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Reservoir Shorelines – An Update on Geomorphic Processes and Hazard Assessment Methodology

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ABSTRACT
Shorelines on reservoirs including those associated with hydro-electric power facilities, particularly in mountainous terrain, are exposed to a number of impacts from geomorphic processes associated with reservoir operations that typically include; flooding, erosion, landslides, fluctuating groundwater, and landslide generated (or impulse) waves. Reservoir shorelines typically take many decades (and some may take many centuries) to reach some level of dynamic geomorphic equilibrium. Some of the time-dependent processes are a function of drawdown range, geology (erosion susceptibility), geomorphology (slope height and gradient, aspect), energy inputs (wind and wave directions, frequency, strength and fetch), frequency of unusually high (floods) or low (drought or for maintenance) reservoir level, and vegetation cover.

This paper presents an update on the understanding and measurement of wind-wave generation, wave run-up, and regression due to erosion and landsliding that dominate the evolution of reservoir shorelines. By way of recent case studies on BC Hydro reservoirs, the application of wind-wave analysis, erosion susceptibility classes, regression vulnerability, and analysis of historical erosion rates are described in the context of establishing setbacks from reservoir shorelines. Setbacks are defined by one or more impact lines and are used to define the legal statutory flowage right-of-way on the shoreline to ensure the safe and secure third-party use of land adjacent to reservoirs.

RÉSUMÉ
Les berges des lacs de barrage, y compris ceix exploités par des aménagements hydro-électriques sont sujettes à de nombreuses perturbations causées par des processus géomorphiques associés aux l'opération de cette réserve d'eau, et ce particulièrement en relief montagneux. Celles-ci regroupent l'innondation des berges, leur érosion, des glissements de terrain, des variations de niveau des nappes phréatiques ainsi que des vagues générées par glissement de terrain. Les rives de ces réservoirs prennent plusieurs décennies, voire siècles, pour s'approcher d'un état d'équilibre dynamique. Certains de ces phénomènes - qui évoluent dans le temps - dépendent telles que le marnage, la géologie des rives (potentiel d'érosion), leur géomorphologie (hauteur de la pente, gradient et aspect), les stimulus énergétiques qui la touchent (direction, récurrence, amplitude et portée du vent et des vagues), leur composition végétale ainsi que la fréquence de valeurs exceptionnelles de niveau d'eau (crues/innondations ou sécheresse/drainage).

Cet article propose une amélioration de la compréhension et les mesures du génération de vagues par le vent, jets de rive, et la régression due a l'érosion et les glissements de terrain qui déterminent l'évolution des berges des lacs de barrage. Par le biais d'études de cas récemment effectuées sur des réservoirs opérés par BC Hydro, le déploiement de méthodes d'analyse des vagues/du vent, du potentiel d'érosion, de la vulnérabilité en érosion régressive, et l'analyse de l'historique des taux d'érosion sont décrits dans l'optique d'établir les distances de retrait du niveau d'eau sur les berges. Ces distances sont définie à partir d'une/plusieurs lignes de portée d'érosion et permet de définir le cadre légal vis-à-vis du droit de laisser-passer sur les propriétés le long des berges afin d'assurer la sécurité de l'exploitation de ces terrains en bordure du réservoir par un tiers.

1 INTRODUCTION

The management of the land use resource adjacent to hydro-electric (and water storage) reservoirs is of major concern to owner-operators who are faced with the responsibility of balancing the societal requirements for land development with the need for protection of such land from geomorphic processes associated with reservoir operations and related geohazards.

In some situations, owners are also being faced with having to consider potential impacts associated with climate change. Such impacts can include increased likelihood of flooding caused by increased inflows, and the increased frequency and magnitude of erosion and landslides caused by increased frequency and intensity of storm events and increased peak groundwater levels. Setbacks from the reservoir margin allow for the impacts of these processes and to restrict certain land uses adjacent to the shoreline. Notwithstanding the changes brought about by natural forces, reservoir owners are under increasing pressure to release land for development or to revise existing setbacks from the reservoir edge to allow for increased land use.

BC Hydro began considering geomorphic processes around its reservoirs and accommodating adjacent land use in the late 1970s (Thurber 1978, 1979). In recent years, BC Hydro has experienced an increasing interest in land development around its reservoirs, and there are increasing demands to apply prevailing geotechnical guidelines and practices for establishing setbacks often with limited data. This situation of limited data introduces considerable uncertainty and results in varying degrees of conservatism in establishing setbacks. This paper reviews some of the key geomorphic processes and some approaches being taken to address data limitations and to assist in managing land use adjacent to reservoirs.

