Reservoir shorelines: a methodology for evaluating operational impacts

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ABSTRACT
Dam construction and reservoir impoundment creates a new or modified shoreline that is subject to frequent, cyclical and sometimes rapid water level changes. Changed water levels and wind and wave action initiate downward erosion of beaches causing regression of the shoreline and destabilisation of reservoir slopes. Establishing setbacks landward of the shoreline are required to safeguard useable shoreline property that may be at risk of flooding, erosion or instability due to reservoir operations.

Reservoirs in British Columbia operated by BC Hydro are largely situated in steep, glaciated valleys with diverse geological, geomorphological and climatic conditions and a variety of eroding shorelines. Operational impacts on reservoir shorelines generally require a geotechnical study. In these studies, impacts relating to flooding, erosion, slope stability, groundwater and landslide generated waves are assessed and *impact lines* established that define areas with limits imposed on future land use and development under flowage agreements. BC Hydro now has over 40 years of experience evaluating reservoir shoreline impacts and recognises that many reservoirs have immature shorelines, and there are difficulties predicting erosion rates and future regression.

RÉSUMÉ
La construction d'un barrage et la création d'un réservoir entraînent la formation d'une ligne de rivage modifiée ou d'une ligne toute nouvelle. Celle-ci subit des changements de niveau d'eau fréquents, cycliques et parfois rapides. Cette variation du niveau d'eau, le vent et les vagues provoquent une érosion vers le bas des plages, ce qui cause la régression de la ligne de rivage et la déstabilisation des pentes du réservoir. Il est donc nécessaire d'établir des retraits vers la terre de la ligne de rivage pour protéger le terrain utilisable de la ligne de rivage, qui peut être menacé d'inondation, d'érosion ou d'instabilité par l'exploitation du réservoir.

Les réservoirs de Colombie-Britannique exploités par BC Hydro sont principalement aménagés dans des vallées glaciaires escarpées, aux conditions géologiques, géomorphologiques et climatiques diverses et qui présentent une variété de lignes de rivages en érosion. Il faut généralement effectuer une étude géotechnique des répercussions de l'exploitation sur les lignes de rivage des réservoirs. Dans ce genre d'étude, on analyse les risques d'inondation, d'érosion, d'impact sur la stabilité des pentes et sur l'eau douce et les risques de production de vagues par glissements de terrain. En vertu d'ententes de fluage, on trace ensuite des *lignes d'impact* qui définissent des zones dans lesquelles on limitera l'utilisation et la mise en valeur du terrain. BC Hydro possède maintenant plus de 40 années d'expérience dans l'évaluation des impacts sur la ligne de rivage des réservoirs. Elle admet que dans bon nombre de ses réservoirs, la ligne de rivage est immature et qu'il est difficile de prévoir sa régression et la vitesse d'érosion.

1 INTRODUCTION

Hydroelectric reservoirs are artificial lakes that create new conditions of impoundment in a former river valley or raise water level(s) in a previously smaller and shallower natural lake. With the establishment of changed water levels, natural processes of flooding, wind and wave action and modification of groundwater levels can have significant impacts on the integrity and stability of the shorelines and slopes bordering the reservoir.

BC Hydro and its predecessors have been operating hydroelectric facilities for over 100 years across British Columbia. Impacts of reservoir operations on shorelines have been recognised for some time and although there is considerable experience in the hydroelectric utility sector, little has been documented over the years. Impacts are primarily related to wind and wave action on largely unconsolidated soils and consequent erosion and instability, but also include changes to the groundwater regime. A significant feature of reservoir operations is the range of water levels (or drawdown) between the licensed minimum and maximum operating water levels and the duration of the reservoir level at any given elevation within the drawdown range.

Since the 1960s BC Hydro has been developing a methodology for evaluating reservoir impacts and determining the land around the reservoir perimeter that should remain as a right of way for operations while limiting liability arising from injury or death or damage to shoreline improvements and safeguarding waterfront development. The methodology was modified in the 1990s to better encapsulate geomorphological and geological processes. However, uncertainties in the methodology still exist due to limited understanding of key issues such as rates of erosion and shoreline regression, immaturity of present day reservoir shorelines and impacts of climate change. Much of this understanding has been improved based on experience gained on recent and active site-specific geotechnical assessments. Compounding the issues is the increasing demand in recent years for waterfront development on many reservoirs in the Province, and the increasing inclusion of erosion protection works in individual developments.

