A Statistical Analysis of the Controls on Shoreline Erosion Rates, Lake Ontario

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ABSTRACT ▄▄▄

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Recession of the cohesive shorelines of the Great Lakes is controlled by the complex interaction of a number of processes and factors, including the magnitude of wave energy reaching the shoreline, sediment supply and beach sediment budget, and several morphological and geotechnical properties of the bluff and bluff sediments. The difficulties of making measurements of processes in this environment have meant that progress in determining the role and relative significance of the controlling variables has been slow. In this study linear multiple regression is used to determine the degree and nature of the relationship between shoreline recession rates and four predictor variables for a section of shoreline at the south-west end of Lake Ontario. The variables used are wave energy, sediment availability, potential longshore sediment transport rate and bluff height. The data are derived from a previous study of littoral drift and sediment budget modelling within the study area and consist of values for each variable for points spaced at 200 m intervals along a 14 km shoreline length. The four variables, account for 72% of the variability in shoreline recession rates. The success of the model in this application is attributable in part to the uniformity of the geotechnical properties of the cohesive sediments within the study area and to the level of detail provided by modelling of wave refraction and littoral drift.

ADDITIONAL INDEX WORDS: *Cohesive shoreline, multiple regression model, bluff recession, coastal erosion, coastal management.*

INTRODUCTION

The term cohesive shoreline is used to describe cliffed coastlines in which the profile is developed in relatively non-resistant sediments with a high silt and clay content. These shorelines are characterised by steep, sub-aerial bluffs, narrow beaches of mixed sand and gravel, and a steep, concave nearshore profile. Rates of bluff recession often range from 0.5–1.5 m yr^{-1}, and in places may exceed 2 m yr^{-1}. Cohesive shorelines have been described on a number of mid- and high-latitude marine coasts (HUTCHINSON, 1973; PRIOR, 1977; MCGREAL, 1979; HEQUETTE and BARNES, 1990) and they are particularly significant in the Great Lakes where they make up about 40% of the shoreline of the lower lakes (Lake Ontario, Lake Erie, southern Lake Huron and southern Lake Michigan) in Canada and the United States. Recession of the bluffs causes economic losses through erosion of properties, roads and agricultural lands, as well as the costs associated with shore protection. These losses have prompted the deployment of a wide range of shore protection measures and many studies of the processes controlling erosion and bluff recession (BIRD and ARMSTRONG, 1970; BOULDEN, 1975; QUIGLEY *et al.,* 1977; EDIL and VALLEJO, 1980; BRYAN and PRICE, 1980; BUCKLER and WINTERS, 1983; CARTER and GUY, 1988; AMIN, 1991). Recently, damage due to flooding

and erosion associated with the period of record high water levels in 1985–1986 led to a major two-phase study by the International Joint Commission for the Great Lakes (IJC) of all aspects of flooding and erosion, including erosion of cohesive shorelines (INTERNATIONAL JOINT COMMISSION, 1993).

The development of strategies for the management of cohesive shorelines requires an understanding of the controls on their evolution. However, erosion and bluff recession on a cohesive shoreline is a complex process, involving a wide range of controlling factors and processes. These factors include: deep-water wave climate; wave energy reaching the toe of the bluff after shoaling, refraction and wave breaking; potential gross and net longshore sediment transport; sediment supply and beach sediment budget; morphological and geotechnical properties of the the nearshore, beach and bluff; lake level fluctuations; and the influence of shore protection structures. In particular, it is evident that these factors are important in controlling the rate of toe erosion, which in turn determines the rate of bluff recession (MCGREAL, 1979; BUCKLER and WINTERS, 1983; CARTER *et al.,* 1986; CARTER and GUY, 1988; AMIN, 1991; JOHNSON and JOHNSTON, 1995).

Some of the factors noted above have a direct effect on recession rates, while others work indirectly—thus some of the factors may be more important in explaining the spatial variability of recession rates, and the complex interaction among these phenomena is likely to be more important than the ef-

fects of any single variable. While there have been a few studies that have examined the effects of individual storm events on toe erosion (McGREAL, 1979; CARTER and GUY, 1988; AMIN and DAVIDSON-ARNOTT, 1995), the focus here is on studies of the controls on long-term recession rates. Most of these have been bivariate in nature (SEIBEL, 1972; GELINAS and QUIGLEY, 1973; QUIGLEY and ZEMAN, 1980; BIRKEMEIR, 1980, 1981; BUCKLER and WINTERS, 1983; LAMOE and WINTERS, 1989; JIBSON et al., 1994; JOHNSON and JOHNSTON, 1995), and only a few have attempted to incorporate the interrelationship between wave energy variables, sediment supply and budget, and morphological variables (HEQUETTE and BARNES, 1990; JONES and WILLIAMS, 1991). The purpose of this study is to evaluate, using multiple linear regression, the statistical relationship between bluff recession rates and a number of morphological factors and processes for a relatively simple section of shoreline at the south-western end of Lake Ontario and to determine which combination of factors provides the best prediction of recession rates.

