operation of the reservoir. The results of this assessment were used to generate preliminary reservoir impact lines that delineate areas of potential hazard. The reservoir impact lines are linked to recommendations for site-specific analysis, land use, and monitoring. They were intended to support the environmental assessment and the management of risks to public safety and infrastructure.

The purpose of this paper is to describe the development of the reservoir impact lines and to describe measures proposed by BC Hydro to manage public safety within those lines.

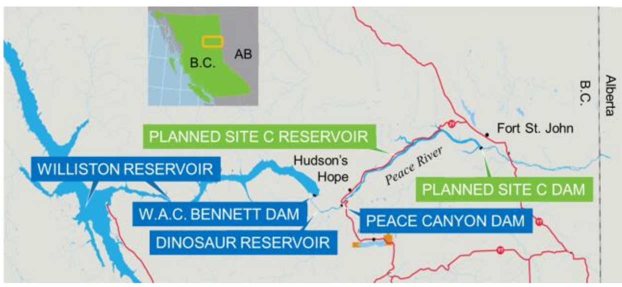

Figure 1. Site C location map.

2 HISTORICAL INVESTIGATIONS

BC Hydro has previously considered the development of a hydroelectric dam at Site C. Numerous reservoir shoreline geotechnical investigations were undertaken by BC Hydro and its consultants in the 1970s and early 1980s. This work included desk study reviews of maps, aerial photographs and published literature on regional overburden and bedrock geology; aerial reconnaissance and field mapping of soil and bedrock exposures and known landslide areas; and completion of geotechnical drill holes and installation of instrumentation to monitor groundwater levels and indications of slope movement.

Historical geotechnical analyses included assessments of shoreline erosion potential; assessments of potential changes in groundwater conditions caused by impoundment and operation of the reservoir; slope stability analyses; and physical modelling of the runup of potential landslide-generated waves.

Results of the historical shoreline geotechnical investigations and analyses were used to establish a 'residential safeline' around the proposed reservoir. The safeline was defined as "a conservatively located line beyond which the security of residents and residential improvements can be reasonably assured" (Thurber 1978). The safeline took into consideration the combined potential spatial extent of flooding, erosion, landslides and landslide-generated waves. The position of the safeline was based on the hazard that could potentially affect land furthest from the reservoir, plus a margin of safety. A shoreline stability classification was established to describe the expected degree of change to slope stability caused by the reservoir.

In 1983, the BC Utilities Commission issued a report in which it concluded that the approach taken by BC Hydro to characterize potential reservoir hazards, combined with commitments made for continued and ongoing investigation and monitoring, were sufficient to protect the public (BCUC 1983). However, the Commission also recommended that every effort be made to distinguish between lands that were truly hazardous and those that could be used safely for certain purposes.

The reservoir impact lines represent an updated approach based on guidelines prepared by the International Commission on Large Dams (ICOLD 2002) and standards of practice employed within the province of British Columbia as documented by the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC 2010) for the assessment of landslide hazards for new residential development. Compared to the residential safeline, the impact lines provide more information on the expected likelihood and nature of the hazards, and therefore facilitate more effective monitoring and flexible land use planning.

3 BEDROCK AND OVERBURDEN GEOLOGY

The bedrock and overburden geology of the Site C reservoir shoreline and adjacent slopes has the greatest influence on the predictions of erosion and slope stability, and, in turn, the position of the reservoir impact lines. Relevant information on the geology of the Peace River valley is summarized below and was used to develop a geological model of the proposed reservoir shoreline. The geological model builds upon information gathered during the historical investigations using the results of subsequent academic research, instrumentation monitoring, and recent investigations that have benefited from the use of modern tools such as high-resolution LiDAR imagery. Results of the geological model update were presented by way of interpreted geological cross sections and fence diagrams (elevation views) of the proposed reservoir shoreline (BGC 2012). A sample portion of a fence diagram is shown in Figure 2.