2 EARLY RESERVOIR ASSESSMENTS

Early in the 20th century, hydroelectric projects in British Columbia were constructed without concern for shoreline impacts. The development of a number of major projects in the late 1960s and early 1970s saw a number of shoreline studies initiated to address land development concerns particularly around Arrow Lakes, Revelstoke, Seven Mile and Williston reservoirs, and the then proposed Site C project (e.g. Thurber 1978, 1979).

In these early studies, reservoir shorelines were assessed using the "residential *safeline* concept". The intent of this concept was to establish boundaries on land that ensured the security of persons residing adjacent to reservoirs would not be threatened by rapid instability caused by the reservoir. This boundary was a conservatively located line concerned only with the affects of the reservoir on processes such as shoreline regression, flooding and groundwater mounding; instability and any other effects from causes unrelated to reservoir action were excluded. The safeline was setback inland some distance inland from the "breakline" and represented a margin of safety beyond the predicted limit of regression. However, through confusion and misunderstanding the safeline was and still is sometimes perceived by the public as a boundary up to which land is acquired by the dam owner, or for which compensation is due for hazards and shoreline regression due to all causes.

Even though the safeline was a useful concept, its limitations led to misunderstandings and the presumption of unnecessary obligations by BC Hydro. Intended only for residential land use it is somewhat conservative and was only of limited use in the management of land for agriculture, industry, forestry and recreational use. The safeline has limited technical basis and does not adequately account for the incremental effects of reservoir impoundment. In view of the shortcomings a new approach was required that equitably balanced BC Hydro's needs for reservoir operations and the development and land use interests of stakeholders.

3 IMPACT LINES CONCEPT

In the early 1990s a new approach was developed by BC Hydro to account for impacts of reservoir operations on existing shoreline conditions in a way that allows consistent management of all stability and groundwater issues. This led to the concept of a family of *impact lines* to replace the former safeline concept and which were incorporated into an internal guideline document (BC Hydro 1993, ICOLD 2002).

Simply put, an *impact line* is defined as the landward boundary indicating the predicted extent of a reservoir impact affecting the shoreline. A variety of different impact lines are possible, but for practical purposes five impact lines are defined, one each for flooding, erosion, slope stability, groundwater and landslide induced wave processes. Most sites are concerned with the first three processes as groundwater and landslide surges are much less common hazards. Impact lines are established independent of land use type and hence remain unchanged if land use policies change; they would only be adjusted or revised for technical reasons.

3.1 Flooding

The flooding impact line marks the extent of land inundated by the reservoir as a result of normal operations (usually the maximum reservoir capacity) or due to flood events. A hydrological study is usually performed to determine flood elevations, which are then projected on the shoreline to establish a flooding impact line. Typically, BC Hydro establishes the flood impact line at the elevation corresponding to the flood with a 1/1000 annual exceedance probability (AEP) if this exceeds the maximum normal operating reservoir level (MNRL). Wave heights and seiche values can be applied in addition to flood levels in a conservative analysis. Also taken into consideration are BC provincial government criteria for habitation on flood plains, which is currently the 1 in 200-year flood level plus 0.6 m.

3.2 Erosion

Progressive erosion by beaching and backslope regression is the dominant shoreline process. The erosion impact line represents the extent of predicted erosion due to normal reservoir action estimated from geomorphologic evidence (Figure 1). Shoreline erosion would not be expected to regress beyond this line. Wind and wave energy drive erosive and beaching processes (including longshore drift) that perpetually shapes the shoreline as regression continues until the shoreline material has the physical composition to resist being mobilised. It is usual to combine normal reservoir action with erosion due to storms; the return period for storm waves is usually determined for individual reservoirs taking into account the range of fetch and wind directions and duration of storm wind velocities.

This erosion is generally slow and is not life threatening. This impact line delineates the area of land that is subject to regression and hence represents the potential net loss of usable land. Impact lines can be determined based on the MNRL with or without an allowance made for the height and run up of design waves (Figure 1). It is recognised that shoreline erosion can often be controlled or mitigated by protective works, such as offshore log booms, rock breakwaters and bioengineered aprons, rip-rap and retaining/revetment walls. Impact lines may be determined for cases of unprotected and protected shorelines.