2 RESERVOIR OPERATIONS AND GEOMORPHIC PROCESSES

BC Hydro's reservoir operations typically include seasonal fluctuations in water levels that can vary from as little as a few tens of centimetres to nearly 35 m. Given the relatively brief existence of reservoirs (typically in the range of 40-115 years), compared with the timescale of most geomorphic processes, many of the shorelines have yet to reach a geomorphologic equilibrium. Consequently, the reservoir shorelines are exposed to, and are still responding to, a range of impacts from processes that include flooding, erosion, landslides, groundwater fluctuations and landslide generated (or impulse) waves (Lawrence et al. 2009).

The degree to which a shoreline is subject to each of these impacts is a function of several operational factors, including the drawdown range (i.e., high pool compared with low pool levels); the residence time for the water level at high pool; and the seasonal timing of both high versus low pool and synoptic patterns of wind speed and direction. Many of BC Hydro's reservoirs in the BC Interior experience a single high pool season after the spring melt, or freshet (generally in July-December). In contrast most reservoirs in coastal locations, including the Lower Mainland and on Vancouver Island, experience a shorter summer season post-freshet high pool (June-August). These coastal reservoirs are then purposely drawn-down in preparation for the fall-winter season rainstorm related high pool (usually in November-February).

There is also the impact of seasonal ice cover on the more northerly reservoirs in the BC Hydro system, and the associated potential impacts of ice erosion on shorelines (Sodhi et al., 1996). Consequently, from reservoir to reservoir, depending on the frequency and duration of reservoir water levels, there is a considerable range of exposure times of the shorelines to periodic flooding, erosion and other destabilising forces (e.g., storm and landslide events). This can account for the lengthy time required for shorelines to reach dynamic geomorphic equilibrium, often in the range of many decades to perhaps many centuries.

A significant component of BC Hydro's operations include head ponds or "run-of-river" type reservoirs with a very small range of drawdown (usually less than about 0.5 m, and some up to about 2 m) and often with no well-defined high pool period. The much smaller drawdown ranges in these instances allow the geomorphic processes acting on shorelines to achieve dynamic equilibrium over a much shorter time period than those reservoirs with a much greater drawdown.

3 IMPACT LINES

In the early 1990s, BC Hydro developed a geotechnical approach to account for impacts from geomorphic processes related to its operations on reservoir shorelines in a manner that allows for consistent technical evaluation of typical geotechnical related issues. The concept of a family of *impact lines,* one for each of still-water flooding, erosion, stability (or landsliding), groundwater and landslide induced waves, is documented in a set of internal guidelines (BC Hydro 1993, ICOLD 2002). The concept of impact lines and how they are applied is described in some detail by Lawrence et al. (2009).

The most important outcome of establishing impact lines is the determination of setback distance(s) from the full pool elevation (or present-day high water mark). For most reservoirs, multiple impact lines are determined and the impact line with the setback furthest landward from the reservoir is selected as the *overall reservoir impact line* and is the basis for determining the land to be included in a statutory flowage right-of-way agreement. These agreements usually include specific restrictions on land use, especially relating to habitable development.

While the technical basis for each impact line is reasonably well established, in many instances there are limited or no site-specific geotechnical data available. For example, around most reservoirs drilled wells commonly do not exist and consequently information on the underlying geology and prevailing groundwater regime is lacking. There is often no site-specific wind or wave directional or frequency information from which to estimate design wave heights. Only in very rare circumstances are there measurements of historic erosion rates that could be used to assist in predicting the extent of future erosion. As well, many sections of reservoir shorelines have limited or inadequate topographic data (i.e., no digital elevation models, or DEMs, from either aerial orthophotography or LiDAR) from which to analyse the shoreline morphology or to facilitate detailed shoreline configuration change analysis.

The most commonly applied impact lines are those relating to flooding, erosion and stability (or landsliding). The evaluation of a stability impact line also incorporates provincially legislated guidance that is applicable to residential development (APEGBC, 2010). The next sections demonstrate, by way of selected case studies on BC Hydro reservoirs, how the understanding of wind-generated wave erosion and beaching are being applied, and how gaps in available data are being addressed.

4 WAVE EROSION

The principal erosive process acting on reservoir shorelines is wind-generated wave action. Open-water wind waves that develop in response to wind-stress events over a reservoir, eventually reach shallow near-shore waters where the energy is expended against the shoreline leading to erosion (and wave related flooding).