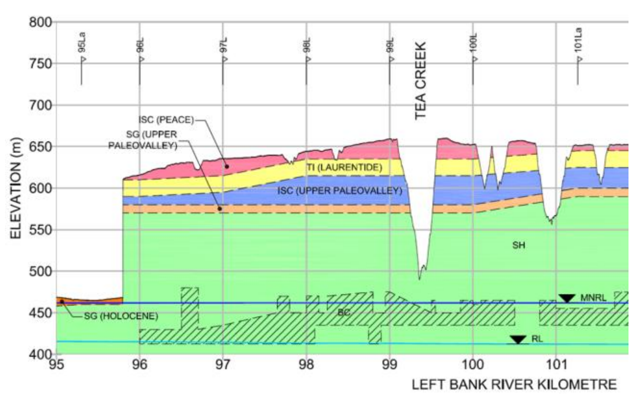

Figure 2. Sample geological fence diagram.

3.1 Physiography

The Peace River valley is broad and flat-floored, occupying a trench approximately 3.5 km wide and 200 m deep. The river typically ranges from 0.5 to 1 km wide. Wide fluvial terraces are common between the floodplain and the broader valley walls, and are typically elevated less than 75 m above river level. At locations where the river is adjacent to such terraces, the slopes are referred to as 'low banks'. Elsewhere, where the river is in direct contact with the deep valley walls, the slopes are referred to as 'high banks'.

Where the river has downcut through bedrock, the valley walls rise sharply at angles exceeding 35°; however, where colluvium has accumulated, the valley walls can slope as low as 10°. The upper limit of the valley slopes is sharply defined and is often notched by drainage gullies and scalloped by landslide scarps.

3.2 Bedrock Geology

The reservoir area is underlain by gently northeast-dipping Upper and Lower Cretaceous sedimentary rocks, which include conglomerates, sandstones and marine shales of the Bullhead Group, shales and sandstones of the Fort St. John Group and sandstones and conglomerates of the Dunvegan Formation (Stott 1982). These rocks were deposited in an extensive marine embayment that stretched from the Arctic to the central part of the continent and included several major deltas (Stott 1982). They are a key source of oil and natural gas in Canada.

For the purposes of groundwater, erosion and stability analyses, the bedrock units were grouped based on similar dominant grain size, age and susceptibility to erosion and landslides. The simplified bedrock mapping groups are:

1. siltstone [SST]
2. silty shale [SSH]
3. shale [SH]
4. sandstone [SS]

Bedrock exposed at the proposed reservoir level was divided into three main groups on the basis of general decreasing grain size and age, and increasing susceptibility to erosion and landslides with distance downstream: 1) siltstone upstream of Gates Island; 2) silty shale between Gates Island and Cache Creek; and 3) shale downstream of Cache Creek. Sandstone is exposed in the Dunvegan Escarpment above the proposed reservoir level between Cache Creek and Wilder Creek.

3.3 Overburden Geology

The Cretaceous bedrock in the reservoir area is overlain by a Quaternary sequence of fluvial, glacial and interglacial deposits cumulatively up to 400 m thick. These include normally-consolidated deposits from Glacial Lake Peace that are present along much of the valley rim, and underlying over-consolidated deposits from Glacial Lake Mathews. An exposure of the typical Peace Valley stratigraphy is shown in Figure 3.

Figure 3. Typical Peace Valley stratigraphy exposed at Halfway River.

Investigations of the overburden materials in the area have been conducted by Mathews (1978), Cornish and Moore (1985), Hartman (2005) and Hartman and Clague (2008). Hickins and Fournier (2011) produced a surficial geology map of the area. Investigations associated with the proposed Site C dam and reservoir have also been completed by Thurber Consultants Ltd. (1978) and BC Hydro (1981). More recently, detailed surface mapping and drilling were completed by BGC (2012).

For the purposes of groundwater, erosion and stability analyses, the overburden units were grouped based on similar dominant grain size, age and susceptibility to erosion and landslides. The simplified overburden mapping groups are:

1. interbedded sand, silt and clay [ISC]
2. overburden colluvium [OC]
3. bedrock colluvium [BC]
4. sand and gravel [SG]
5. till [TI]
6. tufa [TU]

All glaciolacustrine units in the reservoir area were grouped together as ISC, while all fluvial and glaciofluvial units were grouped together as SG. Man-made fills, and a large diamicton exposure across from Lynx Creek, were also included in the SG group.