Shoreline erosion is a long-term process and rates depend on erosion susceptibility of the shoreline geology (i.e. grain size), topography and exposure to erosive forces. Aggregated geomorphologic evidence combined with an understanding of climatic forces allows estimation of prevailing erosion rates since reservoir impoundment. Estimated rates are used to determine an erosion impact line that has an associated time-scale, typically in the

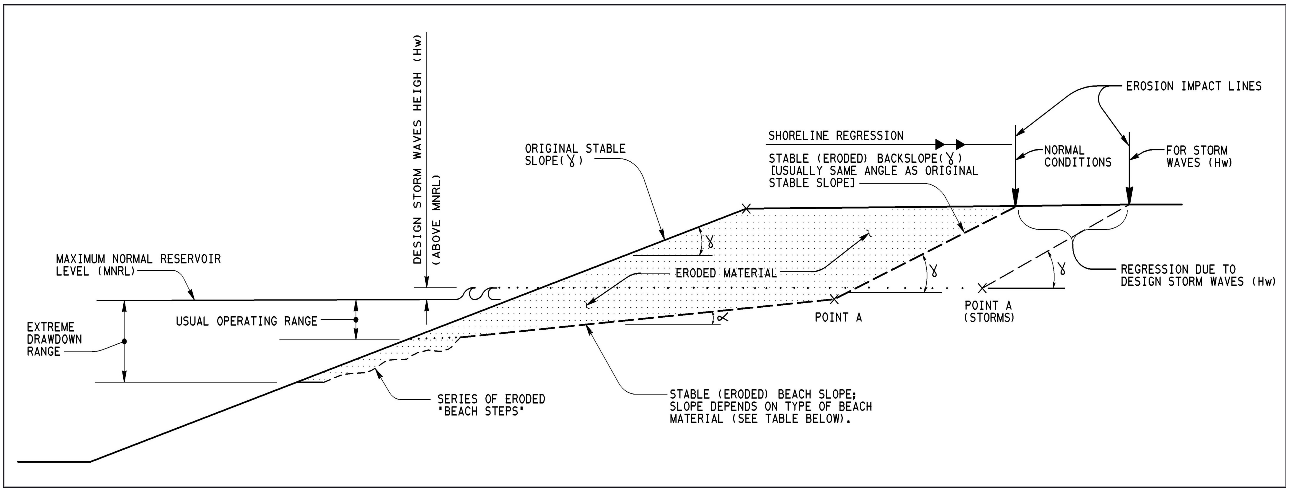

Figure 1. Approach for determining shoreline regression due to beaching and location of erosion impact lines

range of several 10's of years. Where erosion rates are low and there is extensive experience, impact lines may be determined with relatively long time-scales (in excess of 50 years or more). Where erosion rates are high and/or limited experience has been acquired over a short time period, impact lines can be qualified for a short time-scale (i.e. several years) before they need to be re-evaluated.

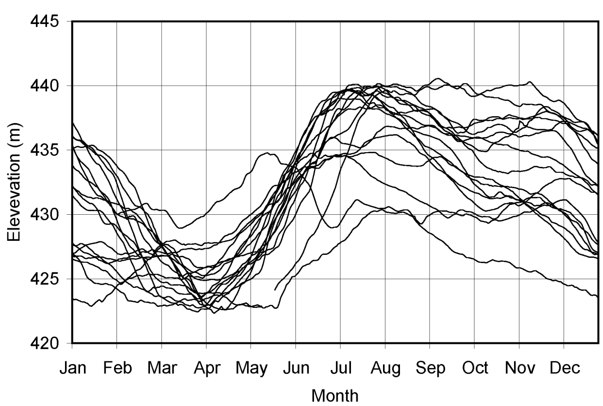

Figure 2. Annual hydrographs for Arrow Reservoir for the period 1990-2006

Cyclical annual patterns of impoundment and drawdown on a reservoir have a marked effect on the rate of shoreline regression. Ultimate stable shoreline configurations are a function of two long-term stable angles; the submerged angle for the beach material and the angle of repose for the backslope material (Figure 1). Penner and Boals (2000) demonstrate the importance of the beach slope angle in determining the long-term limit of backslope regression, and how the rate of downward erosion of the beach material through the process of beaching is controlled by the particle grading of the beach materials.

Figure 2 shows the annual water level (hydrograph) for the Arrow Reservoir operated by BC Hydro over a 16-year period, and shows the range of elevations and varying duration that the beach is exposed to wave action. A notable observation is the variable and often short duration (typically less than 4-6 weeks of each year) that the reservoir is at full pool. This leads to the notion that even after 40-50 years of operation, beaches along reservoirs that have short annual full-pool durations can be significantly immature compared to beaches on storage reservoirs or headponds with small or negligible drawdowns or long durations at full pool. This contrast is particularly acute when compared with natural lakes that have had several thousands of years to achieve shorelines that are more or less in equilibrium with erosive forces.