4.1 Wave Height and Run-up

The energy carried by a wave increases as the square of the wave height, thus larger waves generated by storm winds tend to deliver the majority of potentially erosive energy to the shoreline. The expending of wave energy can result in shoreline erosion (as well as deposition). In general, erosion potential increases with steeper nearshore bathymetry because deep water waves carry their energy closer to the shore before increasing in height (shoaling), breaking and dissipating their energy (Figure 1). Breaking wave height (Hb) is limited to approximately 80% of the water depth close to the shoreline. Low gradient shorelines tend to distribute breaking wave energy over a wider area because in shallower water depths the wave energy is more gradually reduced at the shoreline. Steeper gradient shorelines experience less energy dissipation. This transformation of wave energy in the nearshore through shoaling and breaking is the means by which wave energy is made available for erosion.

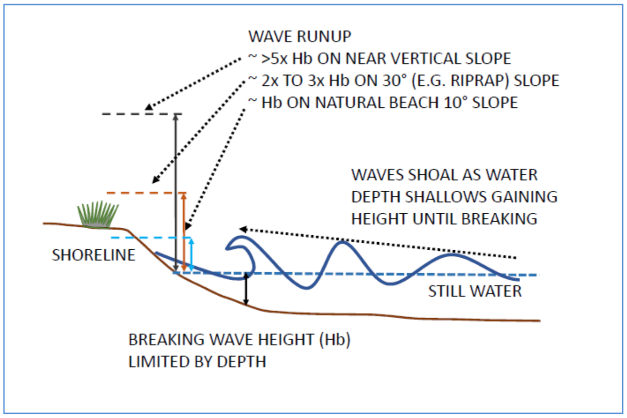


Figure 1. Schematic of relationship between nearshore wave height, shoaling and run-up.

Wave breaking close to the shoreline results in an uprush of water at the shoreline above the still-water level (referred to as wave run-up), that can locally increase flood levels. For shorelines with slope gradients less than about 10°, wave run-up is typically of the same magnitude as the breaking wave height (Hb); for slope gradients steeper than about 30°, wave run-up is typically between two and three times Hb; and for slope gradients approaching vertical, wave run-up is typically more than five times Hb (Figure 1). The frequency of wave run-up and the magnitude of water discharge during run-up can result in flooding and erosion to levels greater than the still-water level. Additionally, over-water winds can impart a stress on the water surface that increases the water surface level in the windward direction (referred to as wind setup). This creates wave conditions whereby water is piled up against the shoreline (wave setup) leading to flood impacts at levels above the still-water level.

4.2 Wind Analysis

For most reservoirs there are no site-specific wind data to analyse wind speeds, directions and frequencies, to estimate, by wave hindcasting, open-water wave heights and periods. Wind data across BC is commonly available for airports or airfields from Environment Canada. If this data is geographically close to a reservoir, it can be calibrated with visual wave observations and anecdotal observations at the reservoir, both of which can be of limited reliability). Obviously, there are a number of limitations associated with using wind data from a location that can be distant (sometimes many tens of kilometres) from the reservoir.

To overcome this data deficiency, BC Hydro in recent years has deployed a directional wind-wave buoy (Figure 2) to collect specific wind and wave data for reservoir shoreline studies and rip rap designs on Upper Campbell Lake and Williston Lake reservoirs. The TRIAXYS^{TM} buoy is manufactured by Axys Technologies Inc. (Sidney, BC), and was initially developed for open ocean waters, but is now being used on inland waterways.

Figure 2. TRIAXYS^{TM} directional wind wave buoy being deployed on Williston Lake reservoir (Photo courtesy - Tetratech EBA).

The buoy continuously collects meteorological (wind speed, wind direction, air temperature, and relative humidity) and wave motion data; this data is usually collected every second. Wind statistics, specifically average wind speed and direction, and maximum wind gust, are computed for ten minute periods.

From the results of recent buoy deployments it is apparent that using data from distant airports or airfields has its limitations. At Upper Campbell Lake, on central Vancouver Island, the wind-wave buoy was stationed in an almost north-south oriented steep sided glaciated valley approximately 30 km west of the Campbell River airport.

The location of the buoy is shown on Figure 3 at the confluence of the Elk River Arm with the main reach of the reservoir, and is approximately 14 km upstream of Strathcona Dam, that was commissioned in 1958.