4 LANDSLIDE INVENTORY

Post-glacial downcutting of the modern Peace River during the Late Pleistocene and Holocene formed steep slopes in Cretaceous bedrock and Quaternary fluvial, glacial and interglacial deposits. The bedrock topography and the occurrence of Quaternary soils in the area are controlled by the presence of ancient Pleistocene valleys infilled by glacial drift, which have been re-excavated by the modern valley. Landslides most commonly occur within the Cretaceous Shaftesbury Formation and within glaciolacustrine deposits of laminated silt and clay. In some cases, the modern river valley intersects older valleys (paleovalleys) in which landslides were present, potentially facilitating the reactivation of paleo-landslide surfaces.

To provide an understanding of past and current landslide processes in the proposed reservoir area, and to support the analysis of potential future landslides and landslide-generated waves under proposed reservoir conditions (Sections 9 and 10), key landslide case studies were reviewed and a detailed inventory of previous landslides in the reservoir area was completed using high resolution LiDAR topographic data.

A total of 1,834 landslide complexes comprising 4,010 individual landslides were identified. Six percent were classified as compound rock slides in Shaftesbury shale, 40% were classified as compound soil slides in Glacial Lake Mathews and older glaciolacustrine deposits, 52% were classified as flow slides in Glacial Lake Peace deposits and 2% were classified as earth flows in overburden and/or bedrock colluvium.

The 1973 Attachie Slide (Figure 4), which occurred in the Glacial Lake Mathews deposits on the south bank of Peace River opposite Halfway River, was one of the largest landslides involving Pleistocene deposits in B.C. in the 20th century. With an estimated deposit volume of 14.7 million m^3, debris from the landslide travelled over 900 m from the toe of the slope and dammed Peace River for approximately 12 hrs (The Province 1973). The landslide also generated a displacement wave that broke trees up to 21 m above river level on the opposite bank (Evans et al. 1996). This event provided a key precedent for the landslide-generated wave modelling described in Section 10.

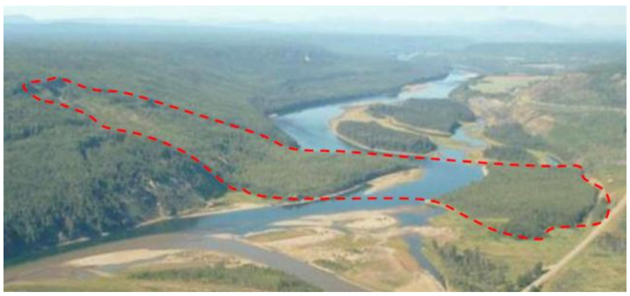

Figure 4. The 1973 Attachie Slide near Halfway River.

5 SLOPE ANGLE INVENTORY

To help establish appropriate setback angles for the Erosion and Stability Impact Lines, an inventory of existing slope angles in the reservoir area was compiled. The results of the slope angle inventory were used to establish predicted 'eroded' (short-term) and 'ultimate' (long-term) slope angles for each of the geological units around the proposed reservoir. The selected values are summarized in Table 1.

Table 1. Predicted eroded and ultimate slope angles.

Simplified Geological Mapping Unit	Eroded Slope Angle	Ultimate Slope Angle
sandstone [SS]	n/a	1H:1V (45°)
siltstone [SST]	vertical	1H:1V (45°)
silty shale [SSH]	1H:1V (45°)	1.5H:1V (34°)
shale (low bank) [SH]	1H:1V (45°)	1.5H:1V (34°)
shale (high bank) [SH]	1H:1V (45°)	3H:1V (18°)
bedrock colluvium [BC]	1.3H:1V (38°)	3H:1V (18°)
sand and gravel [SG]	1.3H:1V (38°)	2H:1V (27°)
intebedded sand, silt and clay (low bank) [ISC]	1.3H:1V (38°)	2H:1V (27°)
interbedded sand, silt and clay (high bank) [ISC]	1.3H:1V (38°)	4H:1V (14°)
overburden colluvium [OC]	1.3H:1V (38°)	4H:1V (14°)

