CHAPTER 172

Analysis of Coastal Processes at Toronto Islands

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Abstract

The paper summarizes the analysis of the coastal processes which have been responsible for the evolution of the Toronto Islands sand spit feature. Both natural and artificial influences have created a situation of a rapidly evolving landform. The purpose of the study was to evaluate the feasibility of rebuilding a school near the shoreline of this rapidly evolving feature. Several different techniques were employed to evaluate the changes including: shoreline recession rate estimates, lake bed surface change comparisons, sediment budget calculations and alongshore and cross-shore sediment transport calculations. These techniques were combined to develop a descriptive model of the changes in order to forecast future changes to the landform over the next 100 years.

Introduction

This paper summarizes the findings of an investigation of erosion processes at Gibraltar Point on the Toronto Islands situated along the northwest shore of Lake Ontario in Canada. The Toronto Islands Nature School is located at Gibraltar Point and the future safety of this location with respect to erosion and flooding hazards is dependent on the future evolution of the Gibraltar Point landform. The Toronto Board of Education has plans to construct a new school on and just west of the location of the existing school. The purpose of the study was to investigate the potential future erosion hazards at Gibraltar Point and the implications for constructing a new school at the existing location.

The following sections of the paper provide: an overview of the geomorphology of the Toronto Islands feature including the background of the problem; a description of the analyses used to prepare a representative nearshore wave climate; a review of the historic changes in the shoreline position; an interpretation of changes to the lake bed; an explanation of the descriptive model of the changing landform including future projections; and study findings.

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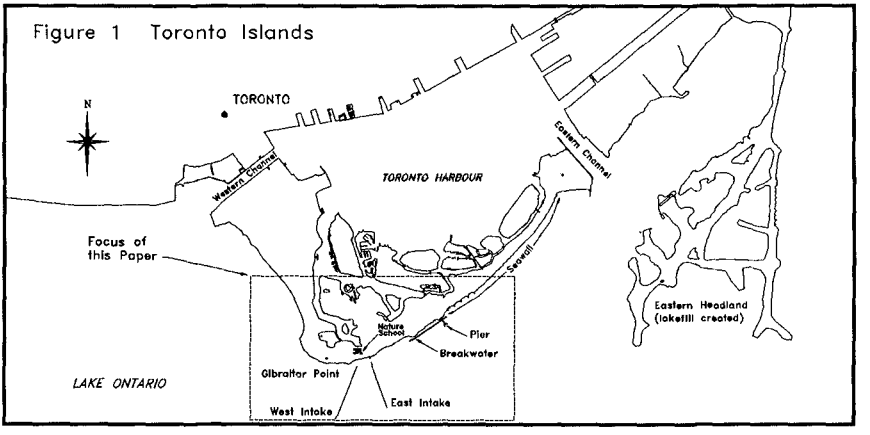
Study Background and Regional Coastal Geomorphology

The City of Toronto is located on the north shore of Lake Ontario and was founded at this location in 1793 because of the presence of a 9 km long sand spit that provided excellent natural protection for a large harbour (see Figure 1).

A geomorphologic review found that the Toronto Islands feature is a complex (compound) recurved sand spit that has formed and developed over the last 3500 to 5000 years as a result of the following factors: stabilization of the existing lake level (+/- 2 m) over the last 3500 years; a dominant northeast to southwest directed sediment transport; a continuous supply of sediment from the erosion of the Scarborough Bluffs to the east (estimated to be 30,000 m^3/yr on average); the presence of an underlying shallow and gently sloping bedrock shoreface platform; and the presence of a significant re-entrant angle in the shoreline orientation (i.e. an embayment). This type of feature is characterized by a progressive extension in the direction of the dominant sediment transport (i.e. to the southwest at this site). The ability of the spit to continue its southwestward growth depended on a continued supply of sediment, both to build the subaerial part of the feature, and essentially, to extend the offshore shelf southwestwards.

The continued extension of the spit to the southwest combined with a severe storm event in 1852 resulted in a breach near the location of the present day Eastern Channel. The breach in the spit expanded between 1852 and 1882 to an extent that threatened the future potential for harbour development at Toronto and the associated economic development. In response to this situation, the Toronto Harbour Commissioners embarked on an ambitious plan to stabilize the naturally formed Eastern Gap to create a navigation channel of controlled width and depth. These plans resulted in the construction of the Eastern Channel jetties which were completed in 1892. In order to protect the shore of the islands from future erosion and potential breaching, a seawall and breakwater were constructed over a length of 2.5 km extending westward from the west jetty.



Sand which continued to move along the shore from east to west was deposited in the Eastern Channel. Records show that on average 25,000 cubic metres of sand was dredged from the channel and dumped offshore on an annual basis

between 1896 and 1965. This suggests that most of the annual supply volume of 30,000 cubic metres was prevented from reaching the shore and lake bed of the Islands feature to the west of the Eastern Channel. This situation has resulted in erosion with 1 to 2 m of lake bed lowering offshore of the seawall immediately to the west of the channel. Therefore, the supply of sediment to Gibraltar Point, although mostly cut off at the Eastern Channel, was probably compensated in part by the erosion of the lake bed offshore of the seawall.

The Eastern Headland (also known as the Leslie Street Spit) is a 5 km long artificial spit feature located immediately east of Toronto Islands that has been created through lakefilling (see Figure 1). The spit was originally created to form a protected outer harbour; however, it has also been used as a dump site for construction refuse (mostly concrete rubble from downtown construction projects), and as a confined disposal facility for contaminated dredge spoil from the harbour area. The construction of the headland was initiated in the early 1960's, and although still ongoing today, its greatest offshore extent was reached by 1978.