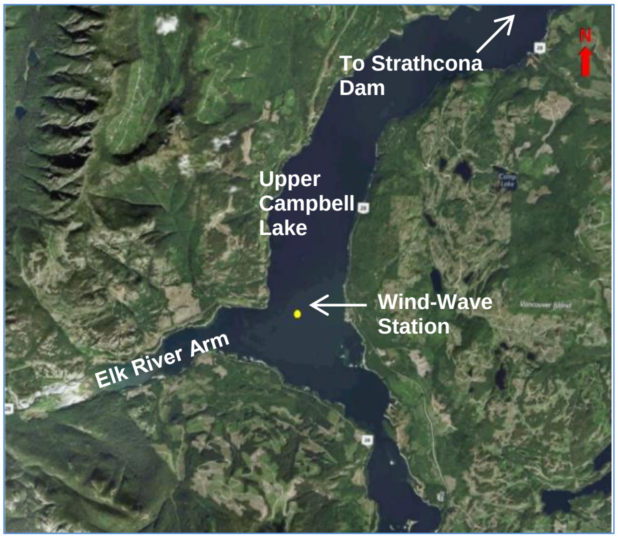


Figure 3. Location of wind-wave buoy station on Upper Campbell Lake.

The dominant northerly winds measured over the reservoir, for September 2016-August 2017, are shown on the wind rose plot in Figure 4. This local wind pattern is in sharp contrast with the bimodal synoptic seasonal northwesterly (summer) and southeasterly (winter) wind pattern recorded over-land at the Campbell River airport, for January 1989-June 2013 (shown on the wind rose plot in Figure 5). The airport is approximately 30 km east of the wind-wave station.

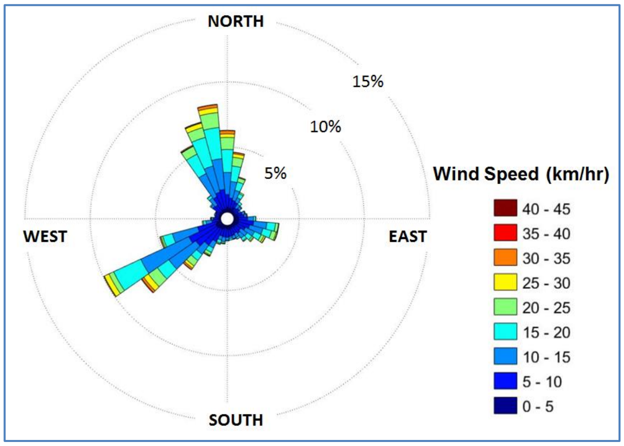


Figure 4. Wind rose plot for Upper Campbell Lake reservoir for the period September 2016 – August 2017.

Clearly the effects of topography, including dominant valley orientations and effects of headlands and embayments (referred to as topographic forcing), are important considerations when understanding local wind speeds, directions and frequencies. This is important in distinguishing local wind conditions from regional patterns. It is acknowledged that the wind rose shown in Figure 4 could appear quiet different if the wind-wave buoy was stationed elsewhere on the reservoir.

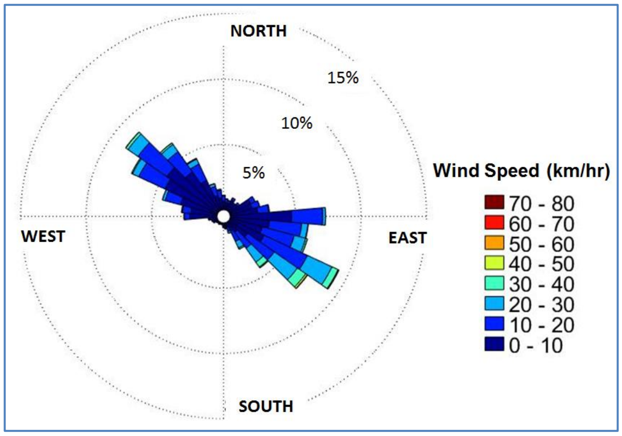


Figure 5. Wind rose plot for Campbell River airport for the period January 1989 – June 2013.

Further study determined that there was also a time lag between peak wind speed events at the reservoir and the airport, because of the time of passage of wind storm events given the distance between the two sites. There was, however, a weak correlation between peak wind speeds over-water and those at the airport, with a ratio of about 0.9:1.0. This correlation suggests that, in this instance, using wind speeds at the nearby airport could be reasonable for estimating over-water speeds on the reservoir.

4.3 Wave Hindcasting

Typically, deep water wave heights and periods are estimated using the local wind data, fetch (the distance travelled by wind or waves across open water) and water depth. Where site-specific open-water wind data are not available this estimation procedure is termed hindcasting. Wave heights and wave periods are usually calculated from the wind data for a range of fetches and water depths using empirical approaches developed for the design of engineered hydraulic rock structures (see for example; CERC 1984, SEBJ 1997, and CIRIA 2007).

As described above, with a directional wind-wave buoy, local wind and wave data can be collected, albeit for a relatively short period of time, to capture some representative storm events. These data can be used for wave model calibration, applied to wave hindcasting, and can provide detailed spatial distribution of wave intensities on a reservoir. However, wave models can be expensive to run and the quality of available data may be insufficient to justify their application.