6 FLOOD AND WIND-GENERATED WAVES

Flood discharges from Peace Canyon Dam upstream of the proposed reservoir, and from tributary valleys within the proposed reservoir, combined with wind-generated waves, have the potential to temporarily inundate lands above the Maximum Normal Reservoir Level (MNRL) of 461.8 m. Operation of the Site C auxiliary spillway would also involve surcharging the reservoir.

To help constrain the range of potential reservoir level fluctuations above the MNRL, for consideration in the establishment of a Flood Impact Line elevation, Klohn Crippen Berger and SNC-Lavalin carried out an analysis of potential floods and wind-generated waves. Flooding is more likely to temporarily inundate land above the MNRL at the upstream end of the reservoir, and where tributary streams enter the reservoir. Wind-generated wave runups are expected to vary depending on beach slope angle, fetch length, and local orientation of the shoreline relative to predominant wind directions.

7 SHORELINE EROSION

Wind-generated waves have the potential to cause shoreline erosion around the Site C reservoir. The potential erosion volumes are a function of the potential wave energy and the erodibility of the geological materials present at the reservoir shoreline. The amount of bluff recession for a given erosion volume at a given site is a function of the bank height and the inclination of the eroded slopes that are predicted to form above the shoreline. The term 'bank' is used to describe slopes within the existing river environment, whereas 'bluff' is used to describe erosional slopes in the reservoir environment.

JD Mollard and Associates Ltd. predicted shoreline erosion volumes and the associated amount of vertical bluff recession for up to 100 years of reservoir operation using wave energy estimates provided by Tetra Tech EBA. The shoreline recession estimates were used as a guide to manually generate Beach Lines, which represent the predicted position of the toe of the bluff at the MNRL after a specified period of time. For example, the 5-year Beach Line is the predicted position of the toe of the bluff at the MNRL five years after impoundment of the proposed reservoir. The 100-year Beach Line was used to develop the Erosion and Stability Impact Lines. Beach Lines were adjusted where preferential erosion of promontories could lead to loss of shelter from the wind and therefore changes in wave energy over time, and where bedrock at reservoir level could eventually become exposed and minimize further erosion. Changes in erodibility over time were also considered in cases where overlying or interbedded geological units would deposit significant quantities of gravel of lower erodibility on the newly forming beaches.

8 GROUNDWATER

To provide pore water pressure results for slope stability analyses (Section 9), groundwater seepage analyses were carried out at 24 cross sections in the reservoir area. The seepage analyses were also used to help predict changes in groundwater flow as a result of the proposed reservoir at locations where potential for soil or groundwater contamination was identified.

Model results under steady-state reservoir conditions showed a predicted increase in groundwater levels of greater than 5 m at 10 of the 24 modelled cross sections. The largest predicted changes occurred within a glacially-carved bedrock basin between Hudson’s Hope and Farrell Creek.

9 SLOPE STABILITY

To better understand the potential response of the valley slopes to erosion and groundwater changes caused by impoundment and operation of the Site C reservoir, limit equilibrium stability analyses were carried out at 21 locations along the reservoir shoreline.

The results indicate that groundwater changes would have a variable influence on the stability of potential slip surfaces that exit the slope below the MNRL, depending on the elevation of the critical slip surface relative to the toe of the slope and the MNRL. In general, where existing groundwater levels are relatively high, slip surfaces closer to the toe of the slope show a stronger buttressing effect of the reservoir, as the added weight of the reservoir water on the toe of the slope would tend to offset the effect of pore pressure increases due to groundwater rise. In contrast, higher slip surfaces closer to the MNRL, which are more likely to be unsaturated or dry under current conditions, would tend to experience a destabilizing effect.