Fluctuating reservoir levels cause seemingly stable beaches to progressively downgrade over time triggering bank erosion and regression. Beaching processes are dependent on material grain size as large diameter material can armour the shoreline and become a natural revetment for the eroding bank. Careful consideration of beaching and the degree of beach maturity in the erosion model are required to substantiate determination of the limit of regression.

3.3 Stability

Slope instability on a scale exceeding that of the slumps and small slides involved in backslope regression is treated separately. The stability impact line is the boundary beyond which land adjacent to a reservoir will not be subject to sudden and rapid landsliding due to reservoir action, to an AEP determined by provincial engineering guidelines. In British Columbia recent guidelines for professional practice require that landslide assessments be carried out for an AEP of 1/10,000 years for residential developments (APEGBC 2008). Although this typically requires extensive geotechnical investigations, different probability levels with different levels of investigation can be selected for specific land-use types other than residential. Destabilising effects of toe erosion and earthquake shaking are also considered as well as fluctuating groundwater levels and potential rapid-drawdown effects.

The intent of shoreline assessments is to include impacts only caused by the reservoir. Consequently, the stability impact line is normally located so that existing instabilities not affected by reservoir impoundment are landward of the boundary.

3.4 Groundwater

The groundwater impact line is a boundary beyond which the groundwater levels adjacent to a reservoir shoreline are not significantly affected by the presence of the reservoir. While reservoir impoundment generally raises groundwater levels compared to original elevations, this impact line is mostly concerned with fluctuation in groundwater levels. On steeply sloping shorelines this is not usually a concern, but in flat-lying ground there can be adverse effects, including flooding of basements, performance of water wells, impeding septic field performance and reversing tributary stream flows. Understanding groundwater fluctuations, if important, may require well drilling especially if related to predicting the performance of water wells. Typically, the impacts of raised groundwater levels and drawdown on slope stability are not included here, but are included in the stability impact line.

3.5 Landslide Induced Waves

The impact line for landslide-induced waves is the boundary beyond which waves produced by a landslide into the reservoir will not cause erosion or other damage. The probability of slide occurrence is the same as that used for the stability impact line for the slide area. Potential slides, not caused by or influenced by the reservoir but whose impacts would be transmitted due to the presence of the reservoir, are also included.

As with any other highly mountainous region, there are numerous large landslide hazards on slopes bordering BC Hydro's reservoirs. The risk of rapid failure of some of the larger known slide features, such as Downie Slide and Checkerboard Slide on Revelstoke Reservoir, and Little Chief Slide and Dutchman's Ridge on Kinbasket Reservoir are being managed by BC Hydro, either by permanent drainage systems and/or permanent monitoring (Imrie and Moore 1997, Moore et al 1997). On these reservoirs the potential impacts from landslide induced waves is minimised. On reservoirs where a hazard is identified, estimates must be made of expected slide volume and velocity, and modelling may be required to determine wave heights, attenuation and resulting run up. The impact line is only applied to shoreline segments that would be impacted by the potential surge wave.

3.6 Implementation

BC Hydro's guidelines set out the technical basis for each of the impact lines (BC Hydro, 1993), but it is recognised that judgement plays a major role in predicting impacts and that experience with existing reservoirs over time forms the basis for most assessments. The procedure for assessing reservoir impacts and determining impact lines can be applied globally across an entire reservoir or on a site-specific basis for individual properties bordering the reservoir shoreline. The procedures can be tailored to desk study as well as feasibility, preliminary and final design stages, but mapping scale is an important consideration depending on the level of detail required; i.e. whether at a high-level planning stage or for detailed site-specific assessments. Procedures include gathering and evaluating available relevant data such as air photos (stereographic) that may show shoreline changes over time, and historic reservoir levels (hydrographs) that show year-to-year seasonal variations and duration of water levels especially the frequency, timing and duration of extreme levels. Other relevant information sources include wind and wave measurements if available, geological mapping and regression/erosion monitoring data. Topographic mapping at an appropriate level of detail (custom photogrammetric or LiDAR preferred) is required in order to project regression predictions to a suitable level of accuracy consistent with land use/development layouts and plans.