STUDY AREA

The study area is located at the south-west end of Lake Ontario, and extends from the town of Grimsby to the Burlington Bar (Figure 1). The area is underlain by red shales of the Queenston Formation which outcrop locally to form the headland at Grimsby with bluffs up to 5 m in height. Westward from Grimsby the coast is characterised by bluffs 2–5 m in height developed in the Halton Till, an overconsolidated silty clay till, which is overlain in places by a thin (<1 m) unit of lacustrine sand (HEGLER, 1974; DAVIDSON-ARNOTT and AMIN, 1985). The Halton Till, is derived primarily from sediments in the Lake Ontario basin and from the underlying Queenston Shale formation. Like many of the tills around the margins of the Great Lakes, it is relatively homogeneous over long distances and, while there is some small-scale variability, the average properties of the till are consistent over the length of the study area (MATAYAS et al., 1976). Average grain size composition is about 20–25% sand and gravel, and roughly equal amounts of silt and clay (MATAYAS et al., 1976; ASKIN, 1981; COAKLEY et al., 1986). The unweathered till has a vane shear strength of 50–80 kPa (ASKIN, 1981; COAKLEY et al., 1986). The Halton Till outcrops over most of the area in the nearshore to a depth of at least 10 m (MATAYAS et al., 1976; DAVIDSON-ARNOTT and ASKIN, 1980).

Rates of bluff recession vary along the shoreline but average about 1 m yr^{-1} and locally may be much higher over periods of a few years (HEGLER, 1974; RUTKA, 1975; BOULDEN, 1975; COAKLEY and BOYD, 1979). The bluff slope generally exceeds 45°, with bluff recession taking place primarily by sheet wash and rill development, and by shallow slides and slumps (Figure 2). Beaches are less than 10 m wide (Figure 2), consisting of a veneer of mixed sands and gravels up to 0.75 m thick, resting on a gently sloping platform cut in the till (AMIN, 1982). The nearshore profile is steep and there is little sediment overlying the till in depths greater than 3 m, except at the extreme western end of the study area (DAVIDSON-ARNOTT, 1986).

Prevailing westerly winds blow offshore and waves affecting the area are generated by winds from the NW, N, NE and E blowing over fetches of 17, 29, 97 and 50 km respectively. The longest fetch is over 200 km to the ENE. The net longshore transport is from east to west (DAVIDSON-ARNOTT and AMIN, 1985) and the study area encompasses a littoral cell with the headland at Grimsby forming the updrift boundary of the cell and sediment being deposited in the sink formed by the Burlington Bar which encloses Hamilton Bay (Figure 1).

Wave action and sediment transport alongshore is restricted for about three months each winter by the growth of an ice foot. At the time that field measurements were made in 1981 the shoreline west of Fifty Mile Point was characterised by the presence of a number of shore protection structures (DAVIDSON-ARNOTT and KEIZER, 1982). These result in some reduction in the length of shoreline exposed to wave attack and may modify the present rate of bluff recession, sediment supply, and rate of alongshore sediment transport compared to values derived from long-term averages.

MODEL AND DATA SOURCES

The model used here is a multiple regression model of the form:

$$Y = a + b_1X_1 + b_2X_2 + \ldots b_nX_n \pm e \qquad (1)$$

where: Y = dependent variable, a = intercept value, b_i = partial regression coefficient, X_i = independent variable, n = number of independent variables, e = error term

The variables used in this study are derived from work carried out by AMIN (1982) and DAVIDSON-ARNOTT and AMIN (1985) which involved determination of the sediment budget and littoral drift modelling within the Grimsby to Burlington littoral cell (Table 1). The data set consists of values derived for a number of variables at 69 points spaced 200 m apart along the 14 km length of shoreline (Figure 3).

