Erosion of Cohesive Bluff Shorelines

A discussion paper on processes controlling erosion and recession of cohesive shorelines with particular reference to the Ausable Bayfield Conservation Authority (ABCA) shoreline north of Grand Bend

Prepared by

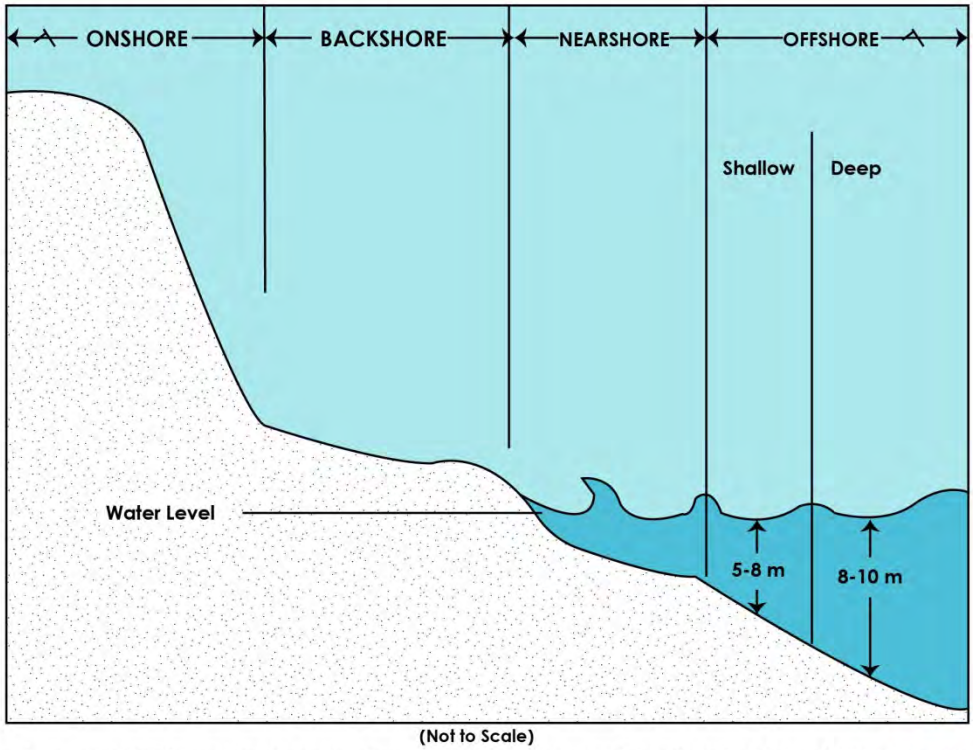
Robin Davidson-Arnott
University of Guelph

July 11, 2016

Source: Ausable Bayfield CA, 2015

Characteristics of Cohesive Bluff Shorelines

The term cohesive shoreline is used to describe cliff coasts where the profile on land and underwater is developed in sediments with a high silt and clay content. Cohesive bluff shorelines are characteristic of about 40% of the shoreline of the lower Great Lakes and are the dominant shoreline type on the east shore of Lake Huron from Point Clarke to Sarnia. They are relatively weak, or 'soft', and are susceptible to rapid erosion due to wave action (Hutchinson, 1986). It is convenient to distinguish three components of the cohesive coast system: 1) the bluff face which generally lies above the level of wave attack; 2) the bluff toe which is subject periodically to erosion by waves during large storms and occasionally during periods of high lake level may be continuously under water; and 3) the beach and nearshore profile which extends from the toe seaward to a depth of about 8-10 metres (m) where erosion by waves becomes negligible (Figure 1).



Source from MNRF Technical Guide-Part 1: Figure A1.2.1 Definition of the Shoreline Zone Page A1-2-2 (2001)

Figure 1 – Definition of Shoreline Zone. Note that the transition from the nearshore to the offshore is defined by the breaker line in this diagram but in the body of the paper it is defined by the limit of wave action on the bed which is about 10-12 m on the ABCA coast.

Erosion at the toe produces oversteepening of the bluff slope and triggers recession of the slope through shallow slides, mud flows, erosion by rain splash and surface runoff, and occasionally by deep-seated failures. Bluff recession rates are large compared to cliff coasts in hard bedrock, generally ranging from 0.3 m/y to as much as 2 m/y along parts of the north shore of Lake Erie. Within the northern portion of the Ausable Bayfield Conservation Authority (ABCA) shoreline Sideroad 30 in Goderich Township to just north of Grand Bend rates are generally low to moderate (0.2-0.6 m/y) and substantial

in some areas where they may reach 1 m/y. The recession of the bluff shorelines is also accompanied by rapid evolution of the underwater profile and it is now recognised that the rate of horizontal bluff recession is in dynamic equilibrium with vertical lowering of the nearshore profile (Figure 2).

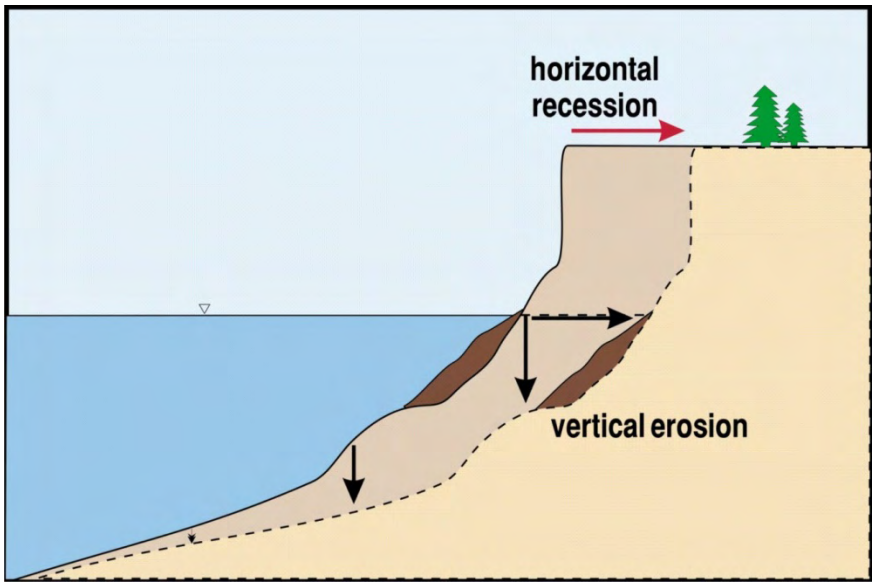


Figure 2: Equilibrium profile development on a cohesive bluff coast. Ongoing vertical erosion permits waves to continue to attack the wave toe as the bluff recedes and the two proceed in equilibrium (Davidson-Arnott and Ollerhead, 1995).