The headland has two important impacts on the regional coastal processes. First, the historic rate of sediment supply from the east, which had been severely reduced by the construction of the Eastern Channel jetties and subsequent dredging, was eliminated completely with the construction of the headland. The Eastern Channel has only been dredged once since 1965. The second and most important impact of the Eastern Headland has been the modification of the nearshore wave climate through sheltering the eastern half of the Islands from the easterly storm waves. Detailed wave transformation analyses (discussed below) revealed that the zone of influence of appreciable sheltering probably extends no further west than the Centre Island pier at the east end of the Centre Island seawall (refer to Figure 1). The headland does not have a significant impact on the waves which reach Gibraltar Point.

The Toronto Islands Water Filtration Plant is located just east and inland of the Nature School in the Gibraltar Point area. While the intake lines for this facility date back to the late 1800's, the two existing intake lines were completed in the early 1950's. Each line extends almost 1 km offshore and consists of a pipe confined by two steel sheet pile walls, which in places extend up to 2 m above the adjacent lake bed. The eastern intake line has an associated steel sheet pile groyne structure at the shoreline which appears to have been constructed in the late 1940's. These structures act to impede the alongshore transport of sediment.

Development of a Nearshore Wave Climate

A wind-wave hindcast was performed to develop an estimate of the long term offshore wave climate at the Toronto Islands. A 1D parametric hindcast model based on the approach of Donelan (1980) was used. Research by Skafel and Bishop (1993) has shown that the available 2D dynamic hindcast models do not give superior results to the 1D models when estimating wave conditions on the Great Lakes. A considerable effort was devoted to assessing wind data input for the hindcast model. Overwater wind speeds for a 35 year hindcast period were determined from comparison of several land based wind data records to available overwater wind data records (Figure 2 shows available wind and wave data for Lake Ontario).

The use of a combined wave refraction / diffraction model was vital to the assessment of the nearshore wave climate at Toronto Islands due to the nature of the underwater topography and the influence of the artificial Eastern Headland. The

REF/DIF 1 model developed by Kirby and Dalrymple (1983), which is based on a parabolic approximation of the mild slope equations, was utilized. Model runs were performed for a range of representative wave directions, heights and periods.

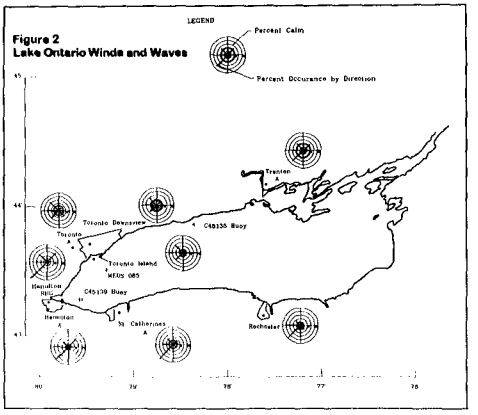


Figure 2
Lake Ontario Winds and Waves

Due to its position at the west end of Lake Ontario, the most severe storms are generated by easterly winds over a 250 km fetch. The maximum significant wave height during the 35 year hindcast period was estimated to be 5.6 m with a peak period of 12 s and a direction just north of east. The prevailing winds are from the southwest and the maximum significant wave height from this direction during the hindcast period was 4 m with a period of 10 s. The considerable year to year variability in the ratio of east to southwest storm events, as well as variations in overall annual wave energy, have an important influence on the pattern of morphologic response.

The level of Lake Ontario has an average seasonal fluctuation of about 0.6 m. There is also considerable long term variability with a 2 m difference between the maximum spring high level and the minimum winter low level.

Change in Shoreline Position

There is a wealth of information on the position of the Toronto Islands shoreline dating back to the initial European settlement in 1793. The accuracy of this information varies considerably; however at the very least, each map or aerial photo provides a snap shot giving some indication of the evolving nature of the Toronto Islands feature at a point in time.

For those sources of data which have an acceptable degree of accuracy, intercomparisons may be made between the different snap shots allowing for the calculation of shoreline recession rates for the various periods. Under the Shoreline Policy of the Province of Ontario, potential hazard areas must be determined in part from an estimate of the shoreline position in 100 years time based on historic shoreline recession rates.

A summary of some of the historic shoreline positions in the Gibraltar Point area that have been corrected for lake level variations are shown in Figures 3a and b. From the shoreline changes between 1835 and 1915 given in Figure 3a, it is evident that between 1835 and 1868 the south facing section of the shoreline moved lakeward

(i.e. the Islands deposit was growing). Between 1868 and 1915 the depositional trend was reversed, possibly due to the influence of the updrift breach. Figure 3b shows that after 1915, erosion was experienced along the south facing shore with deposition along the west facing shore. In the vicinity of the School, and to the east, the shoreline apparently was stable during the period from 1954 to 1993. However, this finding should be considered with caution owing to the highly eroded state of the 1954 shoreline as caused by the abnormally high lake levels in 1951 and 1952.

