RESERVOIR SHORE EROSION PROCESSES AND PREDICTIVE MODELLING: A 30-YEAR REVIEW

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ABSTRACT

Penner (1993) published a 3-volume report entitled, "Shore erosion and slumping on western Canadian lakes and reservoirs." Volume 1 described the current understanding of shore erosion processes in lakes and reservoirs and presented a procedure for predicting future bluff recession rates and eroded sediment volumes. Based on these principles, a GIS-linked shore erosion model was developed and then applied and refined in studies for three major hydroelectric projects in western Canada. In addition to those major projects, shore erosion data from nineteen (19) lakes and reservoirs located across Canada have also been studied. Insights gained over three decades, combined with improved input data and analytical methods, allow for increased modelling accuracy and flexibility to address a range of issues. Model outputs include predicted bluff recession, nearshore slope angles and eroded sediment volume during construction and reservoir operations. Modelled time intervals can be varied, and the model has been run for up to 100 years of reservoir operation. The ability to input different water level and wave energy scenarios allows impacts associated with a variety of operational scenarios to be assessed, as well as those associated with alternative wind, precipitation, and temperature projections from climate models.

RÉSUMÉ

Penner (1993) a publié un rapport en trois volumes intitulé « Érosion et affaissement des berges dans les lacs et réservoirs de l'Ouest canadien ». Le premier volume décrit les connaissances actuelles sur les processus d'érosion des berges dans les lacs et les réservoirs et présente une procédure de prévision des taux futurs de recul des falaises et des volumes de sédiments érodés. Un modèle d'érosion des berges, relié à un SIG, a été élaboré, puis appliqué et peaufiné dans le cadre d'études portant sur trois grands projets hydroélectriques dans l'Ouest canadien. Outre ces grands projets, des données sur l'érosion des berges provenant de dix-neuf (19) lacs et réservoirs répartis dans tout le Canada ont également été étudiées. Les connaissances acquises au cours de trois décennies, combinées à l'amélioration des données d'entrée et des méthodes d'analyse, permettent d'accroître la précision et la flexibilité de la modélisation pour répondre à diverses problématiques. Les résultats du modèle comprennent la prévision du recul des falaises, des angles de pente littorale et du volume de sédiments érodés pendant la construction et l'exploitation des réservoirs. Les intervalles de temps modélisés peuvent varier, et le modèle a été exécuté sur des périodes allant jusqu'à 100 ans d'exploitation des réservoirs. La possibilité de saisir différents scénarios de niveau d'eau et d'énergie des vagues permet d'évaluer les impacts associés à une variété de scénarios opérationnels, ainsi que ceux associés aux projections alternatives de vent, de précipitations et de température issues de modèles climatiques.

1 INTRODUCTION

Penner (1993) published a report entitled, "Shore erosion and slumping on western Canadian lakes and reservoirs" in three volumes: 1) A methodology for estimating future bank recession rates; 2) Erodibility coefficients for common shore zone materials around Lake Diefenbaker, Avonlea Reservoir and Lake of the Prairies; and 3) A photographic catalogue for three western Canadian prairie reservoirs. Volume 1 of this report describes the understanding of shore erosion processes in lakes and reservoirs at that time and presents a procedure for predicting future bank recession rates and eroded sediment volumes based on effective wave energy and erodibility coefficients for various shore zone morphologies

Since that publication, Penner (2002) further refined the methodology for predicting bank recession rates and developed a GIS-based shore erosion model from studies for three hydroelectric projects – Manitoba Hydro's Keeyask and Conawapa projects and BC Hydro's Site C Project. In addition to these major projects, shore erosion assessments were completed on many other lakes and reservoirs located across Canada. Combined, these projects provided valuable opportunities to observe shore erosion processes and effects over a range of time periods and in different geological, geographical and climatic settings. This, in turn, afforded opportunities to develop an improved understanding of shore erosion processes and to refine procedures for predicting shore erosion rates using the JDMA shore erosion model.

1.1 Background

Penner (1993) was in large measure possible because of earlier studies undertaken by Dr. J.D. (Jack) Mollard starting in the late 1950s for the design and construction of Gardiner Dam, the world's largest earthfill dam at the time, and the subsequent impoundment of Lake Diefenbaker in 1966. Dr. Mollard's early work in this area, summarized in Mollard (1986), captured learnings from studies on 32 natural lakes and reservoirs over the period 1956-1986.

Projects completed from 1986 to 1993 include two major reservoir developments in southeastern Saskatchewan – the Alameda and Rafferty reservoir projects – and early work on the Wuskwatim hydroelectric project in northern Manitoba. Since 1993, in addition to the Keeyask, Conawapa and Site C projects already mentioned, studies have been completed at Williston Lake, BC; on the Saskatchewan River for the proposed Pehonan hydroelectric project; in the Codette and Thomson reservoirs and at Elbow Harbor in Lake Diefenbaker, all in SK. Other studies were conducted on Lake of the Woods, ON; Lake Manitoba and Lake St Martin, MB; Beothuk (formerly Red Indian) Lake, NL; and Mayo Lake, YT (Figure 1). These far ranging locations provide data and insights from diverse sizes of reservoirs and from a range of geographical, geological and climatic settings: for example, till-dominated shorelines in the glaciated southern prairies; peatland and permafrost-affected shores in glaciolacustrine-dominated northern boreal forests; sedimentary bedrock shorelines in the western Canada sedimentary basin and in the Rocky Mountains; glaciodeltaic and glaciomarine valley terraces in the Rocky Mountains; Precambrian bedrock terrain; glaciated terrain in Canadian Shield settings; and glaciated bedrock in Newfoundland. These studies were conducted for a range of applications including pre-development prediction of erosion impact lines and eroded sediment volume to support engineering and environmental studies; assessment of predicted impacts during construction, reservoir filling and operation over many decades; re-evaluating reservoir takelines; assessing reservoir sedimentation; evaluating erosion impacts to land and infrastructure; assessing erosion mitigation options; providing input for re-evaluating reservoir operation plans; and assessing the interaction of shore erosion with other processes such as large scale slope instabilities, degradation of permafrost, generation and distribution of woody debris, and peatland disintegration.