The dependent variable, Variable 1, is the bluff recession rate which is extrapolated from measurements taken from HEGLER (1974), BOULDEN (1975) and COAKLEY and BOYD (1979). These were obtained primarily from comparison of shoreline positions on aerial photographs taken between 1934 and 1973. The low bluff height means that errors due to spatial and temporal variability in bluff failure are minimal, and the rapid recession rate over much of the area means that actual recession is large compared to the precision of the technique.

It is evident that there should be some link between recession rates and the amount of wave energy reaching the toe of the bluff (GELINAS and QUIGLEY, 1973; SUNAMURA, 1977; CARTER and GUY, 1988; AMIN and DAVIDSON-ARNOTT, 1995). However, this is difficult to measure directly in the field because of the wide range of wave conditions, the effects of shoaling and wave breaking, and particularly the effects of beach width and water levels on the location of wave breaking and on wave run-up. An alternative is to assume that, over a period of years, wave energy at the break point is a good predictor of wave energy reaching the bluff toe. Thus, variable 2 in the model is the average annual wave energy flux at the break point P_B.
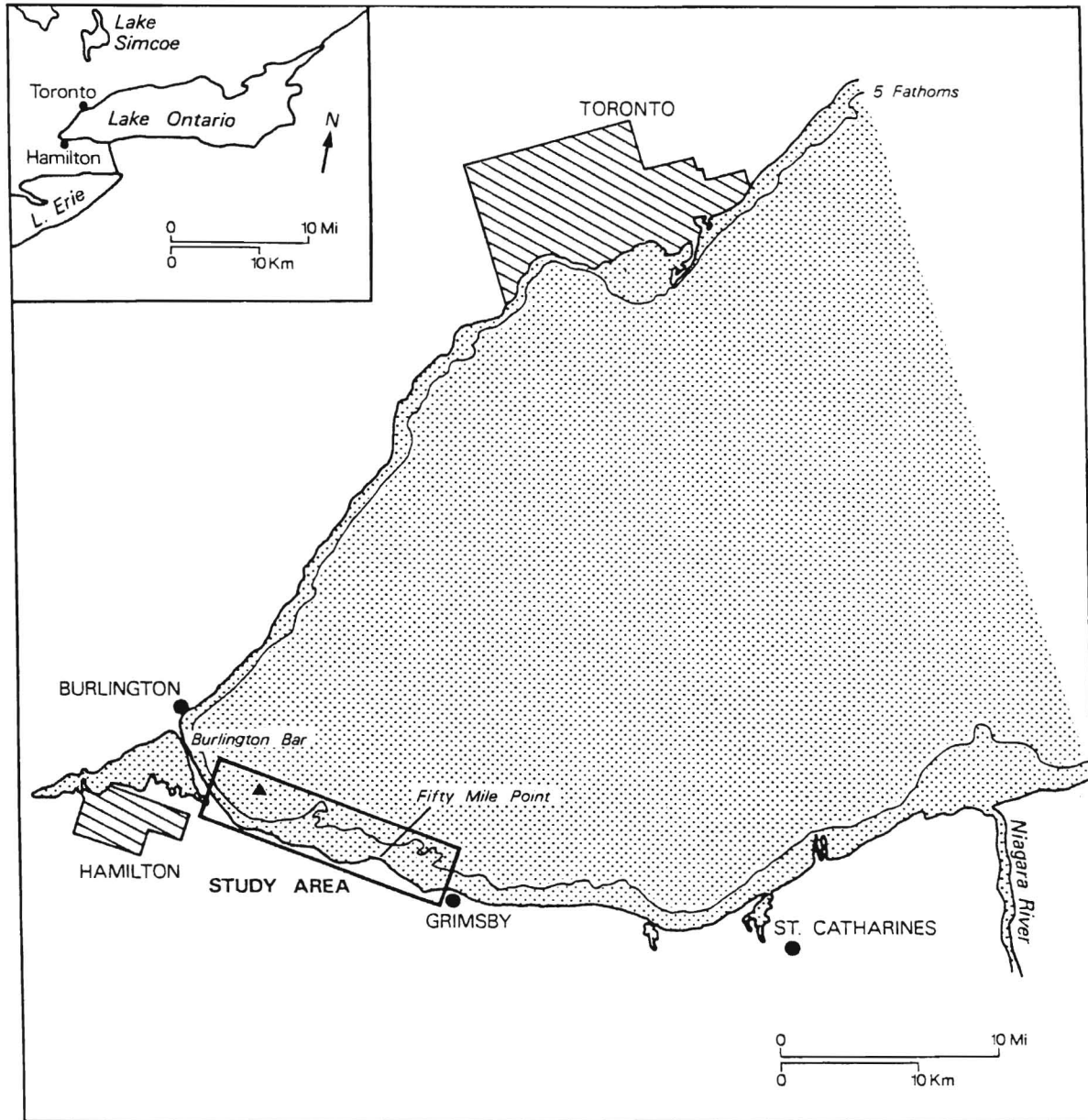
Figure 1.   Location of study area.