Field mapping is an important component of the assessment procedure to observe active reservoir processes, especially the degree and severity of active erosion and the behaviour of beach and backslope materials. Wherever possible it is important to observe the nature and properties of the beach that may be exposed at lower reservoir levels and to record beach and backslope angles. Observations made over a range of reservoir levels can provide important contextual information, as can observations of extant wind and wave activity. Meteorological information across BC is highly localised and wind records are rarely available for individual reservoirs, especially considering their geographic organisation. In the absence of prevailing wind data anecdotal information may be cautiously considered; local lakeshore property owners and mariners often hold a surprising amount of relevant information.

Reservoir shoreline assessments should be performed with a good understanding of lakeshore processes and how they apply to operating hydroelectric reservoirs. Considerable judgement and experience is proving to be a prerequisite for completing field assessments to a satisfactory level. Impact line assessments need to be conducted by a professional geoscientist (geomorphologist or engineering geologist) or geotechnical engineer, with suitable qualifications and experience in this field.

Typically, more than one impact line is determined for each segment of shoreline as shown in Figure 3. In this figure the erosion impact line reflects the contrasting underlying geology and inherent erosion susceptibilities. In situations with multiple impact lines, the impact line furthest landward of the shoreline is adopted as the basis for establishing the area of land adjacent to the reservoir for inclusion in a flowage agreement or right of way. These agreements include specified restrictions on land-use especially pertaining to siting habitable structures, and covenants that limit the dam owner's liability for impacts from erosion and other reservoir shoreline processes.

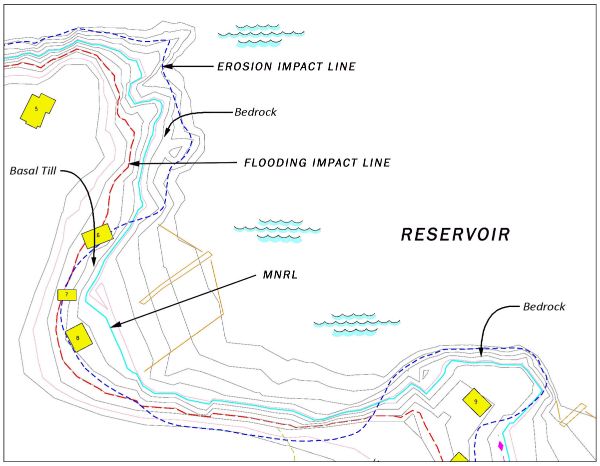

Figure 3. Example of multiple impact lines determined for a segment of reservoir shoreline

4 RECENT EXPERIENCE

Recent shoreline studies in 2008 along approximately 45 km of shoreline on the upper part of Arrow Reservoir in the southern central interior of British Columbia presented several challenges in assigning impact lines on varying terrain. The Arrow Reservoir is impounded by Keenleyside Dam; a 52 m high concrete and earthfill embankment dam completed in 1968 to impound the Columbia River upstream of the city of Castlegar. The reservoir is over 200 km long and typically 2-4 km wide with over 530 km of shoreline, and a gross capacity of over 7.5 billion m^3. The less than 1 km wide Narrows separates the Upper and Lower Arrow Reservoirs.

4.1 Mapping Scale

Map scale is important in any field assessment, and needs to be carefully selected while balancing the objectives of the study with the scale of features to be included in the mapping. The objectives of this study were to provide land-use planning guidance and a nominal map scale of 1:5000 was selected with a digital terrain model derived from 2007 custom-flown ortho-rectified photogrammetry.

4.2 Geomorphic Classification

Along the Upper Arrow Reservoir shoreline there is a high degree of geomorphic variability. An approach to differentiating the shoreline into different categories with similar characteristics was devised. Somewhat similar to the erosion hazard rating classification scheme suggested by Guthrie (2005) the shoreline was classified into 5 classes according to geology, susceptibility and style of erosion (Table 1). One of the challenges when assessing the 45 km long shoreline was to recognise and identify the various geomorphic types and using the classification scheme in Table 1 develop an efficient field-mapping program.