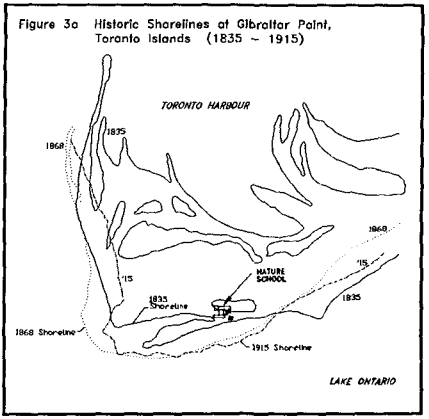


Figure 3a Historic Shorelines at Gibraltar Point, Toronto Islands (1835 - 1915)

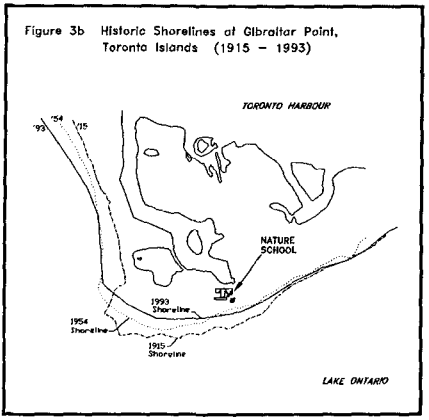


Figure 3b Historic Shorelines at Gibraltar Point, Toronto Islands (1915 - 1993)

In summary, the trend of shoreline change cannot be described as a linear process over the period from 1835 to the present. Prior to 1868, the south facing part of the shore was accreting and since at least 1939 the shore has been eroding. Furthermore, short term and temporary changes to the shoreline position caused by the rapid response of the nearshore profile to storm conditions can obscure long term trends that are based on these snap shots.

Under the Provincial Shoreline Policy, one part of the definition of hazard lands (where development is restricted) relates to those areas which will be threatened by erosion within 100 years time. As noted above, the Policy requires that the position of the 100 year shoreline be established through linear extrapolation of historic shoreline recession rates (with a minimum time span of 35 years between snap shots of shoreline position). For the purposes of these investigations, the 100 year shoreline has been established through extrapolating recession rates for all available periods in order to provide a range of results. Two recent surveys were used as a basis of comparison against historic shoreline positions: a 1988 aerial survey and a 1993 ground survey (only the latter set of comparisons are presented in this paper).

The 100 year shoreline position projections, based on a comparison of historic and 1993 shoreline position's, are presented in Figure 4. Generally, these results feature three different zones of shoreline change consisting of deposition along the north part of the west facing shore, dramatic erosion around the strongly curved point and relatively minor changes for the remainder of the south facing shore. As expected, for the shortest comparison period (1971 to 1993) the 100 year position features the greatest variability while the 100 year projection from the earliest shoreline in the comparison (1915) is distinguished by the least alongshore variability. If the process of erosion was linear, it would be reasonable to assume that the 100 year projection based on the latter comparison was the most reliable.

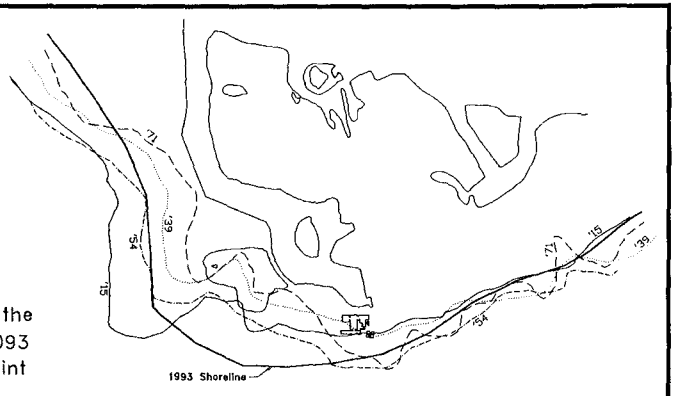


Figure 4
Projections of the shoreline in 2093 at Gibraltar Point

However, a close review of the shoreline positions offshore of the School reveals a distinct difference between projections based on pre- and post- 1940's data. The 1915 and 1939 projections of the 100 year shoreline pass directly through the School site, whereas the more recent projections produce a 100 year shoreline offshore of the existing School. Here it may be postulated that the groyne and intake lines which were constructed for the Filtration Plant in the late 1940's have had an important effect on the shoreline in this area. Therefore, since the effect of this change is not reflected over the full comparison period with the historic shorelines prior to the 1940's, these results do not provide realistic projections of future conditions. In addition, the 100 year projection based on the comparison of the 1954 and 1993 shoreline positions may also be misleading. This result suggests that the shoreline offshore of the School will remain stable or even accrete over the next 100 years. However, it should be recalled that the 1954 shoreline may have been in a temporary highly eroded state. Therefore, any recession rates calculated through comparison to the 1954 shoreline may underestimate future erosion.

In summary, there are several problems with 100 year shoreline projections which assume linear extrapolation. These include the following issues at this site: the erosion process is not linear in time; considerable changes to the regional processes have occurred over the last 100 years; the erosion process will not be linear in the future, as shoreline and lake bed changes will alter the pattern of future change which is related to the transport and redistribution of sediment; existing shoreline protection at Gibraltar Point will not last for the 100 year projection period and obscures the future predictions; the 100 year projections also assume that other structures such as the groyne and the intake lines will be maintained in the future; snap shots of shoreline position may reflect temporary and reversible changes to shoreline position which are not indicative of long term trends, the questionable 1954 shoreline projection is an example of this problem.