There is a large amount of literature on erosion and recession of cohesive bluffs or 'soft cliff' shorelines, including a lot of work on both sides of the border in the Great Lakes (e.g., Gelinas and Quigley, 1973; Quigley et al., 1977; Edil and Vallejo, 1980; Carter and Guy, 1988; Brown et al., 2005). In addition to material presented in the Technical Guide for Flooding, Erosion and Dynamic beaches in support of the Provincial Policy Statement (Ontario Ministry of Natural Resources, 2001), processes associated with erosion of these coasts are reviewed in Brew (2004), Hampton and Griggs (2004), Geomorphic Solutions (2010a) and Davidson-Arnott (2010, Chapter 13).

Erosion of Cohesive Bluffs

The bluffs in the ABCA area are formed almost entirely in glacial till deposited by ice moving out of the Lake Huron basin towards the end of the last ice age (about 25,000-15,000 years ago). The upper layer, which is exposed throughout the bluffs, is the St. Joseph Till composed of about 86% silt and clay eroded from the deep lake basin and the remainder varying amounts of sand, gravel and cobbles. Underlying this is another till called the stony till or Rannoch Till which has a much higher proportion of gravel and cobbles derived from erosion of the bedrock underlying the lake (Figure 3). In addition to cohesion due to the presence of clay, the till gets much of its strength from overconsolidation due to the pressure (weight) of the ice during deposition. In its unweathered form it is very dense and quite strong due to the friction between particles – so much so that it can form vertical cliffs for a short time.

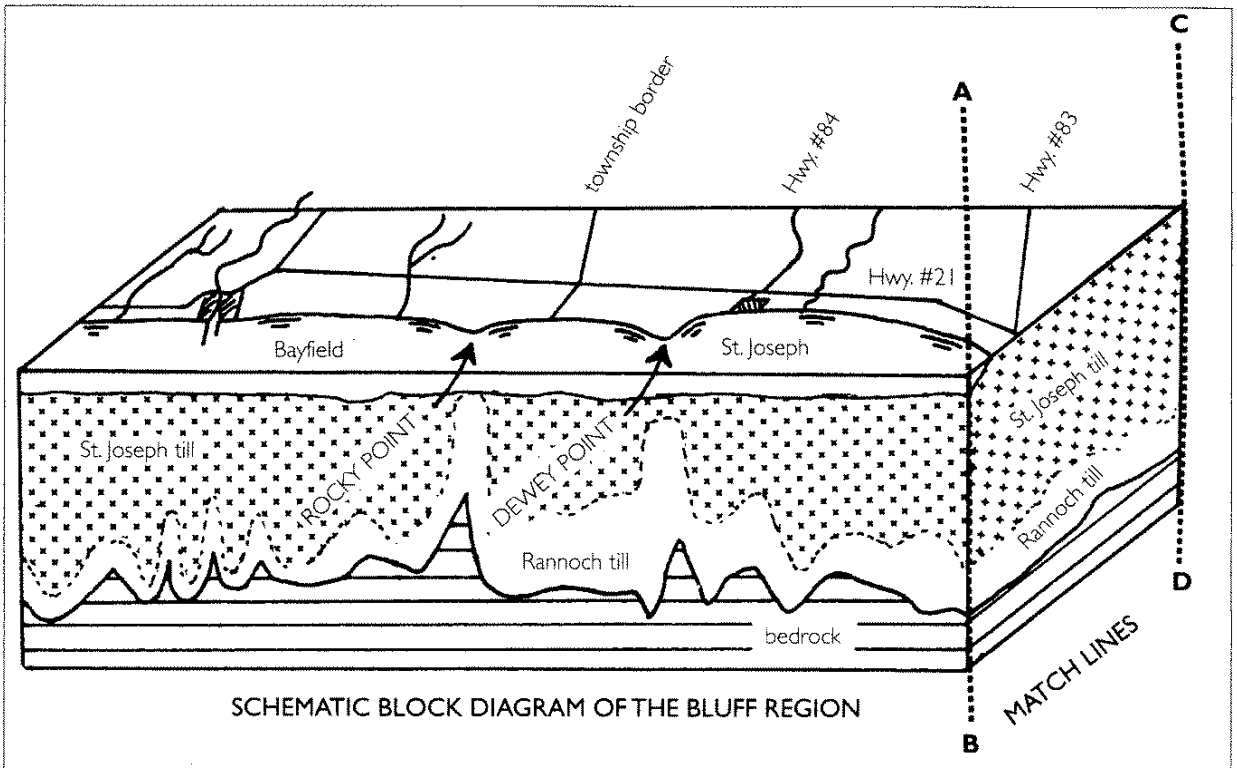


Figure 3: Schematic block diagrams of the northern cohesive bluff shoreline and southern sandy beach and dune shoreline within the ABCA jurisdiction (from Reinders, 1989)

It has been shown that over weeks and months the strength of overconsolidated clay tills decreases close to the surface due to expansion and to weathering processes such as wetting and drying and freeze-thaw action (Hutchinson, 1986 – see Figure 4, a,b; Figure 5). On the face of the bluff this weathered layer is subject to rapid erosion by rain splash, running water and the development of small rills where there is limited vegetation cover. In the spring and during heavy rainfalls it can become saturated and shallow slides and slumps take place bringing material to the toe of the bluff where it is easily removed by waves. As a result of the strength of the till, and the general absence of sandy units through which groundwater can flow, deep-seated failures are rare within the ABCA shoreline. Where the slope is protected by vegetation, and is not subject to overland flow of water and gully development, it can maintain a steep, stable slope as long as it is not subject to wave erosion at the toe. However, where there is wave attack on the bluff toe, undercutting of the slope leads to oversteepening leading to disturbance of vegetation and in turn this triggers the range of erosional processes noted above (Figure 5).

a)

b)

Figure 4: Weathering of till in cohesive bluffs, St. Catharines, Lake Ontario: a) bluff toe - wave erosion has removed weathered till in the right foreground and expansion cracks and fissures are just appearing. In the background small slumps have taken place in weathered material aided by snowmelt in the spring; b) drying of the surface layer in the summer produces a 'popcorn' surface of weathered silt and clay that is easily removed during heavy rains.

Figure 5: Desiccation cracks formed in a layer of weathered till leading to slumping of isolated blocks, ABCA shoreline

The rate at which erosion of cliff shorelines occurs can be viewed (Sunamura, 1983) as being a function of the relative strength of the 'assailing forces' (wave action) and the 'resisting forces' (the strength of the cohesive sediments in which the profile is formed). The controls on erosion of the bluff toe and underwater erosion are quite complex and not very easy to predict – see Figure 6. However, measurements of historic bluff toe recession rates do provide a good estimate of future rates at a point along the shoreline.