Although early versions of the JDMA erosion model accounted for nearshore downcutting, methods to incorporate parameters affecting nearshore downcutting improved over time (e.g., wave energy dissipation across nearshore slopes and water level fluctuation – factors controlling effective wave energy). Observations in many reservoirs have validated the importance of nearshore downcutting, allowing more accurate predictions to be made based on local geological and wave energy conditions.

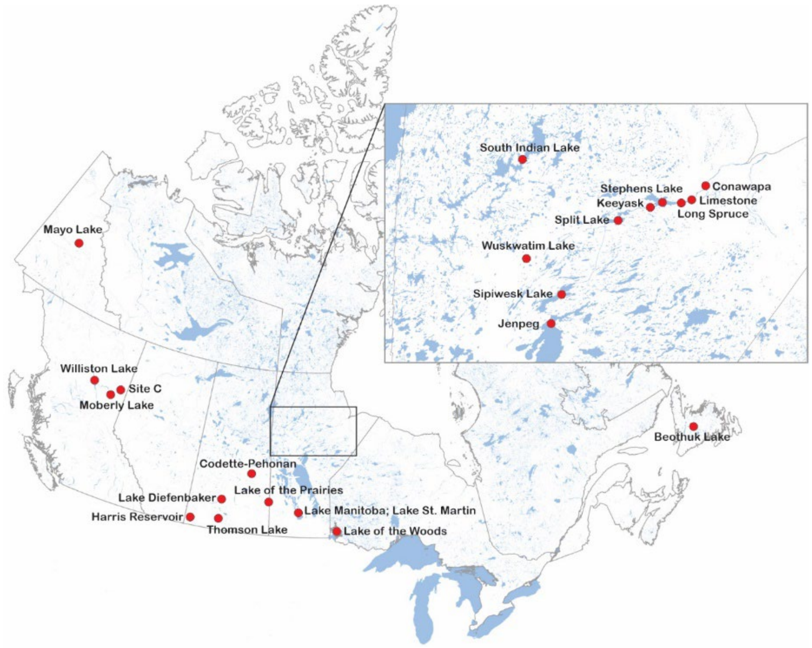

Figure 1. Project locations referred to in this paper

Improved computer technology and the availability of topographic data (e.g., from high resolution photogrammetry and LiDAR sensors) have allowed for improved characterization of input variables and more rigorous modelling. Prior to the availability of these technologies, manual calculations were done at a relatively small number of locations around a reservoir using wave energy equations and charts. These calculations would then be extrapolated across long shoreline reaches. Now numerical calculations can be performed at a high number of short shoreline segments around reservoirs and over more frequent time steps. This allows a greater range of reservoir operation scenarios and erosion calculation periods to be modelled – e.g., days, weeks, months vs annual, biannual or even longer modelling intervals. The model can also be applied over shorter time periods during construction and reservoir filling, and for assessing water level and wave energy conditions related to climate change and operational factors. In the past, erosion assessments focused on predicting changes in bank position over time. More recently, however, questions regarding the volume of sediment generated by erosion and how incoming sediment affects water quality and aquatic habitat within the reservoir and downstream are equally important considerations in reservoir assessments. Bank recession and delivery of sediment to reservoirs are closely related and must be appropriately linked in a correctly understood and formulated model. Reservoir sediment coring studies have helped to form a better understanding of sediment transport and deposition mechanisms within the reservoirs and demonstrate the relationship between bank stratigraphy and nearshore sediment deposition and transport.

1.2 Overview of erosion process

Shore erosion results from several interacting processes: wave erosion of the bluff toe, nearshore downcutting and flattening by current and wave action, mass wasting of the shore bluff from weathering, periodic failure of the bluff, removal of failed bluff slope debris (colluvium) by wave action, and offshore and alongshore transport of eroded sediment. Rates of erosion are affected by factors such as wind speed and fetch, wave and water level conditions, frequency and severity of storms, ice cover period and ice processes during breakup, erodibility of bank and nearshore materials (including permafrost and changing material properties due to thaw), vegetation cover and the presence of woody or rocky material along the shoreline. The shore zone defined for the purpose of shore erosion studies extends from the top of shore bluff to a point on the underwater slope that corresponds to the maximum wave base depth under minimum water level conditions. A shore zone profile and terminology are illustrated in Figure 2.

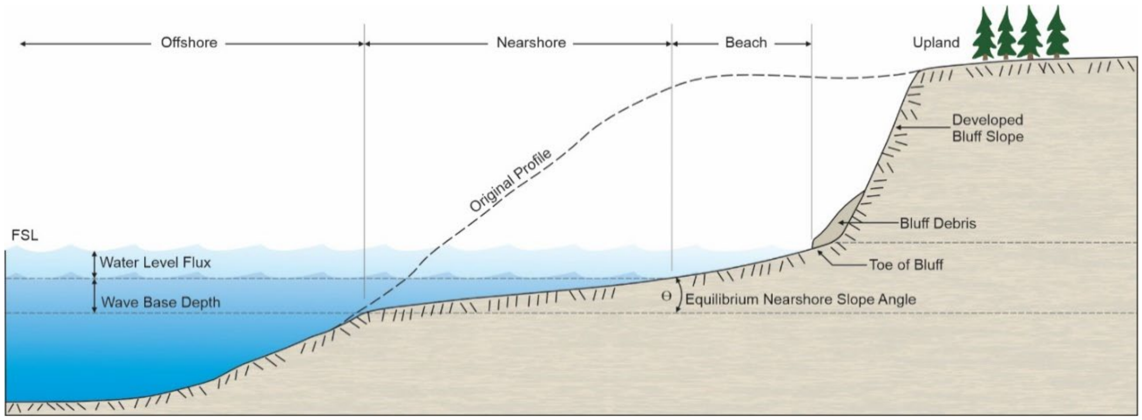

Figure 2. Graphical depiction of the shore zone area

Continued wave action and bluff mass-wasting cause ongoing evolution and modification of the shore zone profile. These processes result in progressive downcutting and flattening of the nearshore slope and related landward recession of the bluff toe. Shore erosion tends to be cyclic, particularly where shore zones are subject to fluctuating water levels and bluff mass wasting processes in lakes and reservoirs, as is the case around multi-purpose reservoirs designed for power development, water supply, flood control and irrigation.