Nevertheless, the 100 year projection results do provide some general findings which are pertinent to this investigation. The strongly curved part of Gibraltar Point has been and probably will continue to be the focus of greatest erosion. The pattern of erosion changed sometime in the 1940's, possibly related to the construction of the groyne and intake lines for the Filtration Plant, such that the shoreline east of the School became more stable.

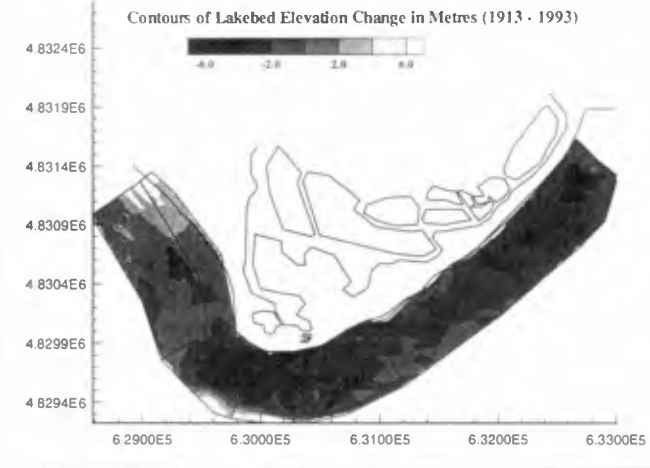
Changes in Lake Bed Levels and Sediment Budget

There is extensive information on the water depths offshore of the Toronto Islands dating back to 1793. Comparisons of changes in the lake bed levels between the various bathymetric snap shots provide a more comprehensive perspective of the changing nature of the Toronto Islands feature than does the shoreline change data. The interpretation of long term trends in lake bed change are not obscured by temporary lake level related changes in shoreline position or the effects of structures.

The complexity of an investigation of the temporal change in an irregular three dimensional surface (i.e. the lake bed) is such that the full value of this information in developing an understanding of the problem is seldom realized. Therefore, the bathymetric change data was considered in four different ways, providing the greatest opportunity of maximizing the value of this information.

Contours of lake bed elevation change were prepared by subtracting one lake bed surface from another. This procedure was completed for five separate time periods between 1913 and 1993. Figure 5 provides the results for the full 1913 to 1993 period, and gives an overview of the findings. The outer boundary of the comparison area varies in depth between 6 and 8 m. There is a pronounced erosional zone all around Gibraltar Point with the highest erosion rates found immediately offshore of the western extremity of the Point (i.e. where the shoreline curvature is at a maximum). Up to 5 m of lake bed lowering has occurred in places. Aside from the heavy deposition offshore of the north part of the west facing shoreline and the transition between this zone and Gibraltar Point, the only other relatively stable section of lake bed is a zone located between the groyne (and the east intake line) and the west end of the breakwater. Offshore of the seawall, erosion is prevalent. There is also evidence of deposition off the southwest corner of the shelf which suggests some of the eroded sediment has been lost offshore of the shelf.

Figure 5



The second approach of considering the evolution of the lake bed surface is based on calculations of volumetric change for various "panels". The panels have been selected on the basis of available lake bed information and to describe sections of lake bed which have similar trends of erosion or deposition. This exercise was completed for five different snap shots, one example is provided in Figure 6 for the full period from 1913 to 1993. There are two tiers of panels corresponding to an inshore set and an offshore set separated by the 3 to 4 m depth contour. The volume change estimates for the inner Panels 1 to 9, while showing much variation between periods, reveal some consistent trends. There is sediment sink in Panel 9 offshore of the north section of the west facing shore. Also, Panels 5 and 4 (offshore of the School and the adjacent panel to the east) often feature either lower erosion rates than neighbouring panels, or even deposition.

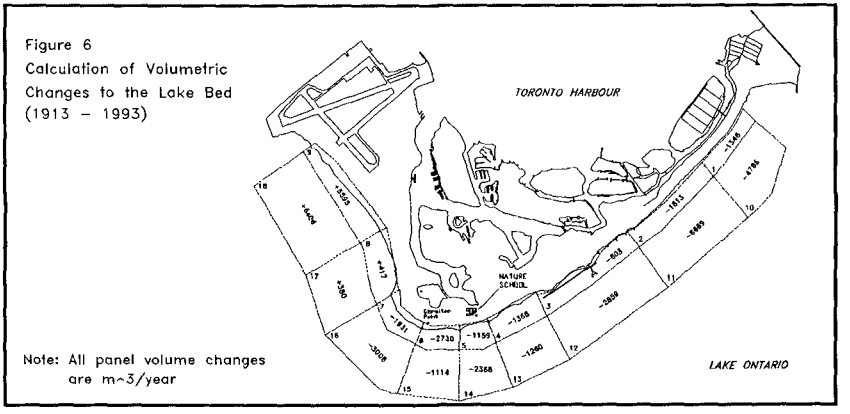


Figure 6
Calculation of Volumetric Changes to the Lake Bed (1913 - 1993)

A comprehensive sediment budget analysis can be applied to the '13-'93 period based on volume change calculations for all of the panels around the shore. As explained earlier, this area now represents a confined littoral cell. For the 80 year period, there was a net loss of 1,620,000 m^3 of sediment from the area covered by the panels, or a little over 20,000 m^3/yr on average. While a significant amount of this sediment may have been transported beyond the ends of the panel area (i.e. northwest of Panels 9 and 18, and northeast of Panels 1 and 10), it is likely that a significant proportion of the sediment has been lost offshore beyond the outer boundary of the panels and perhaps over the shelf at the edge of the wide platform which surrounds the Islands feature. Referring to Figure 5, a zone of deposition along the outer edge of Panels 15 and 16 may represent the growth of the shelf caused by the deposition of the sediment that has been transported offshore.