Erosion by wave action at the bluff toe results from forces associated with the wave itself (lower portion of Figure 6), notably wave impact when waves break on the bluff and from turbulence associated with waves running up the beach and the bluff face. While erosion of cohesive sediments can take place as a result of wave generated currents alone, most of the time this is enhanced by the movement of sand and gravel from the beach which acts to abrade the surface of the till and speeds up the process of erosion of the bluff toe (Sunamura, 1977; Kamphuis, 1990; Blanco-Chaco et al., 2007). At the bluff toe the relatively soft outer layer of weathered material eroded quite quickly by wave action during a storm but the rate of erosion slows down once the underlying harder till is exposed (Amin and Davidson-Arnott, 1995). However, in their study of erosion events in a till on the south shore of Lake Erie with a strength similar to that of the St. Joseph Till, Amin and Davidson-Arnott (1995) found that maximum erosion was generally <10 centimetres (horizontally). In the intervening period between storms weathering produces another layer of softened material which can then be eroded by the succeeding storm. Where waves do not reach the bluff toe for several years during periods of low lake level, a much deeper weathered layer develops and thus in the succeeding high water period erosion of the bluff toe

may proceed quite rapidly as this thicker layer is eroded. Thus, while the magnitude of wave energy is an important control on the overall recession rate during an individual storm event (Buckler and Winters, 1983; Kamphuis, 1987) the time between storms is also important for allowing the weathering processes to act. Where the cohesive profile is formed in sands silts and clays that have not been overconsolidated, erosion may be much greater, as is the case for bluffs along much of the central north shore of Lake Erie where recession rates can be 1.5 to 2 m/y or more.

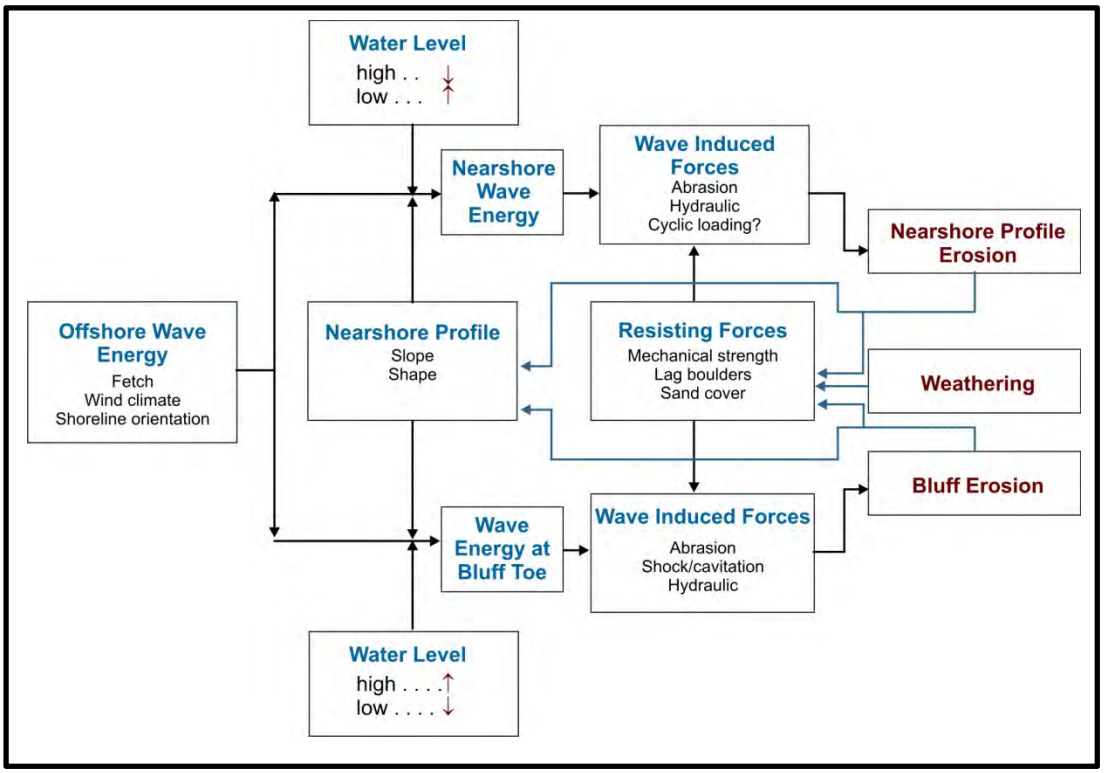


Figure 6: Processes controlling erosion of a cohesive coast. The upper and lower set of boxes relate to the 'assailing forces' on the nearshore profile (upper) and bluff toe (lower) while the centre part relates to the 'resisting forces'. Weathering reduces the mechanical strength of the till both on land and underwater. Note also that high lake level is associated with increased bluff toe erosion while increased underwater erosion occurs with low lake level. (Davidson-Arnott, 1990, 2010; after Sunamura, 1983).

In the case of cliffs formed in hard bedrock toe erosion proceeds more slowly with higher cliffs because the rock material that builds up at the toe of the slope acts to protect it from wave action and it may take many years for weathering and abrasion by wave action to break up the material and move it alongshore and offshore. Measurements of bluff recession on cohesive coasts have generally found little correlation between recession rates and bluff height, likely because the material brought to the toe of the slope is so easily eroded (Buckler and Winters, 1983).It may also be that the role of height is not as easily identified where there is alongshore variation in beach width and thus in the degree of protection offered by beach sediments from wave erosion (Davidson-Arnott and Amin, 1985).

Within the tills that make up the cohesive cliff profile it can be expected that there will be vertical and horizontal variations in properties of the till, including sediment size, the proportion of silt and clay, the hardness of the material and also local permeability. All of these affect the rate at which weathering may occur and also the resistance to erosion locally at points along the shoreline (Joyal et al., 2016). Similarly these may affect the rate of underwater erosion of the till. In turn this may explain some of the local variations in bluff recession alongshore and the development of small, temporary, headlands as recession takes place.

Underwater erosion and vertical lowering of the profile

While toe erosion is the immediate control on bluff recession, it is now recognised that it in turn is controlled by the rate of erosion of the underwater profile which ultimately controls how much wave energy reaches the toe. While it is not as readily visible as is erosion of the bluff face and toe, it can be quite readily demonstrated if the amount of recession of the bluff toe over a period of years is known. Over a period of decades the average rate of downcutting can be estimated by measuring the water depth at a point where the bluff toe was located in the past and dividing by the number of years elapsed since the bluff toe was at that location (Healey and Wefer, 1980; Philpott, 1986). Thus if the bluff toe has receded at a rate of 1 metre per year over 100 years and the water depth at a distance of 100 metres from the present bluff toe (i.e., the position of the toe one hundred years ago) is 3.5m, then vertical erosion has occurred at an average rate of 0.035 m/y – or 3.5 cm a year.

Recession of the bluff face initially produces a wider platform on which wave energy is dissipated and thus maintenance of wave attack at the toe requires erosion of this platform to allow waves to continue to reach the toe (see Figure 2). Over a period of decades there is a dynamic equilibrium between vertical lowering of the nearshore profile and the rate of bluff recession and it is now recognised that the two proceed in dynamic equilibrium (Zenkovitch, 1967; Davidson-Arnott and Askin, 1980; Philpott, 1986; Nairn et al., 1986; Davidson-Arnott and Ollerhead, 1995; Trenhaile, 2009). As a result, if this assumption holds, it is possible to predict the rate of lowering of the nearshore profile at a point on the profile from the local slope and the recession rate of the bluff toe using the expression (Zenkovitch, 1967):

$$\frac{dy}{dt} = \frac{dx}{dt} tan\alpha \qquad \text{(equation 1)}$$

Where dy/dt is the rate of vertical lowering at a point y on the profile, dx/dt is the rate of horizontal recession of the bluff toe and tan α is the profile slope at point y. A comparison of measured rates of erosion underwater with rates predicted using this formula for a site near Grimsby on Lake Ontario shows good agreement (Figure 7).