Wave energy at the break point was derived from littoral drift modelling of the shoreline (DAVIDSON-ARNOTT and AMIN, 1985). They used an offshore wave climate based on three years of measured data to determine the major wave height and period classes affecting the study area. The wave refraction program Wavenrg (MAY, 1974) was then utilised to determine wave refraction within the study area and to predict the alongshore variation in wave energy flux at the break point (P_B) and the longshore component of wave energy flux (P_L) for each of the 39 wave classes. The output for each wave ray was plotted against distance alongshore and then values for each of the 69 locations corresponding to the field observation points spaced 200 m apart along the shoreline were interpolated from these graphs. The values for each wave class were then multiplied by the average annual frequency of that class and summed for all the wave classes to give a total average annual P_B and net annual P_L (DAVIDSON-ARNOTT and AMIN, 1985).

It can be expected that the presence of beach sediments, at least beyond some threshold level, will lead to a degree of protection of the nearshore and bluff toe from wave erosion (SUNAMURA, 1977; DAVIDSON-ARNOTT and OLLERHEAD, 1995) and thus reduce the recession rate. On cohesive coasts sediment cover is generally thin and varies both temporally

Figure 2. Photograph of the beach and bluff just east of Fifty Point taken in July, 1981.

and spatially. In an attempt to incorporate all the effects of sediment cover, and to determine the best predictor(s) of its role in controlling recession rates, three different measures were used.

Beach volume (variable 3) was determined from measurements in the field of beach width, and thickness of beach sediments for each 200 m section of beach made in June, 1981. This is the most direct measure of sediment volume, but it reflects the situation as it existed on a single day, and not average values over an extended time period.

Variable 4, the net annual longshore component of wave energy flux P_L, is derived from the long-term wave climate and from wave refraction modelling.

$$P_L = \sum_{i=1}^{n} P_{Bi} \sin \alpha_i \cos \alpha_i \qquad (2)$$

where: P_L = net annual longshore component of wave energy

Table 1. List of variables used in the regression models.

Variable 1 (dependent)	Average annual bluff recession rate (m yr^{-1})
Variable 2 (independent)	Average annual wave energy flux at the break point, P_B (J m^{-1} yr^{-1})
Variable 3 (independent)	Beach volume (m^3 m^{-1}) measured in June, 1981
Variable 4 (independent)	Average annual net alongshore component of wave energy flux at the break point, P_L (J m^{-1} yr^{-1} - positive values indicate directed toward the left viewed offshore)
Variable 5 (independent)	Sediment availability in the littoral zone = difference between potential sediment transport volume and cumulative sediment supply (m^3)
Variable 6 (independent)	Bluff height (m)

flux, P_{Bi} = total annual wave energy flux at the break point for wave class i, α_i = angle of wave crest to shoreline, n = number of wave classes.

While the value of P_{Li} at any point along the shoreline is directly related to P_{Bi}, the net annual P_L is the algebraic sum of negative (transport to the right) and positive (transport to the left) values and thus the strength of any correlation between P_L and P_B is a function of the relative magnitude of transport in the two directions. P_L is a major control on the longshore sediment transport rate and therefore affects both the rate of removal of sediment from the bluff toe and the rate at which sediment is transported through a particular section; it also influences, through the alongshore gradient in P_L, local deposition and erosion of beach sediments.

P_L is a measure of the potential for longshore transport of sediment, but actual sediment transport rates and local erosion and deposition will also be influenced by sediment availability (variable 5). This was derived from a comparison of sediment supply to the littoral drift system and the potential longshore sediment transport predicted from the littoral drift modelling (DAVIDSON-ARNOTT and AMIN, 1985). The average annual sediment supply to the beach from nearshore and bluff erosion was calculated for each 200 m section of the shoreline from:

$$Q_S = a(L \ H \ R) \ \rho_t/\rho_b \qquad (3)$$

where: Q_S = sediment supply to the beach (m^3/200 m length), a = proportion by weight of beach sediment in bluff, L = length of shoreline reach, H = height from top of bluff to 4 m water depth, R = average annual recession rate for shoreline reach, ρ_t, ρ_b = bullk density of bluff and beach sediments respectively.
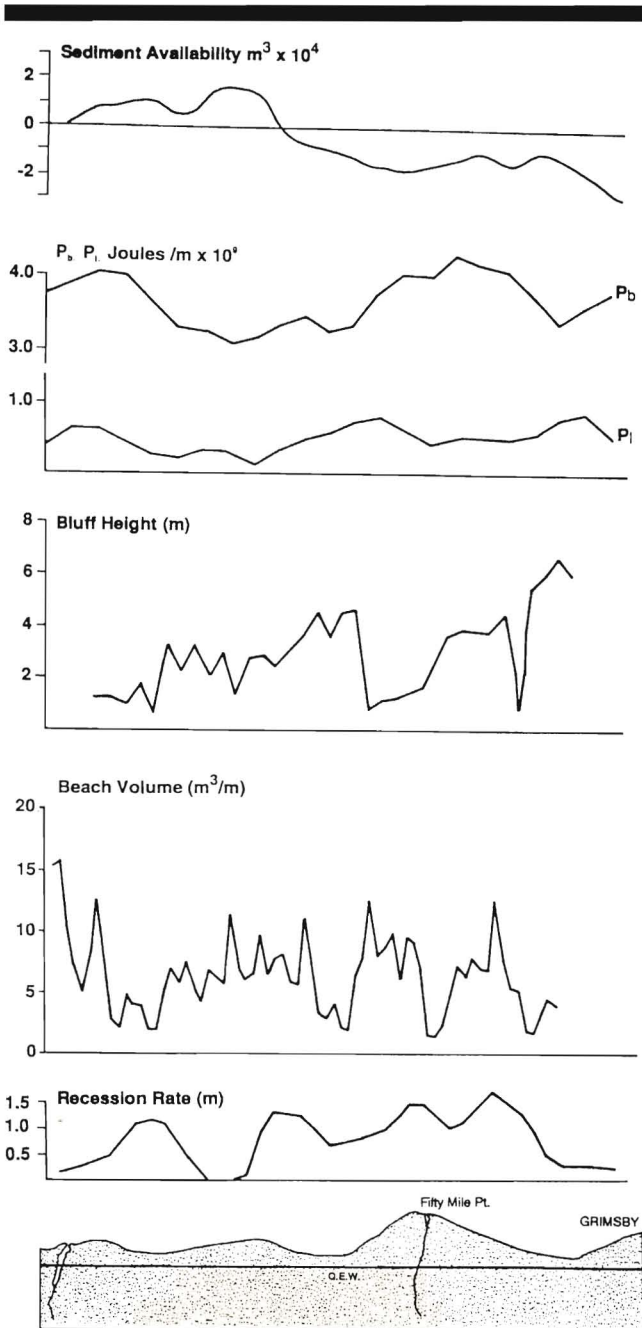
Figure 3. Longshore variations in (a) sediment availability; (b) average annual wave energy at the break point, P_B and the longshore component of this, P_L; (c) bluff height; (d) beach volume; (e) recession rate.

It was assumed that sediment was supplied from erosion of the nearshore zone out to a depth of at least 4 m (DAVIDSON-ARNOTT and ASKIN, 1980; DAVIDSON-ARNOTT and AMIN, 1985) and that silts and clays were not stable on the beach and were lost offshore. Since the littoral sediment transport is from west to east throughout the cell, it was assumed that sediment availability within each reach was

equal to sediment input from updrift plus the input from erosion within the reach (DAVIDSON-ARNOTT and AMIN, 1985).

The potential immersed weight longshore transport rate I_L was determined from:

$$I_L = K\,P_L \tag{4}$$

where: I_L = immersed weight longshore transport rate (kg m^{-1} sec^{-1}), P_L = net annual longshore component of wave energy flux (joules m^{-1} sec^{-1}), K = dimensionless coefficient of proportionality. The study of DAVIDSON-ARNOTT and AMIN (1985) used significant wave heights and thus K was assigned a value of 0.375 which corresponds to K = 0.77 for rms wave heights (KOMAR and INMAN, 1977).