When water levels are relatively high (Figures 3A and 3B), wave erosion at the bluff toe and across the nearshore slope above wave base depth dominates shore evolution. This commonly results in accompanying failures along the upper bluff slope (Figure 3C). When water levels are low, mineral soil and vegetation debris shed during bluff mass-wasting accumulates at the toe-of-bluff, above the temporary reach of incoming waves (Figure 3D). The dominant wave erosion process at times of low water level is therefore progressive downcutting and flattening of the lower nearshore slope.

High water following a period of low water level results in the removal of the bluff failure debris. Debris removal is followed by continued erosion of the nearshore slope. Washing by waves reworks coarser sediment accumulated on the nearshore slope. If water level remains high for long enough, virtually all bluff debris will be removed and wave erosion of the bluff toe will take place, precipitating further bluff failures. As the water level falls, debris shed from the bluff begins once again to accumulate at the toe; remaining there until the next rise in water level and incursion of waves. Topple failures, shallow sloughing and small block slides are common in cohesive till bluffs (Figure 3E and 3F), which usually contain several sets of near-vertically dipping joints as well as occasional horizontal parting planes. These structural discontinuities in clay till result in the development of near vertical bluff slopes, as blocks of bluff material separate along vertical joint planes and topple or slide down. Open joints (fissures) a short distance back from the bluff crest mark the location of the next topple failure. Shallow sloughing is more common in bluffs composed of highly fractured clay till, sand and silty and sandy clay (Figure 3G). Silt rich sediments may collapse rapidly upon initial flooding. Where ice rich permafrost is present, thawing of ice lenses may result in debris flows.

Figure 3. Shore erosion at Lake Diefenbaker, Saskatchewan. Erosion of the shore zone and bluff recession (**A, B, C, D**). Block, topple and block slide failures in cohesive till bluffs (**E, F**) and shallow sloughing in highly fractured clay till (**G**)

1.2 Evolution of Shore Zone Morphology

Shore zone morphology evolves as erosion progress through three stages representing early, intermediate, and advanced stages of evolution, as shown in Figure 4. The early stage occurs when waves wash and erode previously non-flooded slopes around new reservoirs, and where water levels are raised in existing lakes and reservoirs. Initially, a narrow beach forms, backed by an adjoining, typically low, bluff face. During this early stage, toe-of-bluff erosion and bluff mass-wasting dominate the shore erosion process. As erosion continues into an intermediate stage, the nearshore slope widens and the bluff face becomes higher, depending on the topographic relief above the nearshore slope and bluff crest. During the intermediate stage, nearshore erosion becomes increasingly important, although toe-of-bluff erosion and bluff mass-wasting are still significant.

With continued erosion, the nearshore slope widens and flattens. Nearshore slope downcutting begins to dominate the erosion process. Bluff mass-wasting continues but is largely independent of wave erosion except for periodic removal of bluff debris and undercutting of the toe-of-bluff by wave action during times of high-water level. Shore zones reaching an advanced stage of evolution are uncommon around relatively young reservoirs – say, less than 100 years old. Examples of advanced erosion tend to be observed around large, long-lived lakes, such as Lake Winnipeg and the Great Lakes, and ocean coasts.

The duration of each erosion stage (and associated changes in bluff recession rate, bluff height, bluff slope angle, nearshore width, and nearshore slope angle) depends mainly on the sensitivity of the shore zone area to wave erosion. This sensitivity, moreover, is a function of the wave energy environment, shore zone material, bluff stratigraphy, water level fluctuation and the shore zone profile shape prior to erosion.

2 INITIAL FLOODING AND EARLY-STAGE EROSION

Initial reservoir impoundment is usually conducted in distinct stages during construction with the final stage reaching the full supply level (FSL) prior to the onset of reservoir operation. Depending on construction requirements and sequencing, initial inundation of previously unflooded banks begins following completion of the initial coffer dam which restricts downstream flow and increases river stage upstream of the coffer dam. Further raising of the initial coffer dam, construction of additional coffer dams, and staged construction of the main dam, cause additional stepwise increases in river stage during each construction stage. Combined, these stages often span several months or years. During each stage the shoreline elevation will gradually increase with a new shoreline forming when the maximum elevation of each stage is reached and held for some time. The original unflooded bank is subject to erosion while the water level rises to each stage level and then by wave and current erosion throughout the duration of each construction stage.

Although construction stages are much shorter than the operational life of the reservoir, and even though these temporary shorelines will eventually be submerged during successive construction stages until FSL is reached, it remains important to carefully assess the potential for local areas of high erosion to develop during construction which could impact construction activities and infrastructure near the reservoir, or create conditions that affect the stability of the reservoir slopes and sediment concentrations in the river during construction.

The amount of erosion that occurs during construction and upon initial filling of a reservoir to FSL depends on a number of factors with the main ones being:

1) composition of the bank materials (including permafrost) saturated upon reservoir flooding
2) stability of the banks and presence of past and active slope failures
3) rate and height of water level rise during each construction stage
4) extent of drawdown during construction stages
5) bank slope angle
6) existing water table elevation in the bank
7) wave energy exposure after water level rise (wind speed, fetch and duration of each stage)
8) alongshore current velocity after water level rise
9) vegetation cover, its stability when flooded and the duration of each stage
10) duration of the construction stage and length of open water conditions during each stage.