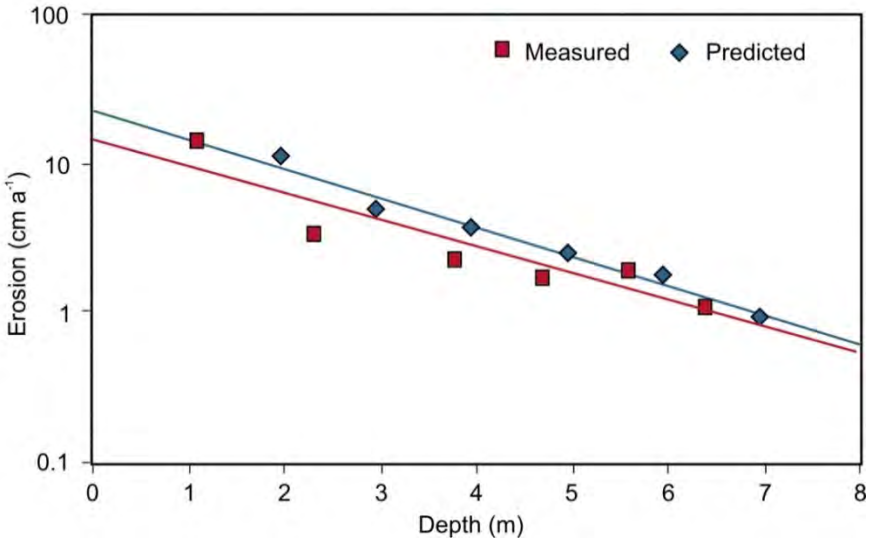


Figure 7: Comparison of measured average annual vertical erosion rates at Grimsby, Lake Ontario with rates predicted from equation 1 and measured average annual bluff recession rate of 1.1 m/y. (Davidson-Arnott, 2010, Fig. 13.16)

Underwater erosion of the till surface results from currents associated with wave orbital motion and also from turbulence due to wave breaking in shallow water (Skafel and Bishop, 1994; Skafel, 1995; Davidson-Arnott and Ollerhead, 1995). Locally, erosion is also enhanced by turbulence around individual rocks and boulders on the surface or embedded in the till. As is the case for erosion of the bluff toe, underwater erosion by waves is also greatly aided by the presence of sand and gravel on the nearshore profile which results in abrasion of the till surface. This has been demonstrated in laboratory experiments (Skafel and Bishop, 1994; Skafel, 1995) and in field experiments (Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000). These and other studies show that a layer of sand and gravel 3-5 cm thick is sufficient to produce a very large increase in the rate of erosion compared to water alone (Figure 8).

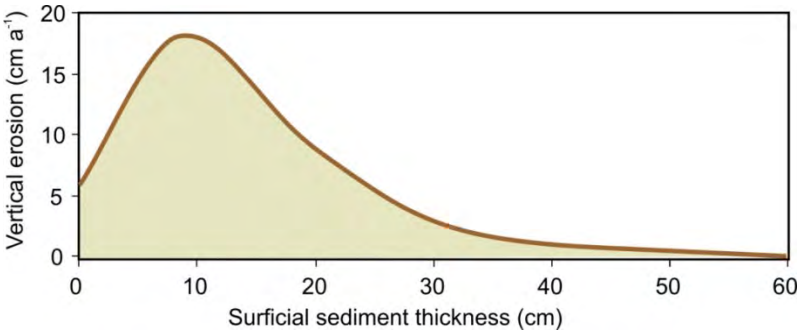


Figure 8: Hypothetical relationship between average surficial sediment cover on the cohesive profile versus average rate of downcutting. The scales are intended to suggest the order of magnitude relationship for a point in shallow water. Note that some erosion will continue underwater in places even with quite thick sediment cover because the sediment is not distributed uniformly (Davidson-Arnott, 2010 – Figure 13.19).

However, a thick covering of sand and gravel or the development of a lag of cobbles and boulders acts to protect the underlying till surface so that the rate of erosion is reduced as the thickness increases (Figure 9).