The immersed weight sediment transport rate was converted to a volume transport rate through:

$$S_L = I_L/(\rho_s - \rho)\,g\,a' \tag{5}$$

where: S_L = volume transport rate (m^3 yr^{-1}), ρ, ρ_s = fluid, sediment density (kg m^{-3}), g = gravitational constant (m s^{-2}), a' = pore space correction factor = 0.6. Finally, sediment availability at each point along the shoreline was determined from:

$$Q_{A(i)} = Q_{S(i)} + S_{L(i-1)} \tag{6}$$

where: $Q_{A(i)}$ = sediment availability (m^3) for point i—where i represents a 200 m length of shoreline.

It should be noted that the absolute value of the potential longshore sediment transport, and thus the value determined for sediment availability, will vary with the value assigned to the coefficient K (e.g. DEAN et al., 1982). However it does not affect the relative values for points along the shoreline and thus should not alter the strength of any relationship of variable 5 to recession rates.

It has been suggested that the larger volumes of sediment reaching the beach from high bluffs, particularly from large-scale slumps, and the greater length of time required to remove this material, might offer a greater degree of protection to the toe of the bluff than is the case with low bluffs. Bluff height (variable 6) was measured directly in the field at the same time that measurements were made of beach width and thickness.

Variables 2–6 all relate to what SUNAMURA (1977) terms the "assailing forces", with variable 2 being a direct measure of incident wave energy, and variables 3–6 acting to modify the effects of this on toe erosion. Variable 3, beach volume, is a direct measure of sediment cover, but for one instant in time. On the other hand variable 5, sediment availability, is an indirect measure of volume but is based on a long-term average. Since one can be regarded as a substitute for the other, the model was run first using variable 3 and then a second time substituting variable 5 for variable 3.

The other major factor thought to control the rate of bluff recession is the strength of the cohesive material itself—termed the "resisting forces" by SUNAMURA (1977). There is little available information on what measure of strength can be used to predict resistance to erosion by wave-induced forces, abrasion by surficial sediments, and the effects of softening or weathering of the till. However, because of the uniformity of the till alongshore, material strength can in effect

Table 2. *Results of a) simple linear regression; b) correlation matrix.*

Variable	R^2	Std. Ccoefficient	Std. Error	F-ratio
2 (P_b)	0.320	0.565	0.117	31.470*
3 (volume)	0.006	0.079	0.017	0.417
4 (P_1)	0.001	−0.036	0.319	0.086
5 (available)	0.169	−0.411	0.041	13.613*
6 (height)	0.003	0.053	0.034	0.190

Pearson Correlation Matrix

	Erosion	Height	P_B	P_L	Availability	Volume
Erosion	1.0					
Height	0.053	1.0				
P_B	0.565	−0.076	1.0			
P_L	−0.036	0.013	0.266	1.0		
Availability	−0.411	−0.369	−0.203	−0.670	1.0	
Volume	0.079	−0.397	0.161	0.043	0.074	1.0

*Significant at the 95% confidence level

Table 3. *Results of multiple linear regression for two models.*

Model 1: N = 69; R^2 = 0.368; S.E. = 0.369; D.F. = 4 and 64; F-ratio = 9.335*

Variable	Coefficient	Std. Error	Std. Coefficient
constant	−1.663	0.450	0.0
2 (P_b)	0.722	0.121	0.623
4 (P_1)	−0.534	0.269	−0.205
6 (height)	0.032	0.030	0.116
3 (volume)	0.005	0.015	0.034

Model 2: N = 69; R^2 = 0.716; S.E. = 0.247; D.F. = 4 and 64; F-ratio = 40.35*

Variable	Coefficient	Std. Error	Std. Coefficient
constant	−0.530	0.322	0.0
2 (P_b)	0.666	0.081	0.574
4 (P_1)	−2.079	0.251	−0.797
6 (height)	0.333	0.038	0.913
5 (availability)	0.064	0.021	−0.230

*Significant at the 95% confidence level

be regarded as a constant within the study area, thus permitting the evaluation of the significance of the other factors. Material strength was thus not included as a variable in the regression modelling.

Simple linear regression, multiple linear regression, and stepwise multiple linear regression were carried out using the program SYSTAT (SYSTAT INC., 1990).

RESULTS

Simple linear regression with recession rate as the dependent variable was carried out first in order to examine the explanation provided by each of the variables separately (Table 2a). Variables 2 (P_B) and 5 (sediment availability) had R^2 values of 0.320 and 0.169 respectively, both of which are significant at the 95% confidence level. The other three variables had much lower R^2 values and were not significant at the 95% confidence level. The relationship among the variables was also assessed through use of a Pearson Correlation Matrix (Table 2b).