At cross sections where overburden is exposed at the MNRL and shoreline erosion is expected to occur, the stability analyses indicate a general destabilizing effect on critical slip surfaces that exit the slope above the MNRL.

10 LANDSLIDE-GENERATED WAVES

To establish Landslide-Generated Wave Impact Lines, support the Highway 29 realignment design and support the assessment of freeboard requirements at the Site C dam site during and following construction, landslide-generated wave modelling was carried out at several key locations. Study sites were selected that involve high bank slopes with a history of large volume landslides in over-consolidated glaciolacustrine deposits (similar to those involved in the 1973 Attachie Slide) that are situated across the reservoir from low bank slopes where the potential consequences of inundation could be high.

A hybrid modelling approach was adopted that combined empirical wave generation estimates with numerical wave propagation and runup modelling. The wave generation stage was analyzed using the set of empirical equations presented by Heller et al. (2009), which are based on statistical analysis of 434 laboratory wave channel and basin tests. The wave propagation and runup stages were analyzed using the depth-averaged shallow flow numerical model *TELEMAC-2D* (Hervouet 2000). This methodology was validated through the simulation of six previous physical model tests carried out for the Site C Project by Northwest Hydraulics Consultants (1983).

For the purposes of wave modelling, landslide volumes were based on the largest landslides in over-consolidated glaciolacustrine deposits that were recorded in the local landslide inventory (Section 4). Corresponding landslide velocities were estimated using a conservative relationship based on the back-calculated peak velocity of the 1973 Attachie Slide. As noted in Section 4, the Attachie Slide provides a key precedent at Site C that suggests that future large overburden landslides in the reservoir area also have the potential to fail extremely rapidly. The recent long-runout landslide in Oso, Washington (GEER 2014), which occurred in similar over-consolidated glaciolacustrine deposits, further supports this assumption.

The highest modelled wave runup (30 m) occurred at Halfway River across from the Attachie Slide. Maximum simulated runup heights at Lynx Creek and Farrell Creek ranged up to 11 m. Although the landslide input parameters at Cache Creek and Wilder Creek were similar to those at Lynx Creek and Farrell Creek, the maximum simulated runup heights in these cases only ranged up to 6 m, reflecting a greater reservoir width at these locations and, therefore, more time for waves to dissipate before impacting the shoreline. The maximum recorded runup heights in each case typically occurred at isolated locations where local topography caused convergence and amplification of waves, increasing peak runup relative to typical conditions nearby.

11 IMPACT LINES

Four preliminary impact lines were prepared: a Flood Impact Line, an Erosion Impact Line, a Stability Impact

Line, and a Landslide-Generated Wave Impact Line. The impact lines are considered 'preliminary' because they currently do not take into account the potential benefits associated with erosion protection and/or slope stabilization measures that could be incorporated into the final designs for the proposed Highway 29 re-alignment sections. Small changes to the position of the impact lines could also be made based on information that becomes available through additional geotechnical investigations carried out to support the final design of the Project.

Schematic illustrations of the Flood, Erosion and Stability Impact Lines are provided below for typical low bank (<75 metre high) and high bank (>75 metre high) slopes. Definitions of the reservoir impact lines follow.

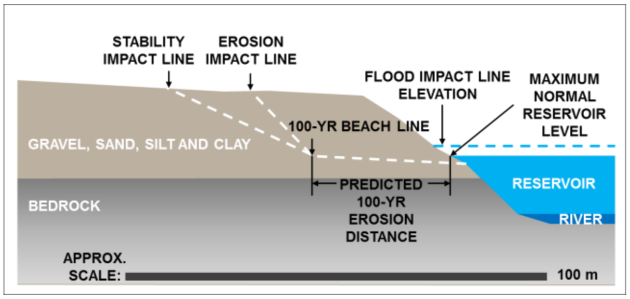

Figure 5. Schematic illustration of the Flood, Erosion and Stability Impact Lines for a typical low bank slope (<75 m high)