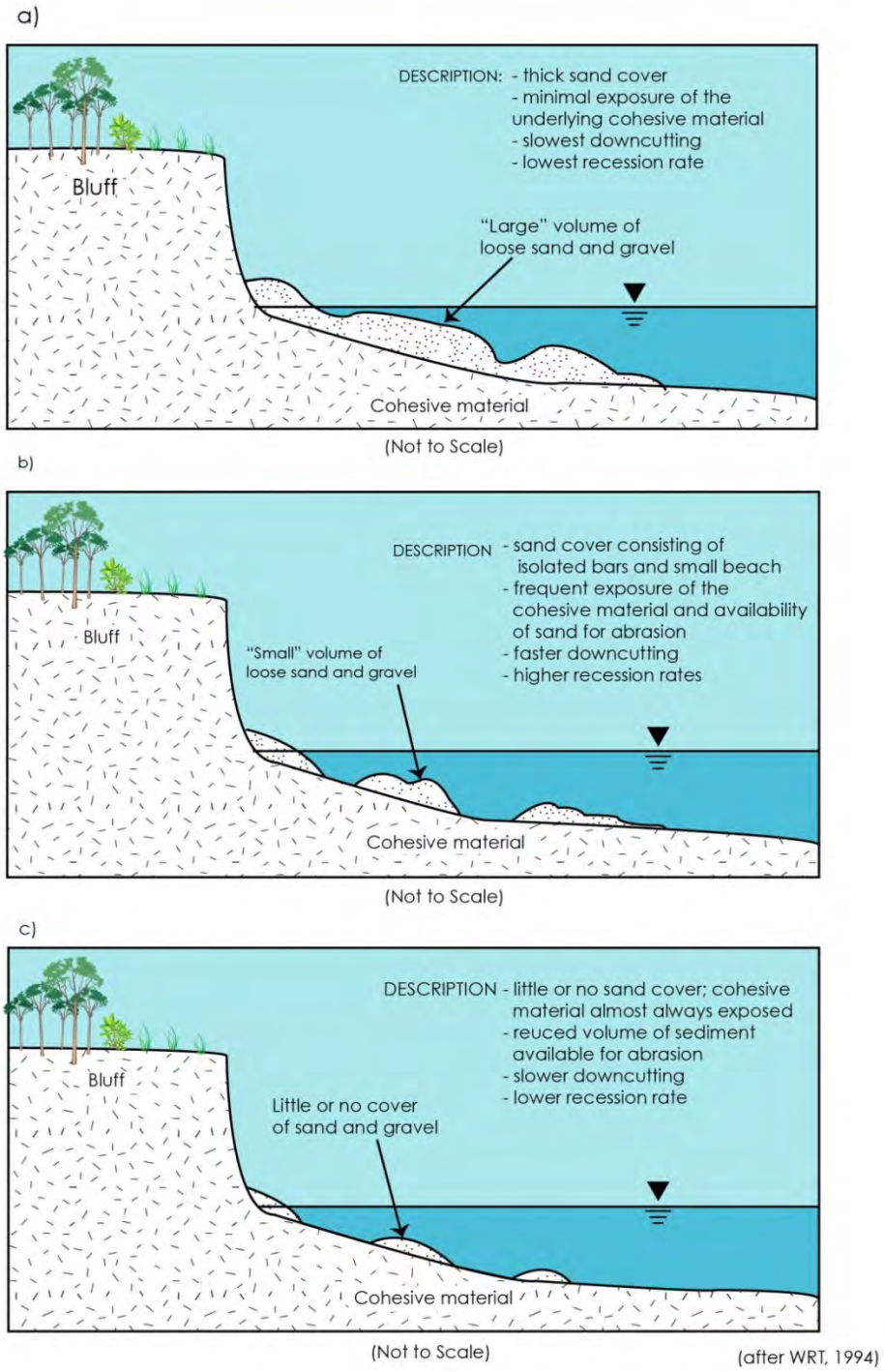


Figure 9: Schematic showing the effects of varying sand and gravel cover on exposure of till underwater (from MNR Technical Guide-Part 1: Figure A1.2.4 Cohesive Shores and the Role of Sand/Gravel Cover. Page A1-2-6 (2001)).

While a layer on the order of 30-50 cm may be sufficient to prevent erosion during an individual storm, sand and gravel tends to move seasonally and over a period of years, e.g. with the movement of bars and decadal fluctuations in lake level. As a result, the till surface may be exposed and eroded at different locations and different times (Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000; Schrottke et al., 2005 - See Figure 9).

Similar to erosion on the bluff face and bluff toe, underwater erosion is also aided by weathering and a reduction in the strength of the till. This occurs due to expansion of the till surface as the overlying material is eroded and is aided by pressure fluctuations associated with the passage of waves which pump water into a thin layer near the surface and gradually increase the size of the pore spaces, thus reducing the frictional strength (Davidson-Arnott and Askin, 1980; Davidson-Arnott and Langham, 2000). The presence of this layer is readily seen on the till surface underwater (Figure 10) and expansion of the surface has been detected through repeated measurements at underwater erosion stations (Davidson-Arnott and Langham, 2000).

Figure 10: Underwater photo of till surface showing removal of a thin surface layer of weathered silt and clay by the finger of a wetsuit glove.

The effect can also be measured in cores of the till taken underwater. Figure 11a shows water content and shear strength measured every 2 cm into a core taken 220 m offshore in 4 m water depth. As the water content increases the grains are forced further apart and this reduces the shear strength from about 50 kiloPascals (kPa) below 20 cm to less than 20 kPa near the surface. Figure 11b and 11c show the same core and two others taken in water depths of 1.5 and 3 m. Because erosion of the till is more frequent close to shore the softened layer is only 10-15 cm thick. In the deeper water erosion takes place only during large storms and so the depth of the weathered layer is up to 20 cm.

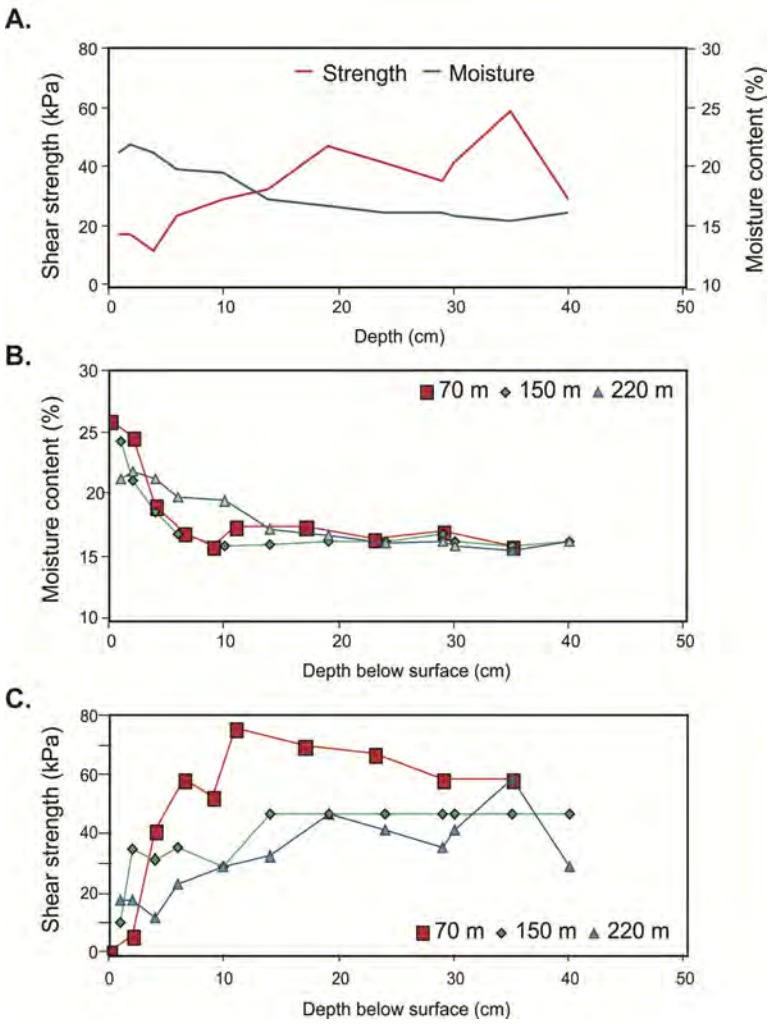


Figure 11: Variations in moisture content and shear strength within 5 cm diameter cores taken underwater in Lake Ontario at St. Catharines: a) variations in moisture content and shear strength in a single core taken 220 m offshore in a water depth of 4 m. Note that increasing moisture content towards the surface is associated with decreasing shear strength; b) variations in moisture content and c) shear strength in cores taken 70, 150 and 220 m offshore (water depth of 1.3, 3 and 4 metres). The softened layer is about 10 cm thick in shallow water, 15 cm at a depth of 3 m and up to 20 cm in water deeper than 4 m. (After Davidson-Arnott and Langham, 2000).

The key factor here is that the reduced till strength permits erosion to occur more rapidly and into deeper water where wave action only reaches the bed during large storms. It is also notable that underwater erosion associated with an individual wave event is generally small – millimetres to a few centimetres at most (Davidson-Arnott 1986; Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000) but it occurs quite frequently, especially in water depths <4m where significant wave action is experienced many times in a year. In addition, while toe erosion of the bluff tends to be associated primarily with periods of high lake level, underwater erosion occurs at all lake levels.