Linear multiple regression was carried out on two sets of variables with variable 1 (recession rate) as the dependent variable. The first analysis was carried out using variables 2, 3, 4 and 6 (P_B, beach volume, P_L and bluff height) as the independent variables and the second substituting variable 5 (sediment availability) for variable 3. The results of the two models are given in Table 3.

While both models are significant at the 95% probability level, it is clear that that the level of explanation of model 2, where sediment availability is substituted for sediment volume, is far superior to that of model 1. Moreover, in model 1 the partial correlation ceofficients of both beach volume and bluff height are positive, which is the opposite to what would be expected. The poor performance of the variable Volume was confirmed by a stepwise multiple regression using the variables of model 1 which showed that the added explanation resulting from the introduction of the variable Volume was not significant at the 95% confidence level.

In model 2, the independent variables together explain about 72% of the variance (Table 3). An examination of the

standardized coefficients shows that recession increases with increasing wave power P_B, and decreases with increased sediment availability and with increasing bluff height. These are all consistent with the expected relationships outlined in the previous section. The coefficient for P_L is negative, indicating that recession rates decrease with higher values of P_L.

Stepwise linear regression was performed on the variables in model 2 in order to examine the contribution made by each variable and to identify any problems of collinearity that might exist (Table 4). At step one variable 2 (P_B), which has the highest partial correlation coefficient, was introduced into the equation and was found to explain about 32% of the variation in recession rate (R^2 = 0.320). With the introduction of a second variable (variable 5, sediment availability) the level of explanation rose to about 41% (R^2 = 0.411). Variable 4 (P_L) was introduced next and R^2 increased to 0.676, or about 68% of the variation in recession rates. With the addition of variable 6 (bluff height) there is a further increase in R^2 to 0.716, or roughly 72% of the variance. The F values for the additional explanation provided at each step are all significant at the 95% confidence level (Table 4).

It is clear that changes in P_L should have little or no influence on bluff recession rates in areas where sediment supply is much smaller than the potential alongshore sediment transport volume, as is the case at the eastern end of the

Table 4. *Results of stepwise linear regression for model 2.*

Step	Variables	SS	DF	Variance	F-ratio
1	2	4.401			
2	2, 5	5.661	2		
	Change in SS	1.260	1	1.260	
	Residual	8.111	66	0.140	9.0*
2	2, 5	5.661			
3	2, 5, 4	9.311	3		
	Change in SS	3.650	1	3.650	
	Residual	4.461	65	0.069	52.89*
3	2, 5, 4	9.311			
4	2, 5, 4, 6	9.862	3		
	Change in SS	0.551	1	0.551	
	Residual	3.91	64	0.061	9.03*

* Significant at the 95% confidence level

Table 5. *Results of multiple linear regression for variables 4 and 5.*

Variable	Coefficient	Std. Error	Std. Coefficient
constant	−1.407	0.149	0.0
5 (available)	0.288	0.049	−0.788
4 (P_L)	−1.471	0.350	−0.563

Model 3: N = 69; R^2 = 0.344; S.E. = 0.370; D.F. = 2 and 66; F-ratio = 17.309*

study reach. Indeed, as was shown in Table 2, a simple linear regression of recession rate against P_L showed no significant relationship. Nevertheless, P_L should have some influence on the alongshore distribution of sediments in areas where there is sufficient sediment available and it does make a significant contribution to the explanation provided by the multiple regression model in conjunction with variable 5, sediment availability (Tables 3 and 4). In order to explore this further a multiple regression was run using just variables 4 (P_L) and 5 (sediment availability) and this resulted in an R^2 of 0.34 which is significant at the 95% confidence limits (Table 5). It is notable that this is almost the same as the increase in R^2 associated with the introduction of these two variables at steps 2 and 3 in the stepwise regression model (Table 3) and suggests that they are both independent of P_B and that a considerable portion of the explanation that they provide is due to their joint variation. The increase in R^2 over that obtained for a simple linear regression against sediment availability is also significant at the 95% level.

DISCUSSION AND CONCLUSIONS

The results presented above show that in this study the average annual total wave energy at the shoreline correlates positively with shoreline recession and is a good predictor of it. A number of other researchers have suggested the link between total wave energy and rates of bluff recession (MARESCA, 1975; DAVIS, 1976; SUNAMURA, 1977; BUCKLER and WINTERS, 1983; KAMPHUIS, 1987). GELINAS and QUIGLEY (1973) found that bluff recession along a portion of the north shore of Lake Erie correlated well with deep-water wave energy, but a similar study along a different section of the shoreline (QUIGLEY and ZEMAN, 1980) showed a much weaker relationship between wave energy and recession. It is likely that the significance of total wave energy as a predictor will be greatest where beaches are narrow and there is limited protection from beach and nearshore sediments. In the section of coastline used in this study beaches are generally narrow and it is only at the western end of the area that sediment accumulation is likely to dominate over wave energy as the primary control on recession.