Another manner of interpreting the changes to the lake bed surface through time is to plot the changing position of selected depth contours. The 2, 4 and 6 m contours were selected for this exercise. In addition, by comparing the historic position of the contours to 1993 as a base year, "recession rates" for the contours may be calculated and projected to determine the 100 year position of the contour lines. It is again cautioned that these are linear extrapolations of a non-linear process.

Figure 7a shows the changing position of the 2 m contour around Gibraltar Point. Between 1951 and 1993, the 2 m contour position has remained relatively

stable everywhere east of the west intake line, whereas west of this point this contour has moved rapidly inshore. The recession rates of the 2 m contour line offshore of the Point for the 1951 to 1993 period reach almost 5 m/yr. This is much higher than the long term rate of shoreline recession of about 1.5 m/yr in this area. Figure 7b gives the 100 year projections for the position of the 2 m contour; these also indicate that the severity of erosion may be far greater than is indicated by the projections of the shoreline position. The erosion of the nearshore zone is outpacing the recession of the shoreline, probably as a result of shoreline structures and vegetation (including the root systems of large trees) which delay the shoreline erosion. The fact that the profile shape is changing from convex to concave also helps to explain the differential recession rates between the shoreline and the 2 m contour.

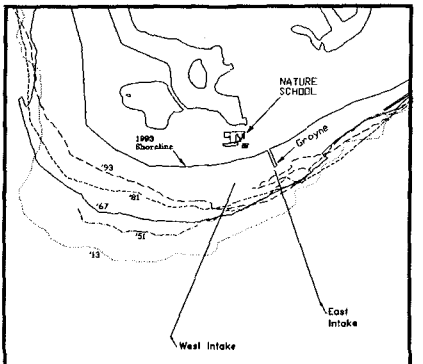


Figure 7a
Change in 2m contour at Gibraltar Point

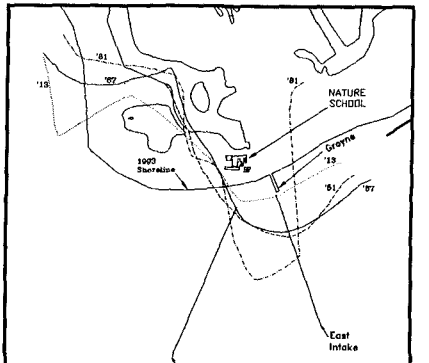


Figure 7b
Projections of the 2m contour in 2093

Interestingly, the 100 year projections of the 2 m contour in the vicinity of the School are in much closer agreement (i.e. for the various snap shot comparisons) than were the shoreline projections. The projections highlight the role of the intake lines in stabilizing the position of the 2 m contour.

The 4 m contour has receded inshore considerably at Gibraltar Point, mostly since 1951, although at a slower rate than the 2 m contour, with average rates of about 1.5 m/yr (see Figure 8). Offshore of the Point, there was minimal erosion between 1913 and 1951. Considering the recession of the 4 m contour was initiated about the same time that the intake lines were constructed, it is possible that the lines, by intercepting westward moving sediment, may have accelerated the erosion of the lake bed offshore of the Point.

There are several interesting features of the changing position of the 6 m contour line (see Figure 9). Starting from a point between the intake lines and moving to the west, the 6 m contour has been completely stable in position over the last century owing to the fact that this contour marks the transition from onshore erosion to offshore deposition. The 6 m contour delineates a pronounced depression or canyon around the east intake line that developed over the period between 1913 and 1951. The canyon represents a zone where the intake line acts as a total littoral barrier.

Representative profiles were also plotted for the midpoint of each of the lake bed panel sections. Around Gibraltar Point, these plots revealed the changing nature

of the feature from a depositional zone with a pronounced convex profile to an erosional zone with the related concave profile shape.

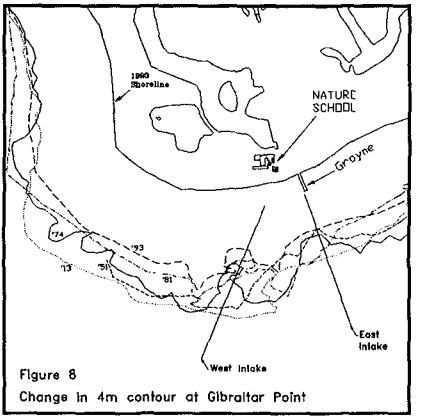


Figure 8
Change in 4m contour at Gibraltar Point

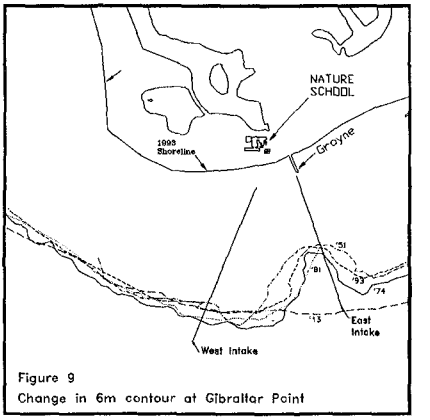


Figure 9
Change in 6m contour at Gibraltar Point

Sediment Transport Predictions

The observed patterns of erosion and deposition that have been discussed in the previous sections have resulted from the transport and redistribution of sediment (e.g. sand). Sediment is transported by the effects of waves and the associated steady currents both in an alongshore direction and in a cross-shore direction. This section presents a brief summary of the results of numerical simulations of these sediment transport processes which were aimed at developing an improved understanding of why the observed changes have occurred and what may happen in the future.