Table 1. Shoreline classification for Arrow Reservoir

Class	Erosion and Regression Characteristics
0	Bedrock with no observable instability. No significant erosion or regression expected.
1	Minor erosion or sloughing and/or ravelling in overburden veneer or low banks. Typically short sections of shoreline or small embayments.
2	Some to moderate erosion and sloughing in moderately high overburden banks or talus over bedrock. Typically more resistive materials (till), or well-developed coarse beach lag deposits provide degree of erosion protection.
3	Moderate erosion and sloughing, typically in moderate to high overburden banks or talus over bedrock. Regression may be limited by developing lag deposits or other natural conditions.
4	Significant erosion and regression expected with slope instabilities. Typically moderate to high overburden banks and fine-grained deposits.
5	Significant erosion and instability. Typically larger rotational and translational slides on steep slopes and high overburden banks in fine-grained deposits. Regression expected up to several 10's of metres to 100m or more.

The reservoir occupies a broad north-south aligned "U-shaped" glaciated valley with moderately steep slopes. The geomorphic history of the reservoir is complex and largely dominated by glaciation and deglaciation processes. Tributary glaciated valleys join the main valley at various locations where now flooded alluvial fans and deltas occur. Elsewhere, significant terrace deposits are known. While a large proportion of the shoreline is bedrock dominated (Figure 4), there are shoreline sections dominated by talus and colluvial deposits, as well as glaciofluvial, lacustrine and till deposits. The existing shoreline at MNRL is irregular with small broad bays, points and indentations that vary depending on topographic and geological conditions.

Figure 4. Bedrock shoreline on Upper Arrow Reservoir

4.3 Site Specific Observations

While it is recognised that there are a number of contributing factors to reservoir shoreline regression, particularly affecting unconsolidated sediments, it is generally assumed that wind and waves are the driving factors since reservoir filling. The following factors are considered to be most significant on Arrow Reservoir.

(1) *Reservoir exposure*: Fetch distances along the reservoir are variable depending on the aspect of the shoreline and are up to 20 km.

(2) *Beach materials*: Many beaches have become self-armoured with a coarser lag deposit developed in the upper drawdown zone up to the MNRL (Figure 5). While the lag deposits vary in extent, they are generally ineffective in terms of backslope toe protection. Beach angles below MNRL are also variable reflecting variations in material type and the maturity of the beach profile.

(3) *Backslope materials*: Ongoing wave erosion has developed shoreline scarps about 1.5-3.0 m high where they are not obscured by ongoing sloughing (Figure 6). Unconsolidated soils are notably variable and strongly influence slope morphology and scale of erosion features.

Figure 5. Naturally armoured beach on Upper Arrow Reservoir

(4) *Groundwater*: Seepage from the backslope was observed at various locations indicative of localised perched groundwater tables. Seepage can be an indicator of elevated groundwater pressures that can reduce the factor of safety against sliding and locally accelerate rates of sloughing.

(5) *Landsliding*: Mapping revealed a range of instabilities including slumps, tension cracks and grabens indicative of overburden instabilities, some of which were not related to reservoir operations.

(6) *Anthropogenic activities*: Modifications to the shoreline morphology by excavation or filling, such as logging roads, boat ramps and subdivision development, create conditions that often increase erosion/stability concerns. While these are technically outside the jurisdiction of reservoir operations their influence on shoreline behaviour are important.

4.4 Shoreline Maturity

The relative maturity of the reservoir shoreline is difficult to ascertain. The most severe erosion and regression rates are generally considered to occur when the reservoir is at or near its annual maximum elevation. Wave action due to infrequent severe storms during these periods could reach elevations along the shoreline in excess of MNRL (El. 440.7 m). However, for much of the winter period when such storms are most likely to occur, reservoir levels are considerably below MNRL. Although these events may significantly redistribute existing beach materials, the direct impact to the shoreline morphology near the MNRL may not be significant. For the recent study at Arrow Lake, it was found that reservoir levels only approached within 0.5 m of the MNRL on an annual frequency of about 16 days, although this can vary widely from year to year. This has a significant bearing on determining shoreline maturity in terms of long-term reservoir operation.

An important parameter in predicting or assessing future shoreline behaviour is the determination of whether or not the shoreline produced subsequent to reservoir filling is at or close to a stable profile; that substantial regression or beach down-cutting has either stopped or has reached a very slow rate.