While vertical erosion of intertidal rock platforms has been carried out in numerous locations world-wide (e.g., Stephenson et al., 2012), there have been relatively few short-term measurements underwater on either rock coasts or cohesive coasts. Measurements were initiated in 1980 near Grimsby on Lake Ontario (Davidson-Arnott and Askin, 1980; Davidson-Arnott, 1986) using a modified form of erosion meter used to measure vertical erosion on rock platforms (Askin and Davidson-Arnott, 1980 – see Figure 12). In that year some measurements were made by Coakley et al. (1986) at a nearby site. Subsequently, measurements were carried out near St. Catharines (Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000) and also at two sites on Lake Huron (Davidson-Arnott et al., 1999).

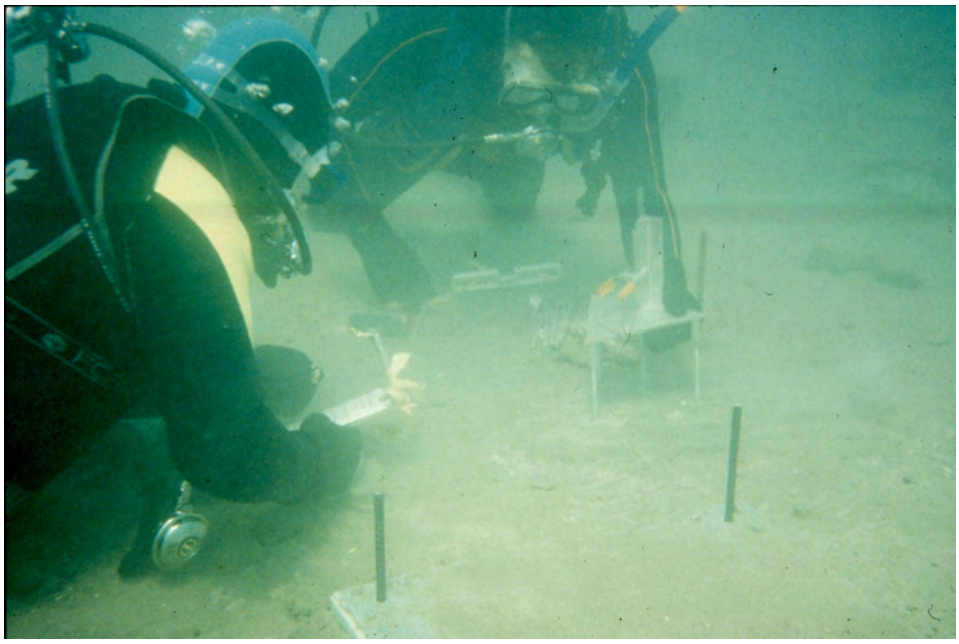


Figure 12: Measuring underwater erosion of in Lake Ontario at St. Catharines. The erosion station (centre right) consists of 3 metal pins hammered into the till and levelled. The MEM is positioned on the pins for each measurement and the distance to the bed in the middle of each side is measured using a 'foot' which slides in a tube and the distance to the till surface is measured against a vertical scale. The large pins in the foreground are holding in place one of the plates used to protect the surface from erosion and wave pressure fluctuations in order to assess the role of till softening over time (after Davidson-Arnott and Langham, 2000).

Annual measurements were made within the ABCA shoreline at a site near Lane O'Pines in 1993-94 and 1994-95. A total of 14 stations were put in in 1993 and measurements were made at 12 in 1994 and 4 in 1995. Some stations in shallow water were lost or damaged as a result of ice action or could not be relocated because of the movement of sand and cobbles. The results for this site are shown in Figure 13.

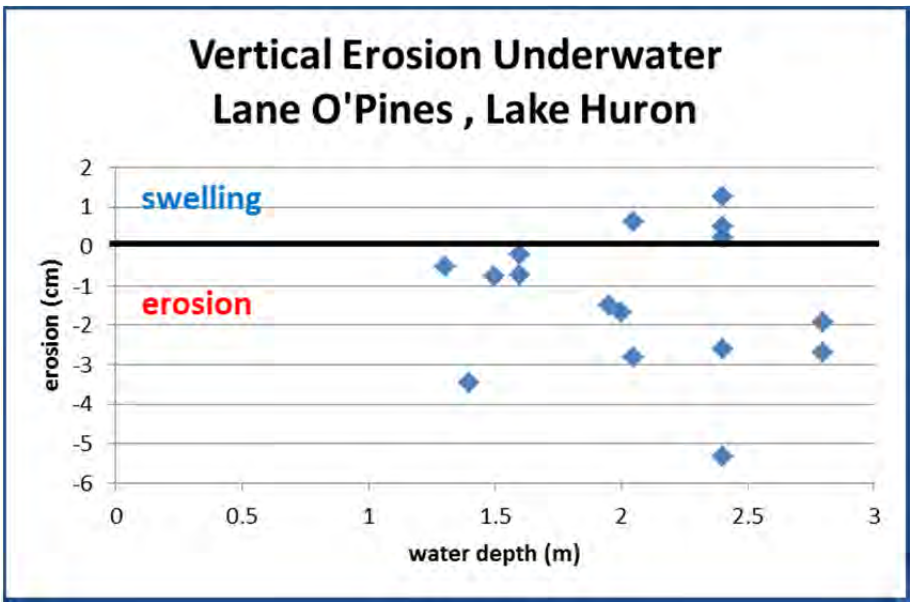


Figure 13: Annual measurements of vertical erosion of till near Lane O'Pines in 1993-4 and 1994-5. The erosion stations are located between 40 and 200 m offshore. Each measurement is an average of three points at that station. Erosion ranged from 0.2 cm/y to a maximum of 5.3 cm/y. Note that positive measurements were obtained on four occasions indicating expansion of the till surface.

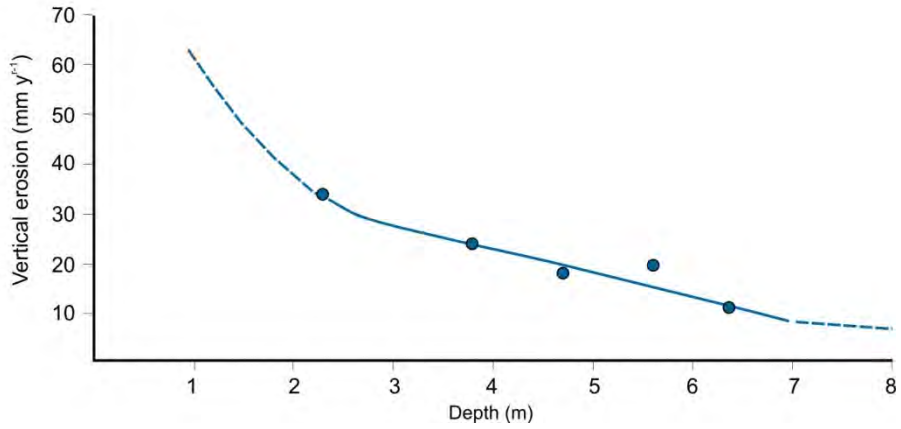


Figure 14: Weighted average annual measurements of vertical erosion at Grimsby, Lake Ontario based on measurements along two lines 1980-1984 (after Davidson-Arnott, 1986, 2010). The dashed lines indicate trends based on a small number of measurements.