The TRIAXYS^{TM} buoy directly measures deep water wave properties by tracking the rise and fall motion of the buoy in response to the incident wave field. Accelerometers measure motion and internal software translates the measurements into wave statistics. The most relevant statistics are the maximum wave height (H_M), significant wave height (H_S) and peak wave period (T_P) usually calculated for 20 minute periods.

The measured wave pattern for Upper Campbell Lake, for the one year period, September 2016 – August 2017, is shown in the rose plot in Figure 6. Moderate range wind speeds of up to 30-40 km/hr (Figure 4) generally correspond to measured significant wave heights (H_S) of up to 0.25-0.40 m for the fetches and water depths influencing the measurement site. The maximum wind speed of just over 40 km/hr was recorded (from the NNE) while the maximum significant wave height (H_S) for the same wind direction was recorded at 0.38 m corresponding to the dominant fetch. These are comparable to calculated H_S values in the range of 0.30-0.39 m using CERC (1984) and SEBJ (1997) empirical approaches.

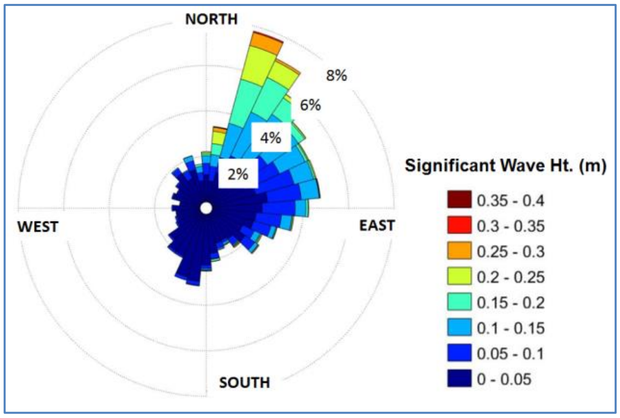


Figure 6. Wave rose plot for Upper Campbell Lake reservoir for the period September 2016 – August 2017.

The dominant fetch for this wind-wave station is to the north (Figure 3). Based on the immediate topographic setting, it is reasonable to expect a wave pattern that is strongly dominated by the approximate north-south orientation of the main valley and that the open water fetch is much larger from the north than the south. Also at this station, southerly to southeasterly winds are under-represented due to the lee effect of the mountain mass immediately behind the south shore. Waves from the south-southeast would be expected to be less frequent because of this lee effect and the shorter southeasterly fetch. A subordinate wave direction from the west might be expected somewhat reflective of the measured wind direction pattern (Figure 4).

However, the wave directions recorded for Upper Campbell Lake are interesting to note. The wave direction from the north-northeast is strongly controlled by the alignment of the main valley and the orientation of the longest fetch, approximately 6-7 km (Figure 3). In contrast, there are relatively few occurrences of waves from the southwest consistent with the limited fetch and few winds from this direction.

Of particular interest are the low frequency and small height of waves from the west-southwest considering the alignment of the Elk River Arm and the coincident subordinate wind direction. The lack of waves from this direction is due to the relatively short fetch, < 4 km, and the shallow water depth associated with the prograding delta at the mouth of the Elk River. The fetch and water depth effects on waves has implications for estimating the heights and periods of waves expected to impact the shorelines of the reservoir, with the largest and potentially most damaging waves being from the north-northeast and hence oblique or nearly parallel to the eastern shoreline.

After developing a snapshot model of the wind and wave climate, a more detailed statistical analysis can be conducted to develop extreme or maximum significant wave heights for a range of return periods (such as 5, 10, 20, 50, and 100 years). Both wind and wave extreme value analysis (EVA) with Weibull or Gumball probability density functions (e.g., Leenknecht et al., 1995) can be developed for each fetch and for different seasonal periods (e.g., summer and winter), and can assist in selecting design wave parameters.

5 EROSION RATES

Rate of shoreline regression is an important consideration in assessing the impact of erosion, and an understanding of past erosion rates can be used to estimate the potential future extent of erosion. In many situations the rate of erosion is difficult to assess because frequently there are very few, if any, dedicated erosion monitoring programs associated with reservoirs. Where there is good quality data, including detailed bathymetry, wind and wave hindcasting and historical erosion data, 3-D GIS-based modelling can be used to predict future erosion (e.g., Penner 1993; Penner and Boals 2003). As inputs into such modelling, or for more empirical approaches, remote sensing can be used to provide useful information. It relies on identifying recognizable features from one image /survey date to another, and measuring the positional changes that occur over a period of time.