The COSMOS-2D numerical model of coastal processes has been applied to simulate the alongshore and cross-shore sediment transport. This numerical model is based on a deterministic quasi-2D representation of the actual physical processes which result in the transport of sand on a profile or cross-section of the lake bed. The calculation scheme is based on a time-averaged finite difference approach for random wave conditions. A comprehensive description of the model is given in two companion papers: Nairn and Southgate (1993) and Southgate and Nairn (1993).

Estimates of average annual alongshore transport have been made for several profiles around the exposed shore for three separate intervals within the hindcast period (i.e. '58 to '67, '67 to '81, '81 to '93). The alongshore transport estimates were made at the boundaries between the panels to determine the sediment transport entering and exiting each panel. An extensive set of sediment samples indicated that a D50 of 0.2 mm would be representative of the average lake bed conditions. An example of the results for the period from 1981 to 1993 is shown in Figure 10. The profile name indicates the panel boundary (i.e. b6/7 is the boundary between Panels 6 and 7) and the annual average sediment transport rate is given for each of the profiles. The distribution of alongshore transport across the profile is also depicted in the figure, providing an indication of the sediment transport pathways along the shore.

For each of the three periods, the alongshore transport estimates indicate that Panel 7, located offshore of Gibraltar Point, is a divergent zone for net sediment transport. In other words, sand is moving out of this panel at each boundary. This

type of situation results in high erosion rates with a potential annual loss of sediment from the panel equal to the sum of the outgoing amounts at each boundary. The neighbouring Panel 6 to the east, which together with Panel 7 represents the zone of highest observed erosion, has incoming sediment on the west boundary (b6/7) and outgoing sediment on the east boundary (b5/6) for each period. The difference between these two values is usually small, however, it must be recognized that the full potential value at b6/7 may not be realized with the net result being that Panel 6 is probably subject to ongoing erosion due to the alongshore redistribution of sediment from west to east (in other words, the divergent zone may extend into Panel 6).

Panel 5, located offshore of the School, is predicted to be a convergent zone (i.e. with incoming sediment at each boundary) and deposition would be expected to occur. It was noted earlier that Panel 5 features relatively low observed erosion rates compared to adjacent panels. Part of the basis for predicting that Panel 5 is a depositional zone relates to the prediction of potential transport from the east (i.e. at b3/4 and b4/5). Concerning the b3/4 prediction, it is likely that this is considerably overestimated since the offshore breakwater will partially restrict the movement of sand supplied from the east. Also at b4/5, the alongshore transport is influenced by the presence of the groyne and the intake line for the Filtration Plant a factor which also restricts the transport along the shore. In addition, the supply of sediment from the east is now derived from the erosion of the lake bed offshore of the seawall and breakwater, and with time, this source of sediment will be exhausted as deep concave profiles develop next to these structures (this outcome has already been observed along a large section of the eastern part of the seawall).

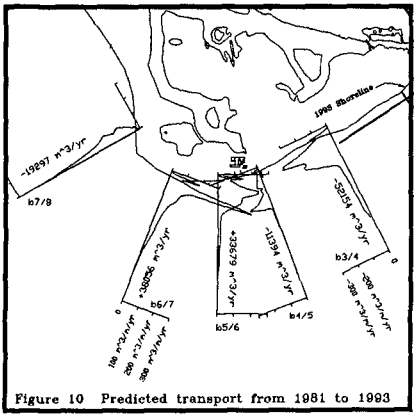


Figure 10 Predicted transport from 1981 to 1993

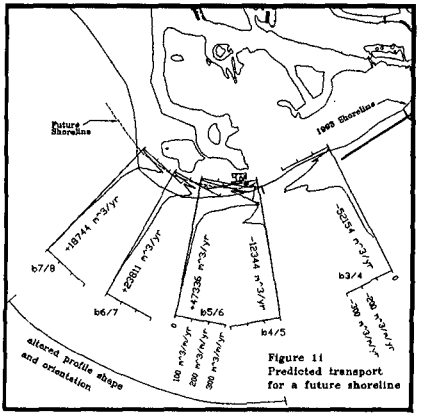


Figure 11 Predicted transport for a future shoreline

As the alongshore transport redistributes the sediment through the erosion of Gibraltar Point and deposition along the southwest shore and offshore of the School, the shape of the shoreline changes and this in turn effects the rate at which sediment can be transported by waves. In other words, there is a feedback system whereby the waves alter the shoreline and lake bed, and these changes in turn alter the waves and therefore the sediment transport. In order to assess how future changes to the shoreline shape may influence the future patterns of alongshore transport, estimates were made for a future shoreline position as determined from the shoreline projections discussed earlier. Revised profile shapes were also considered based on the amount of shoreline recession dictated by the assumed future shore position. The future shoreline position and the revised estimates of alongshore transport at each of the panel

boundary profiles are presented in Figure 11. The 1981 to 1993 waves were used, so these results are best compared to those given in Figure 10.

Only Profiles b4/5 through to b7/8 have been modified. Reviewing the results, there is only a minor change in the estimates for Profiles b4/5 and b5/6, but the net transport at b6/7 is halved and the transport at b7/8 has changed direction from west (or clockwise) to east. These findings suggest that in the future the zone of highest "erosional stress" due to alongshore transport will be shifted or extended from Panel 7 (current position) to the east into Panel 6 and to the west into Panel 8. However, the zone immediately offshore of the School (i.e. Panel 5) will remain a zone of deposition as long as the supplies from the west and east are maintained.