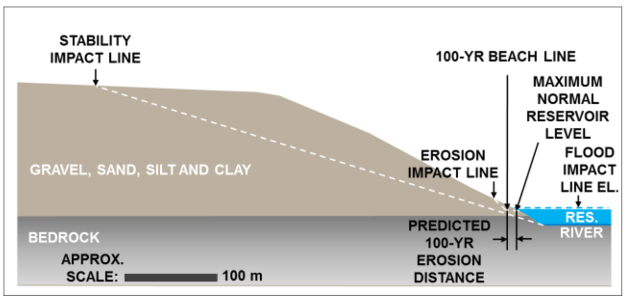

Figure 6. Schematic illustration of the Flood, Erosion and Stability Impact Lines for a typical high bank slope (>75 m high)

11.1 Flood Impact Line

The Flood Impact Line is the boundary beyond which land would not be expected to be affected by extreme floods, wind-generated waves, the operation of the Site C auxiliary spillway, and/or waves caused by boats and small landslides. Based on the analyses described in Section 6, the Flood Impact Line is located at elevation 466 m, approximately 4 m above the MNRL.

11.2 Erosion Impact Line

The Erosion Impact Line is the boundary beyond which the top of the slope adjacent to the reservoir would not be expected to regress due to erosion caused by the impoundment and operation of the reservoir over a period of 100 years. It considers both predicted shoreline erosion (Section 7) and the formation of a slope above the reservoir shoreline using appropriate eroded slope angles for the geological units present around the shoreline (Section 5).

11.3 Stability Impact Line

The Stability Impact Line is the boundary beyond which land would not be expected to be affected by landslide events caused by the impoundment and operation of the reservoir. The position of this line considers extremely unlikely landslide events. It accounts for the predicted amount of shoreline erosion over a 100 year period of reservoir operation (Section 7), potential changes in groundwater levels and slope stability (Sections 8 and 9) and gradual flattening of slopes above the reservoir shoreline using appropriate ultimate slope angles for the geological units present around the shoreline (Section 5). The probability of a landslide, caused or reactivated by the operation of the planned reservoir, impacting lands up slope of the position of the Stability Impact Line was estimated to be less than 1 in 10,000 per year.

11.4 Landslide-Generated Wave Impact Line

The Landslide-Generated Wave Impact Line is a boundary applied to three areas on the north bank of the reservoir (Lynx Creek, Farrell Creek and Halfway River), where landslide-generated waves (Section 10) could temporarily flood elevations higher than the Flood Impact Line. The position of this line is based on combinations of landslide volumes and velocities that are considered extremely unlikely to occur. The annual probability of a landslide-generated wave impacting lands up slope of the position of the Landslide-Generated Wave Impact Line was estimated to be less than 1 in 10,000 per year.

12 SHORELINE CLASSIFICATION SYSTEM

Of the land area encompassed by the impact lines, approximately 70% is currently steeper than 17°. Terrain steeper than 17° in the Peace River valley is prone to erosion and landslides under natural conditions, and is typically not considered suitable for residential use. Consequently, on their own, the impact lines do not facilitate a direct quantification of the predicted changes to slope stability or potential land use caused by the reservoir.

A shoreline classification system was therefore developed to describe current conditions and the degree of potential change caused by reservoir operations, and to illustrate the distribution of shoreline segments where limited to significant change would be anticipated. Shoreline segments were assigned to one or more shoreline erodibility classes based on the material type at the MNRL. Shoreline segments were also assigned to one or more landslide hazard classes, as shown in the following table.

Table 2. Landslide hazard classes.

Landslide Hazard Class	Applicable To	Definition
A	low bank slopes (10-75 m high)	potential for landslides in bedrock with volumes >10,000 m^3 and generally limited velocities
B	low bank slopes (10-75 m high)	potential for landslides in overburden with volumes >10,000 m^3 and possible extremely rapid velocities
C	high bank slopes (>75 m high)	potential for landslides in bedrock with volumes >100,000 m^3 and generally limited velocities
D	high bank slopes (>75 m high)	potential for landslides in overburden with volumes >100,000 m^3 and possible extremely rapid velocities

Bedrock landslides from low bank slopes associated with Landslide Hazard Class A are rare and typically comprise rock falls, toppling, and shallow slumping along steep valley relaxation joints. Overburden landslides from low bank slopes associated with Landslide Hazard Class B typically comprise shallow translational and rotational landslides and earth flows.