Bluff recession is controlled directly by wave attack at the bluff toe (SUNAMURA, 1977) which is linked to P_B through a series of controlling factors which reflect lake level, beach slope, sediment supply, among others (AMIN and DAVIDSON-ARNOTT, 1995). However, over the long-term the overall rate of profile adjustment and shoreline recession is dependent on vertical lowering of the nearshore profile, which itself is more directly linked to P_B (DAVIDSON-ARNOTT and OLLERHEAD, 1995). Thus, while wave energy at the break point is only an indirect measure of wave energy reaching the bluff toe, it does appear to provide a reasonable measure for predicting long-term recession rates.

Sediment availability for beach building has a negative correlation with shoreline recession, indicating that recession is generally lower where there is more sediment available to form a protective beach. As noted above, this probably provides a better prediction of the recession rates in areas where there is sufficient sediment to provide an effective cover, and it likely becomes more important than P_B in these areas. The fact that recession rates showed no significant relationship with beach volume, which is also a measure of the protection provided by sediment, can be attributed to the fact that it reflects measurements made on a single day rather than a long-term average.

The net longshore component of wave energy flux acts with sediment availability to influence the degree of protection afforded by sediments since it determines the potential sediment transport volume and pattern. Unlike the first two variables, P_L by itself is not a good predictor of bluff recession, and clearly it acts in a complex way with sediment availability.

The fact that bluff height makes a significant contribution to the prediction of recession rates was somewhat unexpected, although the contribution is quite small. Previous studies examining the role of bluff height have had mixed results in relating bluff recession to bluff height (*e.g.* BUCKLER and WINTERS, 1983). However, in areas where the bluff stratigraphy is complex, it may be that the effect of height is overshadowed by alongshore variations in composition and strength of the bluff sediments. In this study there is little variation in bluff composition both vertically and alongshore, thus providing a better test of the influence of height alone.

The four variables in the regression model, which together account for some 72% of the total variation in shoreline recession, can all be seen as being linked to a complex controlling variable that might be termed effective wave energy reaching the shoreline. While total wave energy reaching the shoreline is obviously important, its effectiveness can be restricted by the degree of sediment build-up on the beach and in the inner nearshore area. It is likely therefore that variation in total wave energy is most important as a predictor along those sections of the coastline where there is limited sediment cover. On the other hand, in those areas where there is some sediment accumulation, recession is likely to reflect more closely variations in the actual amount of sediment as a result of changes in sediment input and the gradient of net longshore sediment transport (McGREAL, 1979). Bluff height can also be seen as being related to the degree of protection from wave action, both because of the increased length of time taken for waves to break-up and remove slumped debris and the greater volumes of littoral sediment input associated with higher bluffs.

Finally, the success of the multiple regression model in terms of the high degree of explanation provided by the first four variables is attributable to two factors: 1) The section of shoreline studied has a very simple stratigraphy and there appears to be very little variation in the strength parameters of the till that forms the bluff and nearshore substrate. This

means that absolute rates of shoreline recession are primarily controlled by variations in what SUNAMURA (1977) terms "the assailing forces", rather than variations in the "resisting forces" or some combination of both; 2) The combination of refraction modelling and sediment budget analysis provide a good description of the variability of wave energy and the potential degree of protection offered by the accumulation of surficial sediments over the long-term.

In conclusion, the multiple regression model described here shows that in the chosen study area, longshore variations in bluff recession are controlled primarily by variations in total wave energy reaching the shoreline and by the degree of protection by surficial sediment accumulation. Variables that were most successful in predicting recession are related to long-term averages or to inherent properties of the shoreline, rather than to instantaneous measurements of beach width and thickness. It should be noted that the regression model itself was not designed to be applied to prediction of absolute recession rates in other areas. In this study, because of the uniformity of the till alongshore, material strength in effect can be regarded as a constant, thus permitting evaluation of other factors. In areas with a more complex stratigraphy it would be necessary to include some measure of the strength or resistance of the cohesive material in order to achieve the same level of explanation.

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