A rough estimate may be made of the remaining supply of sediment which may be available from ongoing erosion of the lake bed as a source for westward directed transport reaching Panel 5 offshore of the School. It was determined that the potential transport rate of 23,500 cubic metres per year could be sustained for another 28 years. This calculation suggests that the future supply of sediment to the panel offshore of the School from erosion of the lake bed to the east may be exhausted in 25 to 50 years.

Sediment transport calculations were performed to investigate the influence of the Filtration Plant intake lines and associated groyne structure. It was determined that neither the intake lines nor the groyne represent a significant impediment to alongshore transport under the June 1994 snap shot conditions. However, additional model tests indicated that the groyne helps to maintain a small fillet beach during storm conditions and thus the stability of the shore to the east, and similarly, the intake lines appear to act as submerged groynes helping to hold the 2 m contour offshore at this location, particularly during storm conditions (while along the adjacent shore to the west, the 2 m contour has continued to recede inshore). It is anticipated that with the ongoing erosion of the lake bed offshore of the 2 m contour in the vicinity of the intake lines, the stability of the lines could be threatened in about 50 years from now.

Next, the role of cross-shore transport in the reshaping of the Gibraltar Point feature was considered. Of primary concern is the potential for permanent loss of sediment from the nearshore to offshore locations. The COSMOS numerical model provides a description of the cross-shore sediment transport rates for a nearshore profile. In preliminary tests it was found that only the largest waves result in appreciable offshore loss of sediment (i.e. sediment which is transported beyond the edge of the shelf). Therefore, an input wave file with a relatively small number of representative wave conditions (about 20) could be prepared for the calculation of cross-shore sediment transport at each profile. The offshore loss rates for the entire hindcast period and the sub-periods were then estimated based on the product of the total duration for each representative wave condition and the offshore loss rate determined through the COSMOS simulations. Calculations were made for both the 1993 profile shape and the estimated future profile shape that may exist in 50 to 100 years time. The offshore loss rate over the wave hindcast period (1954 to 1993) was determined to be 5.06 $m^3/m/yr$ with the 1993 profile shape. For a future profile shape with a flatter slope based on continued shoreline recession, the predicted offshore loss rate was 3.65 $m^3/m/yr$ representing a 30% reduction from the current rate. As a check on the validity of these estimates, the 1951 to 1993 average loss rate for Panel 15 (i.e. the offshore segment of Profile 6) was found to be 2860 m^3/yr, or about 5.5 $m^3/m/yr$, which corresponds well to the calculated rate of 5.06 $m^3/m/yr$.

In summary, in the vicinity of Gibraltar Point, alongshore transport processes are causing a redistribution of sand from the Point to the north part of the west facing shore and also towards the area of the intake lines. Thus, the Point is a zone of divergent sediment transport while the area of the intake lines is a zone of convergent sediment transport. Also, there is an ongoing offshore loss of sediment due to cross-shore transport processes. This situation is related to the change in the profile shape from a convex form (which developed when the Point was a depositional feature) to a concave form which is consistent with the present eroding condition.

Descriptive Model of the Morphodynamics

A descriptive model was developed to relate quantitatively the observed changes in the Gibraltar Point feature to coastal processes, particularly the alongshore and cross-shore transport of sediment which are the driving forces of change at this location. Another aspect of the model is the temporal and spatial schematization which are required to simplify a continually evolving and complex three dimensional problem. From a temporal perspective, the last 35 years were subdivided into three periods ('58-'67, '67-'81 and '81-'93) in part related to the availability of data and also to identify three quite different periods of response. The spatial schematization is based on the "panel" descriptions presented earlier, which consist of an inner and an outer ring of panels, again in part related to data availability and also to identify unique zones of lake bed change. This approach was inspired by the work of Stive and deVriend (1994). As a check on the validity of the descriptive model, the historic observations of change may be compared to the predictions from the model. In essence, the descriptive model is no more than the application of a sediment budget to past changes (with the aid of sediment transport estimates to explain these changes) and the projection of the future sediment budget for periods of 50 and 100 years from the present based on future estimates of sediment transport and sediment supply.

Figure 12 provides a summary of the descriptive model of the evolving morphology at Gibraltar Point over the last 35 years which illustrates the relative magnitude of the incoming and outgoing sediment transport components along with the transfer between the two sections (i.e. the arrows are drawn to represent the relative magnitude of the transport components). This model explains why the west section (Panels 6/7 and 15/16) is eroding at a much greater rate than the east section (Panels 4/5 and 13/14). These transport patterns and associated lake bed changes also translate to shoreline erosion, with the shore along Panels 6 and 7 experiencing high recession rates and the shoreline along Panels 4 and 5 being relatively stable.

Figure 13 provides a summary of the expected pattern of sediment redistribution in the next 50 years (i.e. 1993 to 2043). The offshore loss rates have been reduced to about 70% of the current rate based on the calculations described earlier. The outgoing alongshore transport along the northwest boundary was found to be almost the same as the '81-'93 value, and therefore, is left unchanged. The incoming transport at the east boundary of the east section has been significantly reduced to reflect the remaining supply of sediment available from erosion of the lake bed in Panels 3/12 and 4/13. With the future evolution of the shoreline, the transfer of sediment between the east and west sections is predicted to be reduced to about 25% of the current rate, resulting in a projected transfer of 2,500 cubic metres per year. The expected changes in the second half of the next century (i.e. 2043 to 2093) were also completed but are not presented here. The only difference in the various incoming and outgoing components from the 1993 to 2043 period is that it the supply of transport

from the east will be exhausted by the second half of the next century, thus eliminating incoming sediment on the east boundary of the east section.