The four dominant types of landslides from high bank slopes are compound bedrock slides, compound soil slides, flow slides and earth flows. Compound bedrock slides are associated with Landslide Hazard Class C, while Landslide Hazard Class D includes compound soil slides, flow slides and earth flows.

One of three landslide likelihood classes was assigned to each landslide hazard class for each shoreline segment, as defined in the following table.

Table 3. Landslide likelihood classes.

Landslide Likelihood Class	Annual Probability
two star (**)	>1:100
one star (*)	1:100 to 1:1,000
no star	<1:1,000

For current conditions, the landslide likelihood classes were assigned primarily based on interpretation of the landslide inventory. For reservoir conditions, the landslide likelihood classes also consider the influence of predicted shoreline erosion and groundwater changes on slope stability, as determined by slope stability analyses on typical cross sections (Section 9).

The resulting shoreline stability classification indicates that the likelihood of Class A landslides in low bank bedrock slopes would not generally be expected to increase under proposed reservoir conditions. The likelihood of Class B landslides in low bank overburden slopes would be expected to increase over a length of approximately 28 km (9%) of reservoir shoreline, primarily at locations where interbedded sand, silt and clay would be present at or below the MNRL and erosion and groundwater changes could affect slope stability.

The likelihood of Class C landslides in high bank bedrock slopes would be expected to increase over a length of approximately 49 km (16%) of reservoir shoreline, primarily downstream of Wilder Creek, where weak bedding planes associated with previous landslides, including the Tea Creek Slide, would be subject to pore water pressure changes during reservoir impoundment and operation. The likelihood of Class D landslides in high bank overburden slopes would be expected to increase over a length of approximately 67 km (21%) of reservoir shoreline, primarily at locations where sand and gravel and interbedded sand, silt and clay would be present at or below the MNRL and erosion and groundwater changes could affect slope stability.

13 LAND USE

The estimated likelihoods of landslides or landslide-generated waves caused by the impoundment and operation of the reservoir affecting lands beyond the position of the Stability and Landslide-Generated Wave Impact Lines, respectively, are less than 1 in 10,000 per year. These likelihoods align with hazard-based criteria that are being used in other parts of B.C. to guide the approval of new residential development in landslide-prone terrain.

BC Hydro has developed the following approach to land use on private property within the impact lines. The approach focuses on public safety, maximizing flexibility for land owners, and minimizing the amount of land required by the Project.

- No new residential structures would be permitted within the impact lines.
- Non-residential structures could remain within the impact lines, pending site-specific geotechnical assessment. To protect public safety, existing residential structures within the Flood, Erosion, and Landslide-Generated Wave Impact Lines would not be permitted to remain.
- Within the Stability Impact Line, and outside the Flood, Erosion and Landslide-Generated Wave Impact Lines, existing residential structures could remain for a period of time, at the owner’s request, and provided a site-specific geotechnical assessment determines that it is safe to do so.

Shoreline protection adjacent to part of the community of Hudson’s Hope would be constructed by BC Hydro prior to impoundment of the reservoir. The planned shoreline protection includes a combination of a granular berm and slope flattening to prevent shoreline erosion and to offset changes in slope stability caused by the reservoir. The shoreline protection would extend from a location where the reservoir shoreline transitions from bedrock to interbedded sand, silt and clay materials at the upstream end of Hudson’s Hope, downstream to beyond the current location of the municipal sewage treatment facility, for a total length of about 2,650 m. Erosion and Stability Impact Lines have not been established along this section because the shoreline protection would offset the predicted changes to erosion and slope stability caused by the reservoir.