Erosion of the profile tends to occur more frequently in shallow water and on the beach, and the rate decreases with depth offshore (Figure 14). The effect of this is to produce a typical concave profile producing a typical concave profile such as those for St. Catharines (Lake Ontario) and Horizon View (Lake Huron) - see Figure 15a. However, where the sediment cover is quite thick, erosion in shallow water proceeds more slowly and the profile flattens out more quickly, as it does for the Lane O'Pines profile (Figure 15a, b).

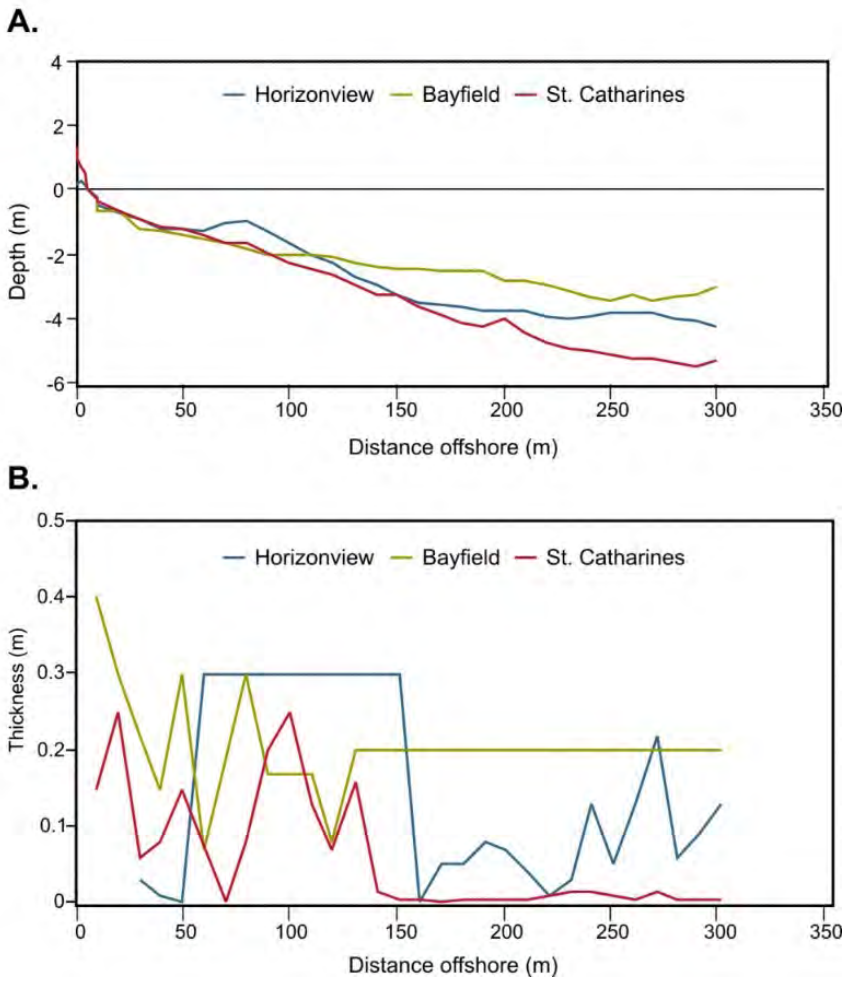


Figure 15: Nearshore profiles from three locations with cohesive bluff shorelines on the Great Lakes: a) nearshore profiles for Horizon View (Lake Huron south of Point Clark) Bayfield (Lake Huron north of Bayfield) and St. Catharines (west of Port Dalhousie); b) thickness of surficial sediment overlying the till for each of the profiles shown in (a), (from Davidson-Arnott, 2010, Fig. 13.22).

Modelling of the littoral sediment transport pattern and sediment supply on Lake Huron at Stoney Creek (Amin and Davidson-Arnott, 1997) and on the north shore of Lake Huron from Point Clark to Goderich (Lawrence and Davidson-Arnott, 1997) has shown that there is generally a strong correlation between modelled pattern of supply and longshore sediment transport rate, and factors such as beach width and bluff recession rate. Thus, for example, results for Lake Huron show that the area with the highest recession rate at Horizon View coincides with relatively little sand supply from updrift, a narrow beach and increasing wave energy (Figure 16). At the south end of the section near Wrights Point there is little erosion despite high wave energy because of the large sand supply and wider beaches (Figure 16).

The rate of underwater erosion, and hence the rate of bluff recession, will decrease with increasing sediment cover across the nearshore profile. In the littoral cell from Goderich to Grand Bend, including the ABCA cohesive shoreline, sand is transported southward under the influence of the dominant NW waves. It is evident from an examination of the shoreline within the ABCA jurisdiction that the extent of beach and nearshore sediment cover varies spatially, and in some area also temporally, so that the degree of protection provided is not uniform. It has been demonstrated this is a function of both the