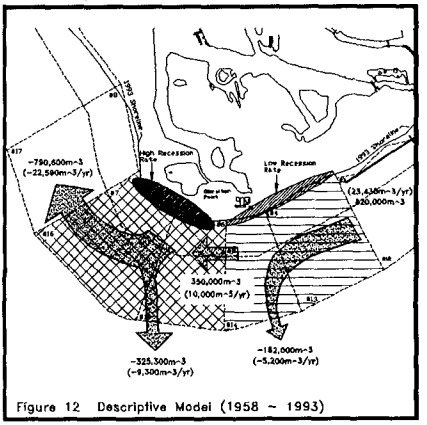


Figure 12 Descriptive Model (1958 - 1993)

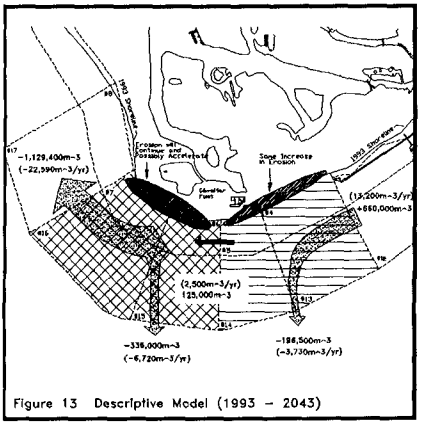


Figure 13 Descriptive Model (1993 - 2043)

For the west section of Gibraltar Point (i.e. Panels 6/7 and 15/16), the findings suggest there will only be a slight decrease in overall sediment loss over the next 100 years. As noted earlier, the shoreline recession has been outpaced by the erosion of the lake bed. The lag in the response of the shoreline is due presence of ad hoc protection structures and natural vegetation, but is also partly explained by the change from a convex to concave profile shape. With the failure or removal of the shore protection structures, it is anticipated that accelerated shoreline recession will occur. Therefore, the linear projections of future shoreline position, if anything, may under estimate the potential shoreline erosion along the inner boundary of Panels 6 and 7.

The results also point to increasing erosional stress on the lake bed of the east section of Gibraltar Point (i.e. Panels 4/5 and 13/14 offshore of the School) through the next 100 years. The analysis presented earlier showed that a linear extrapolation of the historic rate of recession of the 4 m contour over the next 100 years would destabilize the currently stable deposit offshore of the School (i.e. bracketed by the two intake lines, the shoreline and the 2 m contour line). Considering that the descriptive model projects that the erosional stress will be increased in the future, the linear projections may underestimate the future erosion of the lake bed and the future shoreline recession.

The intake lines, which help to stabilize the shoreline and nearshore lake bed offshore of the School, will be increasingly threatened with the projected lake bed lowering. It was noted above that based on the projected rate of recession for the 4 m contour, the stability of the steel sheet piles on either side of the intake pipes would be threatened in 50 to 100 years time. The predictions from the descriptive model suggest that the linear projections underestimate the future lake bed erosion and therefore, the stability of the intake lines could be jeopardized in 50 years time, or possibly less.

Findings and Concluding Remarks

The findings of shoreline comparisons, which give the projected position of the shoreline in 100 years time based on a linear extrapolation of historic rates, were ambiguous with respect to the security from erosion hazards of the existing Nature

School position. Some projections indicated that the School position may be satisfactory after accounting for 100 years of erosion, while others found the existing School location would be completely eroded in 100 years time. This investigation revealed serious shortcomings in the method of linearly extrapolating historic shoreline recession rates to determine future shoreline positions.

In a review of historic and recent lake bed changes, there were both positive and negative implications with respect to the safety of the School position. On the positive side, the lake bed offshore of the School out to the 2 m depth contour and bracketed by the intake lines has been relatively stable over the last 50 years. Also, the section of lake bed to the east of the intake lines has experienced much less erosion than the lake bed offshore of Gibraltar Point or offshore of the seawall further to the east. However, the continued lowering of the lake bed offshore of the 2 m contour in the vicinity of School over the last 50 years has a very negative implication to the future stability of the shoreline in this area. The various ways of depicting the changes to the three dimensional lake bed surface each provided valuable insight to the nature of the evolving morphology.

The descriptive model of the evolution of Gibraltar Point has shown that erosion of the lake bed offshore of the School will be accelerated in the future. Therefore, the currently stable deposit offshore of the School and inshore of the 2 m depth contour will be destabilized, possibly in less than 50 years time. This outcome will allow the erosion of the shoreline in the vicinity of the School to accelerate. Therefore, the linear estimates of the 100 year shoreline position will underestimate the future shoreline recession. In other words, the existing School position will be susceptible to erosion hazards in less than 100 years time.

The application of a fully deterministic model of changing morphology over a 100 year period was considered to be unrealistic given the current state of our understanding of the processes. As an alternative, the descriptive model extends the traditional sediment budget approach by accounting for possible changes in future sediment transport rates to provide a highly schematized projection of future changes to the morphology of the Gibraltar Point feature.

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