BC Hydro has located planned realigned segments of Highway 29 outside of the impact lines, where practical. The highway realignment at the Halfway River crossing is situated inside of the Landslide-Generated Wave Impact Line. The potential for landslide-generated waves was considered in determining the realigned highway embankment elevation, bridge elevation, and bridge design parameters. The highway and bridge designs at Halfway River have been reviewed by the Ministry of Transportation and Infrastructure and satisfy provincial design codes and safety guidelines.

An operational monitoring plan is currently being developed for the Project. As part of this plan, BC Hydro would commit to regular monitoring of shoreline conditions, including groundwater levels, shoreline erosion rates and landslide activity. The results of this monitoring would be used to facilitate a detailed review and update of the impact lines following approximately five years of reservoir operations.

14 CONCLUSIONS

Geotechnical investigations were undertaken to prepare reservoir impact lines for the planned Site C hydroelectric reservoir in northeastern British Columbia. The impact lines provided rational input to highway re-alignment design, the assessment of environmental impacts, and for planning land use and shoreline monitoring activities.

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REFERENCES

Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) 2010. Guidelines for legislated landslide assessments for proposed residential development in BC.

BC Hydro 1981. Peace River Development, Site C Project, Report on Reservoir Slopes. Report No. H1361.

BC Utilities Commission (BCUC) 1983. Site C Report and Recommendations to the Lieutenant Governor-in-Council.

BGC Engineering Inc. (BGC) 2012. Site C Clean Energy Project, Preliminary Reservoir Impact Lines. Report to BC Hydro, November 2012.

Cornish, L.J. and Moore, D.P. 1985. Dam Foundation investigations for a project on soft shale. Proc. 38th Canadian Geotechnical Conference. Canadian Geotechnical Society. pp. 171-178.

Evans, S.G., Hu, X.Q. and Enegren, E.G. 1996. The 1973 Attachie Slide, Peace River valley, near Fort St. John, British Columbia, Canada: a landslide with a high-velocity flowslide component in Pleistocene sediments; 7th International Symposium of Landslides, Trondheim, Norway, Vol. 2, pp. 715–720.

Geotechnical Extreme Events Reconnaissance (GEER) Association 2014. 2014 Oso, Washington Landslide. July 22, 2014.

Hartman, G. 2005. Quaternary stratigraphy and geologic history of the Charlie lake (NTS 94A) map Area, British Columbia. Unpublished MSc thesis, Simon Fraser University.

Hartman, G.M.D, Clague, J. 2008. Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia. Canadian Journal of Earth Sciences. Vol. 45-5, pp. 549-564.

Heller, V., Hager, W.H. and Minor, H.E. 2009. Landslide generated impulse waves in reservoirs: Basics and computation. Mitteilungen 211, Versuchsanstalt für Wasserbau, Hydrologie un Glaziologie, R. Boes, Hrsg., ETH Zürich.

Hervouet, J.M.,2000. TELEMAC modelling system: an overview. Hydrological Processes, 14: 2209-2210.

Hickins, A.S. and Fournier, M.A. 2011. Compilation of Geological Survey of Canada surficial geology maps for NTS 94A and 93P; BC Ministry of Energy and Mines, Energy Open File 2011-02, Geoscience BC Map 2011-08-1, 1:250 000 scale map.

International Commission on Large Dams (ICOLD) 2002. Reservoir Landslides: Investigation and Management, Guidelines and Case Histories. Bulletin 124.

Mathews, W.H. 1978. Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map area, British Columbia; Geological Survey of Canada, Paper 76-20, 29 p.

Northwest Hydraulics Consultants Ltd. 1983. Peace River, Site C Project, Model of Landslide Waves at Attachie and Bear Flat Areas. Issued to BC Hydro and Power Authority, June 1983.

The Province, May 28, 1973.

Stott, D.F. 1982. Lower Cretaceous Fort St. John Group and Upper Cretaceous Dunvegan Formation of the Foothills and Plains of Alberta, British Columbia, District of Mackenzie and Yukon Territory. Geological Survey of Canada, Bulletin 328, 124 p.

Thurber Consultants Ltd. (Thurber) 1978. Reservoir shoreline stability assessment. Report to BC Hydro, File No. 15-2-62.