A dramatic example of the effect of bank material on erosion during reservoir filling was documented by BC Hydro during filling of the Williston Reservoir. In that case, over 350 meters of bank recession occurred as the reservoir level rose over 100 m inundating fine-grained sandy and silty glaciolacustrine sediments. Rapid increases in pore pressure resulted in the extensive collapse of cohesionless sediments within the first five months of reservoir filling (International Power Engineering Consultants 1968).

Rapid recession can also occur in ice-rich permafrost where inundation of reservoir water results in the thawing of permafrost ice. Where bank sediments are ice-rich, thawing results in saturation and collapse of the sediment and rapid recession of bluffs and shorelines (Figure 5a). The rate of these changes is mainly a function of the ice content, sediment composition and rate at which the ice melts upon inundation.

Inundation of glaciolacustrine clays, interbedded clay, silt and fine sand sediments, and banks affected by active slope instability, can also result in intermediate to high rates of short-term bluff recession due to wetting of weakness layers and increased pore pressure leading to failure of the banks (Figure 5b). Erosion rates also depend in part on wave energy exposure, the steepness of the existing banks and on vegetation cover which may help mitigate effects of inundation due to the stabilizing effect of roots. However, the mitigating effect of vegetation in this circumstance is generally temporary as the gradual breakdown of the vegetation cover and protective root system will eventually leave geotechnical factors and wave energy controlling long-term bank recession rates.

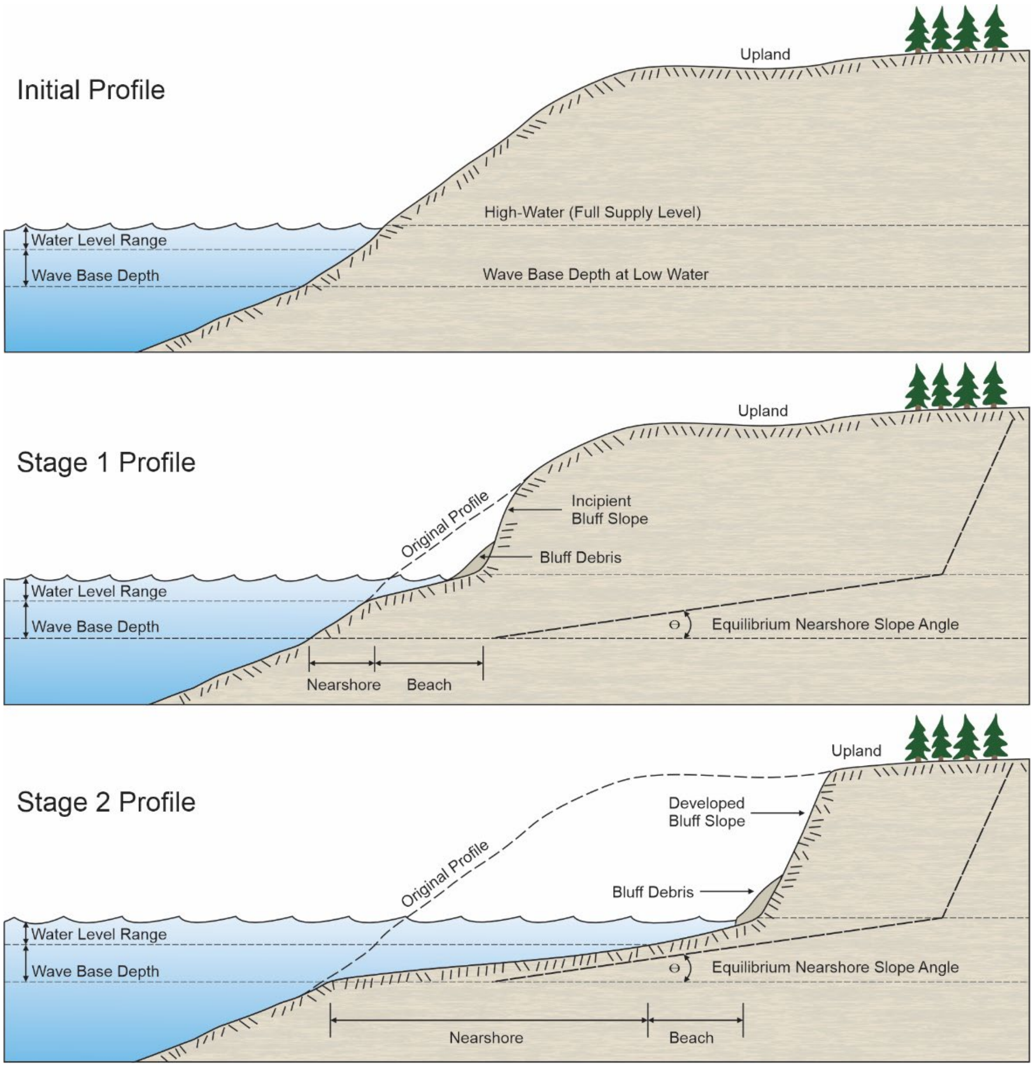

Figure 4. Conceptual model illustrating the evolution of shoreline morphology over time

Figure 5. (a, left) Sediment collapse and rapid recession of a permafrost bluff during the inundation of Stephens Lake, Manitoba. (b, right) Short-term bluff recession in Glacial Lake Agassiz deposits at Wuskwatim Lake, Manitoba

Where bank materials consist of dense clay till or moderately cemented bedrock, banks will usually remain relatively stable as reservoir levels rise because the primary erosive force is wind-driven wave action. In these materials, recession rates during construction and immediately upon reservoir filling are primarily a function of the erodibility of the bank materials and the wave energy. Vegetation cover may play a secondary role in delaying erosion of the bank until the root mat breaks up sufficiently to allow wave action to reach the underlying mineral soil. If the construction stages are sufficiently short, the vegetation cover may remain intact and negligible erosion of the mineral soil may occur before the water level rises at the start of the subsequent construction stage. Current flow can also be a factor in narrow riverine reservoirs but is less important in wider reservoirs.