Figure 6. Typical example of unstable beach and active backslope regression on Upper Arrow Reservoir

Some shorelines rapidly stabilise when stable angles are quickly attained especially when the beach becomes naturally armoured (Figure 5). Others might stabilise when non-erodable material (such as dense till or bedrock) is reached, but most shorelines display slowed rates of regression after a number of years. It can be difficult to determine if a beach has achieved a state of stability by visual observations alone; often many years of surveys or monitoring would be required to determine this definitively. Research by others (Penner and Boals, 2000) suggests that for new shorelines the rate of shoreline regression is high just after reservoir filling, but declines rapidly to a slow, almost steady rate, typically in the time frame of about 5 years. However, this will vary with soil type (i.e. particle size), frequency and duration of high water levels and frequency of windstorm events. Typically, long term and possibly stable beach angles of 4-9º have been reported, but may be as steep as 14º where armoured (Guthrie 2005, Penner 1993a).

For the Arrow Lake Reservoir, it was initially thought that some degree of shoreline stability would have been attained after 40 years of operations. The recent work, however, revealed that although some beaches had approached a stable condition (Figure 7) many sections of shoreline in overburden appear to be very active (Figure 6). This can be explained by the short period that the shoreline is exposed to high reservoir levels and generally in the summer months when severe storm action is rare (Figure 2). At many locations it is likely that the shoreline on Upper Arrow is still eroding at rates similar to the first few years after filling. Monitoring over many years in the future would be required to determine if and when sections of the shoreline achieve some degree of equilibrium.

Figure 7. Near-stable beach on Upper Arrow Reservoir

The immature nature of much of the shoreline is evidenced by beach profiles that are often considerably steeper than would normally be expected, considering the material type, gradation and exposure to reservoir action. Such shorelines in a juvenile stage of formation will require a much longer period of time, at the current intensity of wave energy dissipation, before long-term stable profiles are established.

4.5 Erosion Rates and Regression Limits

Challenges faced in determining erosion rates based on experience and forecasting potential regression limits, were primarily due to lack of data with which to appropriately assess the conditions within each class of shoreline. Considerable effort was directed at gathering relevant data to support field observations.

Topographic, geological and climate data was gathered and reviewed along with air photos and past reservoir reports. In addition, detailed shoreline topography from 1964 was systematically compared with 2007 topography. However, the results of this analysis were not conclusive and although some localised down-cutting and regression was identified, the magnitude of estimated differences was often within the margin of error of the topographic surveys.

The shoreline was classified during the fieldwork into 5 different classes in terms of relative erosion susceptibility and stability characteristics (Table 1). It was recognized that the degree of confidence in evaluating regression limits depends on the availability of quality of geological data. Detailed investigations are required in order to achieve a good understanding of erosion rates (Penner 1993b). In his work on reservoirs in Saskatchewan and Manitoba, erodibility coefficients were developed for a range of materials, including till, sand and gravel, boulder lag and soft bedrock. While these can be used as guides, it is recognised that for reasons of contrasting geology and climate they have limited application in other regions of Canada.

The determination of erosion rates and regression limits on Upper Arrow Reservoir was constrained by a number of factors.

(1) The fieldwork was carried out within a short timeframe during high reservoir levels. While the entire shoreline was inspected and all locations with potential reservoir impacts were identified, full beach profiles were obscured. Inspections at lower water levels would be required to improve regression limit estimates based on a better understanding of beach profiles.

(2) Field assessments were primarily based on visual examination of surface conditions and materials present at and above MNRL. As no subsurface information was available (e.g. drillholes), especially at sites with significant erosion and instability, it was necessary to apply geological/geotechnical judgement in order to assess the future behaviour of the shoreline.

(3) The intensity of reservoir wave action on the project shoreline was indeterminate. The principal sources for determining the extent of this were anecdotal observations of the Galena Bay – Shelter Bay ferry operators and the results of a geomorphic examination of the MNRL shoreline to determine the past maximum extent of reservoir wave action.

(4) A simple model was employed to estimate shoreline regression through beaching, in part based on assumed stable profiles and that long-term beach slopes are principally a function of the gradation of beach materials and related lag deposits. It was also recognised that most of the existing beaches have not achieved stable profiles and that such profiles may not be formed within a 100-year time-period. For this reason, long-term beach angles were not typically employed in modeling shoreline regression for the next 50-100 years. Few examples of reliable stable beach slope angles were observed (Figure 7). Consequently, measured beach slope angles were adopted with an allowance for the long-term stable angle based on local conditions and published typical angles (Thurber 1978, BC Hydro 1993, Penner 1993a).

(5) It was not possible to predict the extent of shoreline impacts that would result from a very severe storm with a very low probability of occurrence, such as a severe gale or hurricane event. Any allowance for such an uncertain event would be impractical for the level of assessment. The issue of “climate change” is problematic, but as there is no way to predict how this might affect the rate of shoreline processes in the next 100 years, no allowance for this was made.