5.1 Orthophotography and LiDAR Digital Elevation Models

The confluence of the Ingenika Arm with the Finlay Reach, at the north end of Williston Lake reservoir in northern BC, is situated approximately 240 km upstream of the WAC Bennett Dam, completed in 1967. In 2010, an erosion study was completed using historical air photos and LiDAR. The annual drawdown of the reservoir averages 11 m but ranges between 6 and 17 m. Because of the large drawdown range, it is expected that the shoreline will take many decades to reach dynamic geomorphic equilibrium. The shoreline geology at the study location is dominated by erodible unconsolidated glaciofluvial sand and gravel terrace deposits over a thin layer of glacial till, in turn overlying bedrock that is exposed in places at low pool elevations.

Erosion rates were estimated by quantifying the regression of the top of bank above the eroding shoreline. A digital elevation model (DEM) was generated, by orthophotogrammetry, for air photos taken in 1964 (pre-impoundment), 1971 (year that first filling was completed), and 1988, and LiDAR in 2009. The accuracy of DEMs was an important consideration because the older air photos are less accurate due in part to a higher flying altitude and less reliable ground control (Table 1).

Table 1. Comparison of air photo (orthophoto) and LiDAR-based digital elevation models.

Date	Type[1]	Nominal scale	Horizontal accuracy	Pixel size (cm)
1964	B&W	1:31,860	+/- 1.2 m	50
1971	B&W	1:30,000	+/- 1.2 m	50
1988	B&W	1:25,000	+/- 0.8 m	50
2009	LiDAR	1;20,000	+/- 0.6 m	50

[1] B&W refers to monochrome air photos; colour air photos were taken at same time as LiDAR.

It should be noted that more recent LiDAR surveys, flown at altitudes of about 300 m, can now achieve substantially better positional accuracies with a relative accuracy of about +/- 0.10-0.15 m, and a photographic pixel size of 15 cm. In the case study on Williston Lake, only differences between successive DEMs greater than 1-1.5 m were considered to be significant.

Eleven profiles through the top of bank–backslope–beach were analysed for changes on the successive DEMs. Figure 7 shows one typical profile.

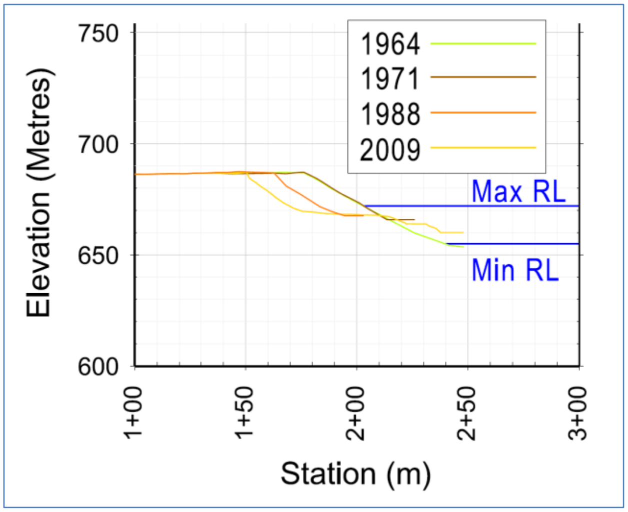


Figure 7. Typical profile showing top of bank-backslope-beach regression for 1964 to 2009 (RL = reservoir level).

As would be expected, for some profiles there was little difference in the position of the top of bank from 1964 to 1971, because the reservoir had only just begun to reach full pool for the first time in 1971 (Figures 7 and 8). For other profiles, where the fluvioglacial deposits are deeper, some top of bank regression had already commenced by 1971. Most of the observed top of bank regression occurred after 1971, and over the 39-year period the total retreat of the top of bank typically ranged at 9-26 m (or 0.24-0.68 m/yr).

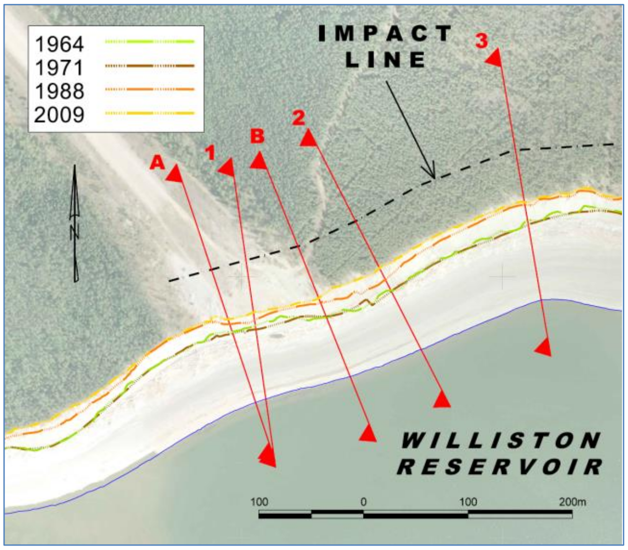


Figure 8. Section of reservoir shoreline on Williston Lake reservoir showing top of bank regression from 1964 to 2009, and location of erosion impact line.