Another situation that can occur is inundation of erosion resistant bedrock and cobble and boulder deposits. In these cases, erosion during construction and upon reservoir filling is generally low to negligible (Figure 6).

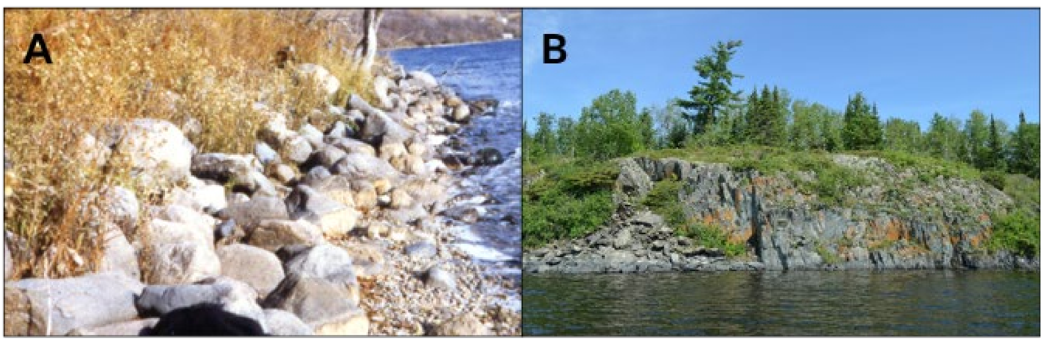

Figure 6. Cobble and boulder (**A**) and bedrock (**B**) deposits bounding surface water bodies

The duration of the initial transition of a newly flooded shoreline to a more settled environment that is amenable to predictive modelling depends on the newly flooded shoreline materials and conditions, with a few notable examples described in the preceding section. Therefore, the duration of the initial stage varies from reservoir to reservoir, and even from one location to another within a given reservoir. As a rule of thumb, however, the initial stage typically lasts up to 5 years or so. This is followed by an intermediate stage that may last several decades to a century, or longer, before entering what may be considered a mature stage where further shoreline changes are generally very gradual. Shore erosion modelling work considered in this paper largely focusses on predicting changes during the intermediate stage.

3 NEARSHORE EROSION PROCESSES

A key concept described by Penner (1993) and incorporated in early versions of the JDMA erosion model is the process of nearshore downcutting. In the past, some methodologies relied on a template method that recognized that long-term nearshore slope angles tend to develop in reservoirs over time, but incorrectly concluding that once developed, the long-term nearshore slope angles remained stable, not only in terms of slope angle but also in terms of lateral position. As a result, the positions of the bank and nearshore slopes were assumed to stabilize when long-term nearshore slope angles had been reached. Although such stabilization can occur in certain circumstances, it is not the general case. Authors such as Davidson-Arnott (1986), Nairn et al. (1986) and Kamphius (1986) demonstrated the concept of nearshore downcutting in studies from Great Lake and coastal shorelines. However, this process was not widely recognized by practitioners studying western Canadian reservoirs at the time. Although the process of nearshore downcutting in western Canadian reservoirs was suggested by Penner (1993), it wasn't until later that data demonstrating this to be true were collected and understood. It is now clear that nearshore downcutting is responsible for: 1) the gradual progression of the beach slope towards a long-term slope angle and 2) for the continued downcutting of the beach slope on that angle and landward recession of the bank even after the long-term nearshore slope angle has been reached (see Penner (2002).

As defined here, the onset of the intermediate erosion stage is marked by development of a nearshore slope of sufficient width that nearshore erosion processes begin to play an increasingly significant role in further evolution of the shore zone morphology. Through the process of nearshore downcutting, the steepness of the nearshore slope decreases, the bluff recedes, and the nearshore slope widens (Figure 7). The upper extent of the nearshore slope coincides with the maximum level of wind setup and wave runup at the expected maximum reservoir level (i.e., the full supply level or maximum extreme event level defined for the reservoir). The lower extent of the nearshore slope coincides with the maximum wave base depth below the minimum water level (see, also, Figure 4).

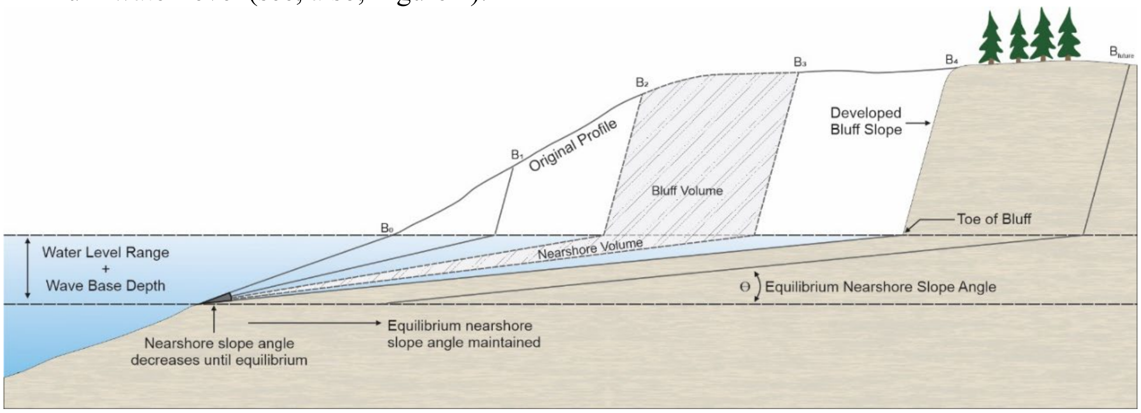

Figure 7. Illustration of erosion model increments showing bluff recession and nearshore slope downcutting associated with one modelling increment (shaded area)

Processes controlling the evolution of the shore zone morphology are discussed below:

1) Downcutting or vertical erosion of the nearshore slope by wave action is of primary importance. The maximum downcutting occurs on the steepest part of the nearshore slope and in areas most frequently exposed to waves. Therefore, over time the overall slope of the nearshore slope decreases. Once the ultimate angle is reached, nearshore downcutting continues but at a relatively uniform rate across the entire nearshore slope. In this way the ultimate angle is maintained while vertical erosion of the nearshore slope continues.