(6) It is likely that human activity will continue to modify shorelines at least on a local scale. Activities such as the removal of vegetation, shoreline excavations and construction, alteration of beaches by grading, removal and addition of beach materials, installation of shoreline protection works, changes in surface and subsurface hydrologic regimes, and increased boat wake activity, etc, can significantly influence regression behaviour. No allowances were made for these changes, as future shoreline land use cannot be predicted at the time of the study.

(7) Little is known regarding rates of beach down-cutting or accretion in areas of erodable overburden banks. In such cases the determination of impact line locations required the application of geotechnical judgement with necessary inclusion of a degree of conservatism in locating impact lines beyond that merely based on obvious physical evidence or data.

5 FUTURE CONSIDERATIONS

There are a number of potential sources of additional data that could be considered in future projects as time and project finances allow.

(1) Multiple reconnaissance periods such that shorelines and especially beaches can be inspected at both low and high reservoir levels.

(2) Use of differential satellite GPS for greater accuracy in locating field stations.

(3) Improved detailed topographic mapping and photogrammetry and other imaging techniques can provide valuable detail especially if repeated in areas of significant and rapid erosion. Such techniques include terrestrial photogrammetry, LiDAR (airborne and terrestrial) and interferometric synthetic aperture radar (InSAR) to compare shorelines over several decades.

(4) Installation of weather buoys for wind and wave data collection could be installed particularly where this type of data is important for multiple uses (shoreline regression, shoreline mitigation measures, marine infrastructure and general weather data).

6 CONCLUSIONS

Since the 1960s, BC Hydro has developed methodologies for evaluating reservoir shoreline impacts. Implementation of the current BC Hydro methodology is based on an established set of technical principles. The methodology has limitations. Ongoing studies by BC Hydro and work on lakeshore and reservoir erosion in other jurisdictions has and will continue to gather data that improves the geotechnical community's understanding of the principal erosion and regression processes. Clearly more studies are required and more data needs to be collected on specific reservoirs so that impact lines can be determined with improved levels of confidence.

At the outset of the Upper Arrow Reservoir study, it was recognized that reliable data for impact line assessment would be limited. It was only possible to observe the shoreline during periods of high reservoir levels and available data related to past and ongoing rates of beach down-cutting and shoreline regression was very limited. Therefore, assessments such as these rely on observable geomorphic evidence and interpretation of existing erosion and regression patterns combined with geotechnical judgement by appropriately trained and experienced practitioners.

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REFERENCES

APEGBC 2008. *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC*, Revised, 74 pp.

BC Hydro 1993. *Geotechnical Guidelines for Determining Slope Stability and Groundwater Impacts on Reservoir Shorelines for Land Use Purposes*, Report No. H2293.

Guthrie, R.H. 2005. *Lakeshore Erosion Hazard Mapping*, BC Ministry of Environment, Technical Handbook No. TH1, 25 pp.

Imrie, A.S. and Moore, D.P. 1997. BC Hydro's approach to evaluating reservoir slope stability from a risk perspective in *Landslide Risk Assessment, Cruden and Fell (eds*), Balkema , Rotterdam, p 197-205.

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

Moore, D.P, Imrie, A.S. and Enegren, E.G. 1997. Evaluation and management of Revelstoke Reservoir Slopes, *International Commission on Large Dams*, Florence, Q.74 R.1, p 1-22.

Penner, L.A. 1993a. *Shore Erosion and Slumping on Western Canadian Lakes and Reservoir – A Methodology for Estimating Future Bank Recession Rates*, Environment Canada, Final Report, 100 pp.

Penner, L.A. 1993b. *Shore Erosion and Slumping on Western Canadian Lakes and Reservoir – Erodibility Coefficients of Common Shore Zone Materials Around Lake Diefenbaker, Avonlea Reservoir, and Lake of The Prairies*, Environment Canada, Final Report, 7 pp.

Penner, L.A. and Boals, R.G. 2000. A numerical model for predicting shore erosion impacts around lakes and reservoirs, Canadian Dam Safety Association, p 75-84.

Thurber Consultants Ltd 1978. *Arrow Lakes Reservoir Shoreline Stability Assessment*, report prepared for BC Hydro.

Thurber Consultants Ltd 1979. *Site C Hydroelectric Development – Physical Environment Impact Assessment*, report prepared for BC Hydro.