Early average erosion rates (1970-1988) of 0.67 m/yr compared with later average erosion rates (1988-2009) of 0.16 m/yr indicating a trend of decreasing erosion rates. This decrease was more or less consistently recorded on all profiles. Based on the observed decrease in erosion rates, an erosion impact line was established with a setback of 20-50 m from the top of bank to allow for future regression over the next 100 years (Figure 8).

6 SHORELINE CLASSIFICATIONS

A critical method of efficiently evaluating reservoir shorelines that are prone to geomorphic impacts is to classify segments of the shoreline according to a number of parameters. These parameters typically include; aspect and fetch; geology (including soil type and/or presence of bedrock, their inherent strength properties and resistance to erosion); geomorphology (including current landforms and present-day active geomorphological processes); topography (specifically beach and upland slope gradients, and complexity); vegetation (absence or presence of vegetation cover and types); and presence of anthropogenic excavations, fills and erosion protection structures.

6.1 Erosion Susceptibility Classes

For a series of studies on Seton Lake reservoir, near the town of Lillooet in southwestern BC, the shoreline at various locations was classified in terms of erosion susceptibility. The average water level in Seton Lake was raised by about 0.45 m with the construction of Seton Dam in 1956. The reservoir is operated as a “run of river” with a daily fluctuation in water levels of only about 0.40 m. Consequently, the geomorphic impacts are relatively concentrated and broadly contained within the range of pre-reservoir lake levels.

To efficiently study the 10 km of reservoir shoreline, it was necessary to develop a classification system that allowed segments of shoreline with similar erosion susceptibility to be evaluated with the same set of setback parameters. An example of an early classification system, developed in 1999, is shown in Table 2. This classification was based, in part, on identifying the existing condition of the shoreline in terms of the extent or severity of observed erosion (i.e., a combination of length and height of an existing erosion feature such as a scarp), and the likelihood of future erosion (e.g., scarp regression).

The classification scheme in Table 2 was primarily used to quantify the lengths of shoreline in each class and to assist in defining the length of shoreline that was susceptible to significant ongoing loss of land (i.e., classes D and E).

Table 2. Relative erosion susceptibility classes for Seton Lake reservoir, 1999.

Erosion class	Description
A	No active erosion
B	Minor erosion[1] in places
C	Minor erosion[1] on long sections of shoreline; or moderate erosion[2] in places
D	Moderate erosion[2] on long sections of shoreline, or severe erosion[3] in places
E	Severe erosion[3] along entire shoreline

[1] Minor erosion: toe of backslope (< 0.5 m high scarp), unlikely to propagate much further upslope.

[2] Moderate erosion: up to several metres of backslope (0.5-2.0 m scarp), possibility of propagating further upslope.

[3] Severe erosion: greater than several metres of backslope (> 2.0 m scarp), often involving most of slope and may lead to significant slope instability.

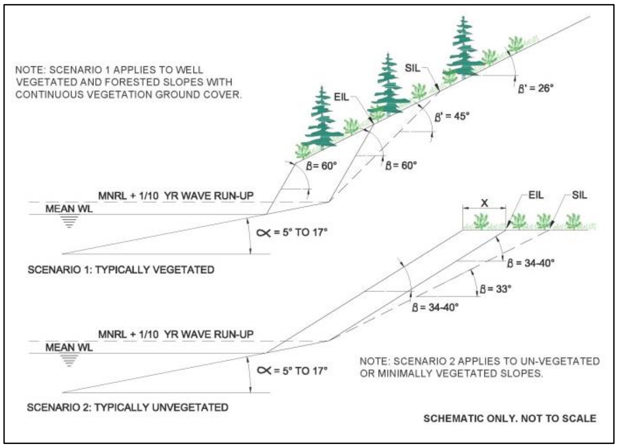
In a subsequent study in 2001, a more detailed classification was developed to assist in establishing an erosion impact line along the shoreline (Table 3). This updated classification incorporated new classes that recognised modifications to the shoreline from anthropogenic activities including a BC/CN Rail embankment, which was constructed as the Pacific Great Eastern Railway in 1914, and which in many places runs along and immediately adjacent to the shoreline. Other new classes included the prograding delta at the mouth of Seton Portage River and the associated low-lying floodplain, and the aggrading creek fans of several ephemeral creeks. In this respect this updated classification scheme included conditions that both promote and resist erosion, as well as define limiting conditions to the ultimate extent of shoreline regression.