2) An important implication of nearshore downcutting is that it allows waves to continue to reach the bluff toe when the reservoir is at full supply. Therefore, bluff recession can occur indefinitely provided that the reservoir reaches full supply and that the nearshore slope and bluff toe are erodible.

3) While nearshore downcutting generally promotes ongoing long-term recession of erodible bluffs, bluff recession due to wave erosion may cease in response to: 1) removal of fines and accumulation of coarse material that effectively "armors" the nearshore slope against further downcutting; 2) exposure of erosion-resistant bedrock on the nearshore slope; 3) a gentle initial nearshore slope that dissipates wave action without downcutting; 4) accumulation of organic debris or emergent vegetation that reduces wave energy and downcutting rates.

4) At any point in time, one or more beach ridges may be present on a nearshore slope. Beach ridges are temporary features that form as waves transport (wash up) sediment (sand, gravel, cobbles, organic sediment) at the upper extent of wave runup during sufficiently long periods of steady lake level. A single beach ridge may be visible if observed during a period of water level rise whereas

more than beach ridge may remain following multiple periods of water level drop. When water level rises again. Sediment in these beach ridges will be re-distributed (washed away), and a new ridge may form above the rising water level.

5) Where abundant granular or organic sediment is present on the nearshore slope, waves reaching the shore at an oblique angle will transport the sediment along the shore and may lead to the formation of spits and point deposits. These landforms represent depositional features where the rate of deposition exceeds the rate of erosion. The accumulation of sediment prevents future nearshore downcutting and protects the bluff from wave attack at these locations.

6) Erosional scarps or steps on the nearshore slope are an indication that nearshore downcutting has removed sediment from below multiple sustained water levels. In these cases, rather than sediment being washed up to form a beach ridge, the nearshore slope has eroded with the sediment transported offshore.

7) Wave action combined with fluctuating water levels results in the transport of fine sediment down the nearshore slope towards deeper water and below the wave base depth where deposition occurs.

8) Ice processes can also impact the nearshore slope by transporting entrained sediment onto the nearshore slope in wind-driven blocks and sheets of ice which become grounded in shallow water.

4 PREDICTIVE SHORE EROSION MODELLING

Predicting future shore zone erosion in reservoirs is required to forecast land loss and develop erosion impact lines, help assess slope stability hazards and risks to public safety and infrastructure, predict loss of reservoir capacity and impacts to water quality and aquatic habitat. Two modelling approaches are commonly considered for developing predictions: 1) empirical modelling based on projection of historical erosion rates into the future; and 2) deterministic modelling based on physical processes and quantitative input parameters. Where the availability of data permits, a combination of these methods can provide an increased level of confidence. However, direct empirical methods are not possible in cases where a new reservoir is to be created – quite simply, there are no direct historical data because no reservoir exists at the time of study. To help overcome this constraint, historical data from nearby reservoirs with comparable operational parameters, size, topography, geology, vegetation, etc. may be utilized, but it is rare to find a perfect match. An alternative approach is to use a deterministic model to predict future erosion rates in new reservoirs using appropriate input data and numerical methods. A deterministic model concept and fundamental inputs were described by Penner (1993). At that time some inputs could be measured in a straightforward manner (e.g., original nearshore slope and fetch), while others were determined quantitatively (e.g., wave energy), but at a low-resolution given available data and methods at the time. Still others were based largely on reasonable assumptions where quantitative methods hadn't yet been developed or data were unavailable (e.g., effective wave energy, erodibility coefficients).

Here the general concepts presented by Penner (1993) are reviewed and the previous understanding of erosion processes is either validated or improvements suggested. Updated information on how input parameters can be better represented in the model is presented and guidance is provided on techniques for implementing the model. The primary advantages of applying a deterministic approach are: a) the capability to predict bluff recession distances, nearshore slope angle and eroded sediment volume over user-selected time intervals; and b) the ability to run the model for a range of input variables which allows a broad range of factors and model sensitivities to be considered. This is especially useful for evaluating potential climate change impacts and alternative operational scenarios.

The JDMA erosion model was built on nearly 60 years of erosion assessment studies in western Canadian lakes and reservoirs. Key references pertaining to the development of the model are Mollard (1986); Penner (1993); Penner and Boals (2000), Zimmer et al. (2004) and Cosford et al. (2013). Foundational studies for development of the model originated in 1961 with studies aimed at assessing future erosion impacts related to construction of Gardiner and Qu'Appelle dams and impounding of Lake Diefenbaker in southern Saskatchewan. Early numerical approaches were investigated in 1964. The techniques were applied and refined during studies on over 30 western Canadian lakes and reservoirs by Dr. Jack Mollard over the subsequent 25 years. Mollard (1986) summarized advances made up to that time. Studies on the Rafferty and Alameda reservoirs in the late 1980s and a three-year research project from 1990-1993 lead to the formulation of the first GIS-based application of the model. That research project culminated with three reports describing a methodology for predicting erosion on lakes and reservoirs (Penner, 1993a, b, c). Early versions of a GIS-based model were applied to the Wuskwatim Lake erosion assessment studies in the 1990s and early 2000s. The model has undergone considerable further development following the completion of the Wuskwatim Lake studies to better incorporate effects of nearshore downcutting, two-dimensional wave energy modelling, wave energy dissipation on nearshore slopes and water level fluctuations. In its current form the model has been applied on the Keeyask and Conawapa projects for Manitoba Hydro and the Site C Project for BC Hydro.