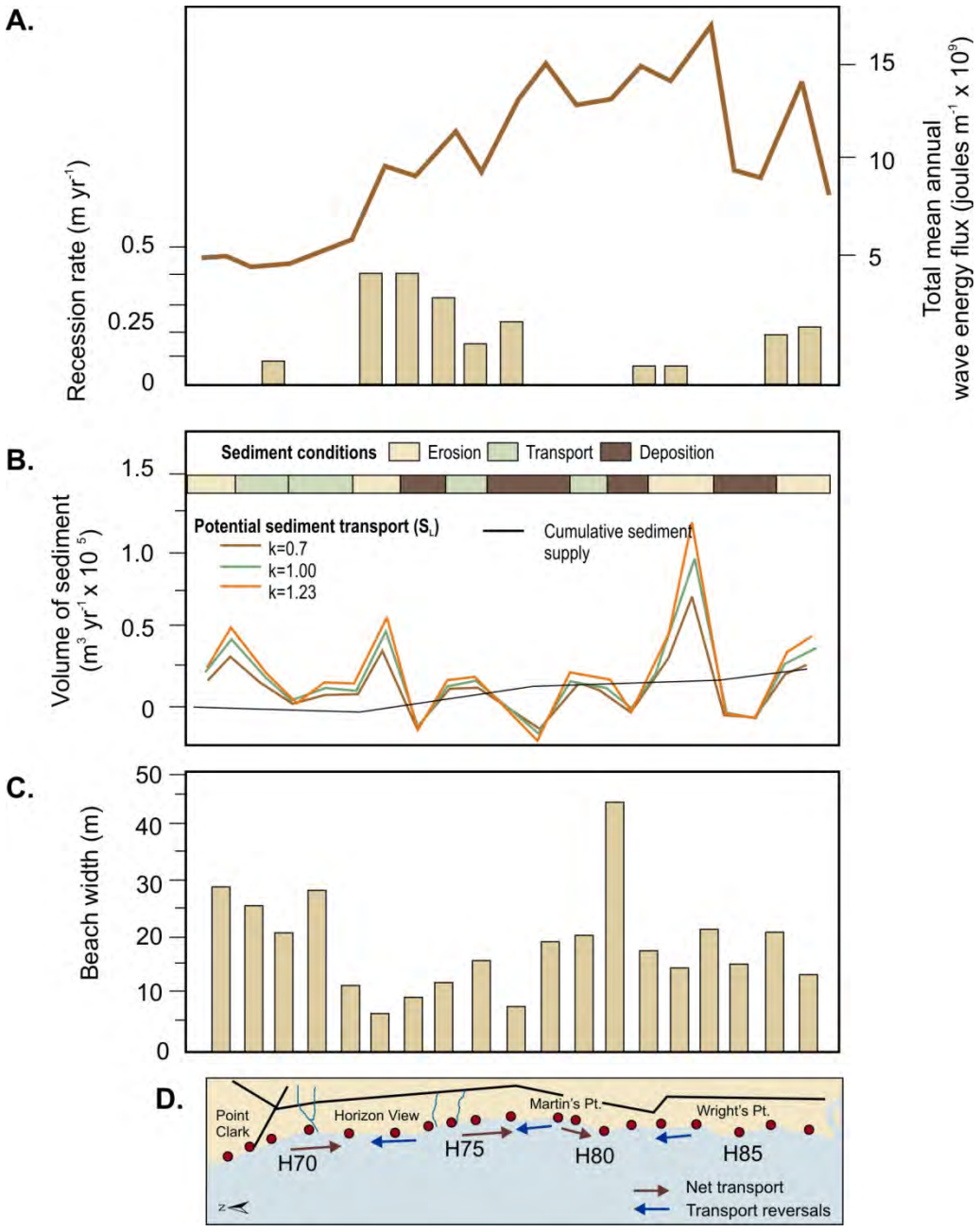


Figure 16: Comparison of modelling of littoral sediment transport with geomorphic indicators for a section of the Lake Huron shoreline: (a) plot of the spatial distribution of the mean annual bluff recession rate versus the mean annual total wave energy flux predicted from the model; (b) the alongshore distribution of potential sediment transport based on modelling and the available littoral sediment supply based on the bluff recession rate and bluff composition. Zones of potential erosion, transport and deposition are based on the alongshore transport gradient; (c) alongshore variations in beach width measured on one day; (d) map of the coastline between Pt. Clark and Goderich. The dots mark locations of calculations for model values and the numbered stations are sites of long-term bluff recession monitoring (Lawrence and Davidson-Arnott, 1997; Davidson-Arnott, 2010 Figure 7.23).

sediment supply from bluff and nearshore erosion updrift, and the pattern and rate of longshore sand transport which in turn reflects the local nearshore bathymetry and shoreline orientation.

Similar controls on sand supply and beach width likely influence the patterns of bluff recession within the ABCA shoreline. While more sophisticated models such as Mike 21 and Delft3D may improve the modelling process, the results indicate just how important ongoing sand supply from updrift is as a control on local bluff recession rates. In particular, a decrease in sand supply to much of the cohesive bluff shore of the ABCA would likely lead to a significant increase in the measured rates of bluff recession.

Effects of lake level fluctuations

Fluctuations in the level of Lake Huron seasonally, and especially on a decadal scale, influence the pattern of vertical erosion underwater as well as horizontal bluff recession (Davidson-Arnott, 1990). Seasonal and longer term fluctuations combined with storm events lead to onshore and offshore migration of sediment in the nearshore and thus affect the thickness of the sand cover overlying the till on a temporal basis. As is depicted in Figure 6, periods of low lake level produce an increase in the rate of erosion at any point on the nearshore profile because with the shallower water depth the bed is exposed to greater wave energy and sediment transport across the till surface. In particular the zone of intense wave breaking during major storms, which produces the greatest scour of the bed (Skafel and Bishop, 1995), moves offshore. During high lake levels this zone is located further landward closer to the shoreline and erosion tends to be focussed at the beach and in some cases at the bluff toe. In contrast, periods of low lake level, such as experienced recently from about 2000 to 2014, are associated with wider beaches in most areas and in places the build-up of small sand dunes. Sections of shoreline where the long-term recession rate is quite small may be protected from toe erosion for periods of years to a decade or more. However, when there is a succeeding rise in lake level wave attack at the bluff toe is enhanced by the deepening of the nearshore profile during the low lake level phase which allows large waves to break closer to the beach and the bluff toe. Over a period of 100 years these variations in bluff toe erosion tend to even out to a long-term average, and indeed, on Lake Ontario where long-term lake level fluctuations have been greatly reduced because of the regulation of outflow from the lake since the early 1950s bluff recession takes place much more evenly.

Models of cohesive coast erosion processes (Nairn and Southgate, 1993; Trenhaile, 2009) have provided an appraisal of the assumptions of the equilibrium between toe recession and lowering of the nearshore profile. They have also been utilised to assess the effects of changing wave climate and water level as part of several IJC studies, including the most recent Upper Great Lakes Study. Modelling of the effect of lake level fluctuations on bluff recession rates has shown that over a period of about 100 years the average recession rate will be the same as for a regulated lake (Nairn, R.B. and Southgate, H.N. 1993; Geomorphic Solutions, 2010b).

Implications for shore protection structures

Ongoing erosion of the nearshore profile poses a problem for the longevity of shore protection structures that are placed at the bluff toe, beach and into the water. While the till can be sufficiently strong to provide a firm foundation for anchoring structures such as revetments, vertical steel sheet pile walls or groynes, the structure itself is subject to increasing wave energy over time because of the increased water depth in front of the structure, in the case of seawalls and revetments, or at the lakeward end of groynes. The lifespan of the structure can be increased by making it more robust, e.g., by using materials such as armourstone, but the trade-off is that these structures are a lot more expensive to construct. Erosion rates in front of shore parallel structures will be accelerated by reflection from the structure, particularly during high lake level phases and undercutting of the foundations ultimately leads to collapse of all or part of the structure.

Potential effects of climate change on erosion of the cohesive bluff coast within the ABCA shoreline

The reduction in the extent and duration of winter ice cover as a result of climate change will bring about an increase in the number of intense storms with large waves that will affect the shoreline of southern Lake Huron (see the associated discussion paper on Climate Change accompanying the ABCA Shoreline Management Plan update). This occurs primarily because some storms which did not generate waves due to the presence of ice will now be able to do so and thus the total number of storms in a year that generate large waves will increase. The increased level of wave energy will likely lead to increased underwater erosion and thus, ultimately, to an increase in the rate of bluff recession. While this will generate an increase in the supply of sand and gravel, it is likely that the rate at which this is transported alongshore will increase and thus there will be no accompanying increase in the level of protection provided.

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