6.2 Application to Impact Line Setbacks

Using such a classification system enables a consistent approach to be adopted when applying setbacks for one or more impacts to the reservoir shoreline. Figure 9 shows examples that distinguish key differences in slope morphology (gradient and complexity), severity of active toe erosion (presence or absence of eroding toe scarp), and presence or absence of a mature, and stabilising, vegetation cover.

Table 3. Updated erosion susceptibility classes, including anthropogenic activities, for Seton Lake reservoir (2001).

Class	Description
1	Intact resistant bedrock with no potential for significant regression.
2	Actively prograding river mouth and delta with some locally slowly regressing low-lying shoreline.
3	Steeply sloping overburden steepened or blanketed by excavation spoil or track ballast, some ballast/riprap provides erosion protection at slope toe.
4	Moderately to steeply sloping overburden, with little or no human disruption, often with a mature tree and bush vegetation cover.
5	Railway embankment fills (locally with natural slope deposits) at angle of repose.
6	Active aggrading creek fans, mostly ephemeral but displaying evidence of recent debris flows or floods.
7	Actively slumping overburden slopes - either naturally unstable or destabilised by human activities.
8	Shoreline highly modified by human activity, including lockblock or gabion basket retaining walls.


NOTE: SCENARIO 1 APPLIES TO WELL VEGETATED AND FORESTED SLOPES WITH CONTINUOUS VEGETATION GROUND COVER.

NOTE: SCENARIO 2 APPLIES TO UN-VEGETATED OR MINIMALLY VEGETATED SLOPES.

SCHEMATIC ONLY. NOT TO SCALE

Figure 9. Examples of key differences in applying setback distances for erosion and stability impact lines on Seton Lake reservoir.

The profiles in Figure 9 show that erosion is the dominant process, whereby wave action at the toe results in incremental regression of the backslope (and top of bank). In the short term this regression can result in a relatively steep slope angle that is usually short-lived. Over time, processes of ravelling and shallow slumping, including small sloughs and landslides, can reduce the backslope angle that further extends the setback distance from the reservoir edge. Depending on the topography and slope complexity the additional setback for the stability impact line (SIL) can extend significantly beyond the erosion impact line (EIL).

In some instances on Seton Lake, where the erosion potential is low, the EIL setback can be as low as 2-4 m and the SIL setback can be 4-8 m. Where the slopes are steeper and higher, and the erosion potential is moderate or severe, the EIL setback can be as much as 17-23 m and the SIL can be a further 2-8 m, for a total setback of 19-31 m.

7 CONCLUSIONS

Many challenges confront the geotechnical professional when evaluating reservoir shorelines and establishing practical setbacks related to geomorphic processes. Relevant information, such as site-specific wind and wave data, subsurface geology, groundwater level data, and historic erosion rates are often not available, or are very limited. Very seldom are reservoir shorelines investigated by test pitting or drilling, so commonly there is very little information on subsurface geology and groundwater.

Compounding the challenges are those created by the modifications to the shoreline by anthropogenic activities, such as excavations, embankment and related fills, and the construction of erosion protection structures. As the case studies presented above show, ongoing technological developments provide a means of overcoming some of the major data gaps.

The deployment of directional wind-wave buoys will not only provide much needed site-specific data, but also provide the ability to better understand local wind and wave settings when compared with regional meteorological patterns. New datasets of this nature can help ensure that empirical relationships continue to be appropriately applied and wind and wave models can be calibrated where data is otherwise limited or absent.

Recent advances in photogrammetry and airborne LiDAR provide means of determining historic erosion rates that can be used to estimate future erosion rates. Applications involving very low altitude UAV platforms with high resolution digital photography and structure-in-motion (SiM), and LiDAR provide the promise of even greater resolution for critical situations. Although BC Hydro has been using UAVs for a range of Dam Safety related projects, the technology has yet to be applied to reservoir shoreline assessments.

The application of the concept of impact lines, first developed by BC Hydro in the early 1990s, continues to be refined on several fronts. However, there is increasing pressure from land developers, private landowners, and other land users, continuing challenges posed by mountainous and often remote terrain, and possible impacts from climate change. Nonetheless, the application of the impact line concept continues to be an effective and efficient way of managing BC Hydro's operational liabilities on its reservoir shorelines. The overall reservoir impact line, as defined in this paper, is an invaluable instrument to define a setback for inclusion in flowage right-of-way agreements, and to facilitate land development that is compatible with the geomorphic processes acting on reservoir shorelines.

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