A key geomorphic feature that requires definition in the model is the 'shore zone.' The shore zone refers to the eroding bluff face directly impacted by wave erosion and bluff failure, and the nearshore slope that is affected by wave action. Defined in this way, the shore zone extends from the bluff crest to the point on the nearshore slope defined by the maximum wave base depth below the minimum water level, taking in the full water level fluctuation range anticipated during reservoir operation. The nearshore slope is the section of the shore zone below FSL (Figure 7). The model has two main components: 1) predicting the volume of material that will erode for a given effective wave energy value and shore zone material; and 2) predicting the change in eroded shore zone profile that will occur due to the loss of the predicted volume of erosion. Execution of these two modelling components requires knowledge of the pre-erosion shore zone profile geometry and the predicted nearshore and bluff slope angles that will form due to erosion. Figure 8 illustrates how the model progresses iteratively through the stages of nearshore downcutting and bluff recession. Steps A-D illustrate the progression from the original flooded nearshore slope to where the nearshore slope reaches the ultimate slope angle anticipated at a particular site (shown to be 4° in this case). At that point, nearshore downcutting continues while maintaining the ultimate nearshore slope angle, causing the nearshore slope to progress laterally toward the bluff. As the bluff continues to recede, a very gentle shelf (represented as a horizontal surface in the model) forms below the nearshore slope (i.e., below the maximum wave base depth). The width of this shelf then matches the amount of bluff recession at the upper end of the nearshore slope. The rate at which the nearshore slope progresses toward the ultimate slope and the rate at which the bluff recedes is dependent on the volume of sediment that is eroded during a given time period. In applying the model, the volumetric erosion rate is determined based on the erodibility of the shore material (i.e., the erodibility coefficient) and the effective wave energy. The shaded polygon in Figure 7 represents the volume (cross-sectional area x unit length of shore zone) eroded in a given modelling time interval.

Model Inputs

Key inputs to the model are total annual wave energy, water level range, initial nearshore slope, initial above-shore (bluff) slope, ultimate eroded above-shore (bluff) slope, bluff height and the erodibility coefficient for the shore zone material (single coefficient for nearshore and bluff materials). Model inputs are illustrated in Figure 8.

A fundamental assumption is that all model inputs are known with a reasonable degree of confidence. Erodibility coefficient is back-calculated using data from an existing reservoir(s) with similar materials and stratigraphy, using the total erosion volume and the effective wave energy calculated for a given time period Figure 10. Before applying the model, therefore, it is necessary to establish the model input parameters and then validate the model results against observations at eroding sites with similar shore zone materials, wave energy conditions, and shore zone profiles. In this regard, model validation tests have demonstrated the ability of the model to predict recession setbacks to within 5-8% of observed recession in two reservoirs after 16 and 28 years of operation (Torgunrud et al. 2012).

Wave energy values are determined by 2D wave modelling using wind data obtained from representative weather stations. Transformation algorithms can be applied as needed to account for spatial offset of the wind measurement station and local topographic influences. Input water level data are developed based on anticipated operating conditions during the open water season. Initial bluff slopes, nearshore slopes and bluff heights are measured from topographic data (generally derived from LiDAR digital terrain models). Predicted eroded bluff slopes and ultimate nearshore slope angles are based on shore materials and information from existing reservoirs with similar geological materials and conditions.

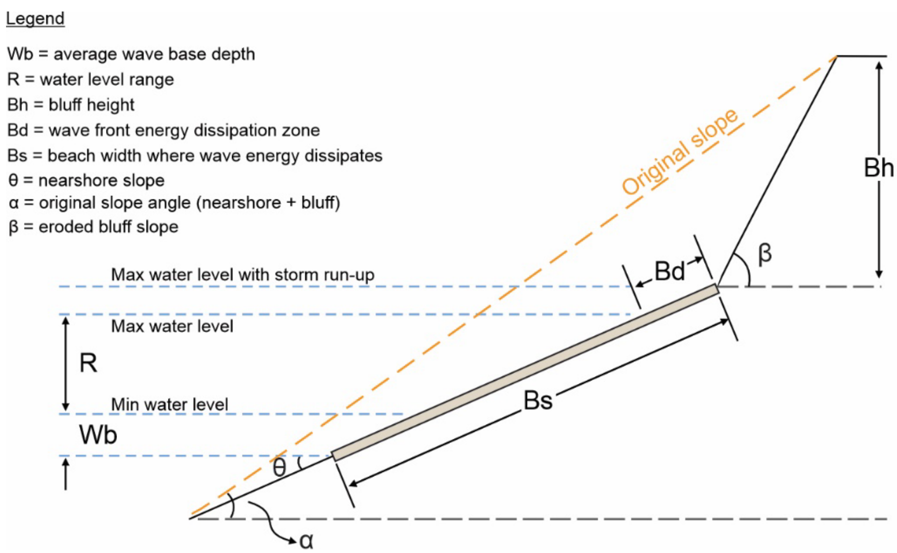

Figure 8. The conceptual model of shoreline erosion

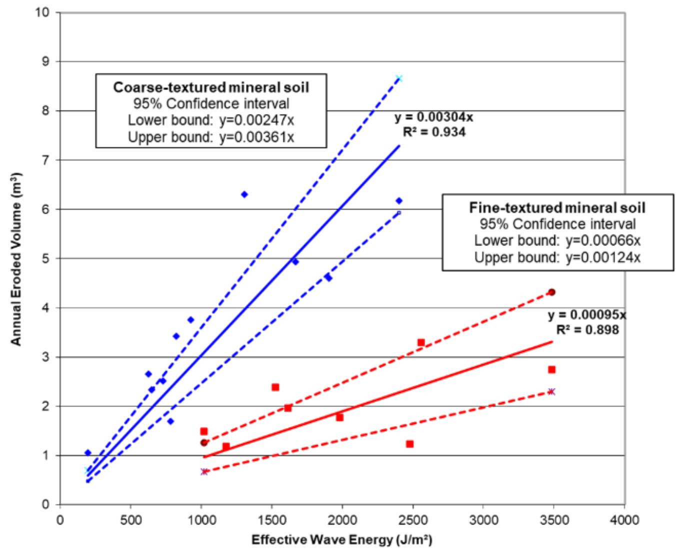

Figure 10. Erodibility coefficient calculations for coarse-textured mineral soil (blue) and fine-textured mineral soil (red) derived from the annual eroded volume (y-axis) and effective wave energy (x-axis)

The erodibility coefficient for shore zone materials is calculated from measured historical erosion volumes and effective wave energies at selected transect sites in reservoirs with similar shore zone materials and conditions. Eroded volume is determined graphically or numerically by overlaying historical, pre-reservoir, topographic profiles on recently surveyed profiles. Eroded volume is then plotted against effective wave energy at each site (Figure 10). The slope of a line drawn through these data defines the erodibility coefficient. Observations in several reservoirs suggest that erodibility coefficients between major differences in material types usually vary by roughly an order of magnitude (Table 4).

Selection of erodibility coefficient must consider the material that will be exposed to wave action at the toe of bluff as well as on the nearshore slope. Where reservoir bluffs are characterized by stratigraphy with more than one geological material, one must also consider the nature of these materials and how bluff stratigraphy and material properties may change as the bluff recedes. These changes also impact the erodibility of the nearshore slope as eroded and failed bluff material will be deposited on the nearshore slope. Changes in toe of bluff material may be caused by lateral changes in stratigraphy (e.g., changes in contact elevations between stratigraphic units and the properties of the materials), while changes in nearshore material may occur as the proportion of different material types in the bluff face changes (e.g., greater thicknesses of different units contributing material to the nearshore as the bluff recedes). The presence of one or more of these conditions will require that the erodibility coefficient be adjusted as erosion progresses over the life of the reservoir.

Application of the model requires that the shoreline is mapped continuously around the entire reservoir with mapping attributes that capture the necessary model input parameters. This includes wave energy, nearshore slope, bank slope, bank material and specific parameters related to local bank stratigraphy. Other parameters required for modelling such as the erodibility coefficient, ultimate nearshore slope and eroded bluff slope are entered into the model separately.

Figure 11 provides an example of the model output for a section of the shoreline along Keeyask Reservoir in northern Manitoba, impounded in 2020. Predictions were made for Year 1, 5, 15, and 30, using a Day 1 shoreline as the initial condition. Along many sections of the reservoir, the initial shoreline formed in peatlands, which required modelling peat disintegration before modelling wave erosion of the underlying glacial sediments. Comparisons of the predicted Year 1, 5, 15 and-30 shorelines, with the 2021 and 2024 imagery, respectively, indicate that the model performed quite well over this short initial time frame.

Figure 11. Aerial photo (Left: 2021; Right: 2024) depiction of predicted bank recession (Year 1: Red; Year 5: Orange; Year 15: Green; Year 30: Blue)

7 CONCLUSIONS

Following publication of Penner (1993) erosion modelling studies have been conducted at three major hydroelectric developments and field observations and historical data have been considered from 19 reservoirs located across Canada. This body of work has confirmed the general understanding and concepts presented by Penner (1993) and has provided opportunities to improve the model presented at that time. A key finding is confirmation that nearshore downcutting is of fundamental importance for modelling the erosion process and for understanding long-term erosion in reservoirs. Observations have provided important insight into factors affecting the rate of nearshore downcutting and the prospective of shore zone stabilization over time.

Much insight has also been gained related to erosion processes during reservoir filling and immediately following the onset of reservoir operation. These processes can be difficult to incorporate into models and must be accounted for before the model is applied to reservoir operation. With those processes taken into account, the model has been successfully applied to assess erosion during construction characterized by successively higher head pond levels corresponding to discrete construction stages. The ability to apply the model to a variety of time intervals and water levels is an important advancement in this regard.

Utilizing 2D wave modelling and successfully capturing the influence of water level fluctuation are important developments that allow for better characterization of effective wave energy and prediction of changes in nearshore slope with time. This is evidenced by predicting reductions in bluff recession with time as a function of decreased effective wave energy due to reductions in nearshore slope angle Development of algorithms for different types of shore zone profiles has allowed for wider application of the model and provides an improved ability to incorporate the effects of more complex stratigraphy on erodibility coefficients and related changes to shore zone conditions change reservoir operation. Studies in a range of reservoir settings have provided valuable insight into processes such as peatland disintegration, response of permafrost-affected terrain, ice processes and interaction between shore erosion and broader slope stability issues. Application of the model in a variety of settings has demonstrated flexibility in adapting to and incorporating local conditions.

Model validation tests have demonstrated the ability of the model to predict recession setbacks to within 5-8% of observed recession in two reservoirs after 16 and 28 years of operation, respectively. Elsewhere, model predictions have provided results that are consistent with changes that are reasonably expected over 50 - 100-year time periods and which reflect differences in local bank materials and wave energy conditions around the reservoir. Integration of model results with independently conducted sedimentation modelling studies and observations from coring studies provides further evidence that model results are reliable. Notwithstanding these results, modelling shore erosion remains complex and challenging due to many contributing factors, physical processes and site characteristics, and the ability to adequately capture these factors in a numerical model. Therefore, a clear understanding of processes and factors involved is of critical importance to apply model results with right and measured judgement. In this regard, the understanding of shore zone processes, which are unchanging, is of prime importance as modelling efforts continue to improve.

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