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The Canadian Great Lakes: Coastal Environments and the Cleanup of Oil Spills

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THE CANADIAN GREAT LAKES:
COASTAL ENVIRONMENTS AND
THE CLEANUP OF OIL SPILLS

by

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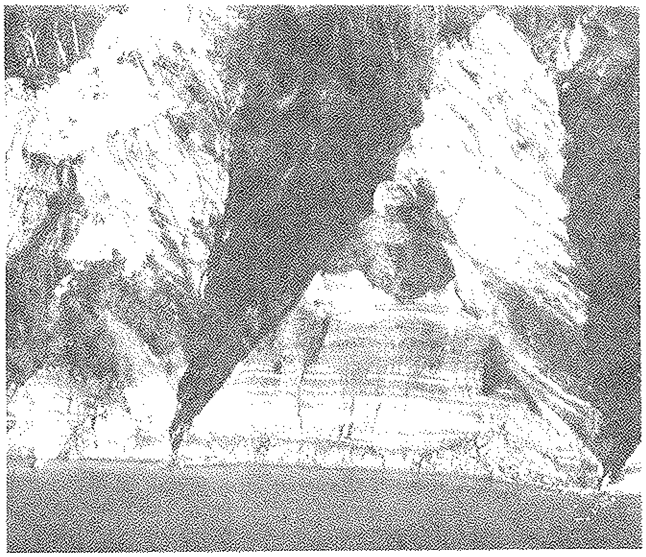

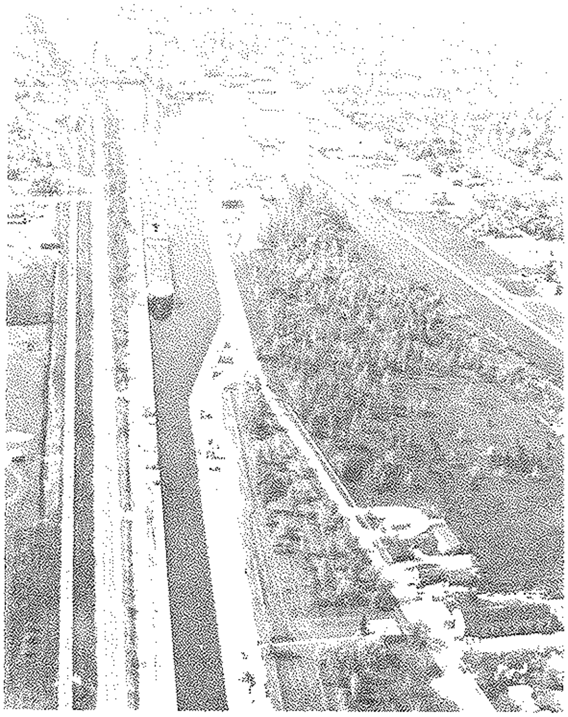

ABSTRACT

The coasts of the Canadian Great Lakes account for less than 5% of the total coastline of Canada, but the region has the highest population density within the country. A major oil spill would, therefore, have a dramatic impact. As part of a contingency plan development programme for oil spills, this review of the shoreline and process characteristics of the Great Lakes' coasts within Canada involved the definition and description of 32 coastal environments. There is a distinct contrast in shore-zone character between Lakes Ontario, Erie, St. Clair, southern Lake Huron, and the areas to the north. The "lower" lakes region has predominantly straight coasts of eroding, unconsolidated till cliffs and isolated, large depositional features. Sediments are relatively abundant due to cliff erosion, and rates of shoreline change are high. This region is also characterized by a high population density. The "upper" lakes have a complex shoreline configuration; over 50% of the total coastline length is comprised of islands. The shore zone is predominantly resistant bedrock outcrops, sediments are very scarce in all but a few isolated locations, and rates of shoreline change are extremely slow. This region is also an area of low population density and many coastline sections are inaccessible by land. As the Great Lakes system is a major shipping artery, high-risk areas for spills are identified on the basis of traffic density and navigation difficulty. Lake Huron and the St. Clair-Detroit waterway have the highest traffic density, but navigation difficulty is greater in the St. Mary's River and the St. Lawrence River regions. These four regions have the highest ranking within the Great Lakes in terms of potential shipping accidents and spills.

The text discussion of shoreline sensitivity, shoreline protection, and shoreline cleanup is supplemented by a series of checklists that can be used to identify the major information requirements for protection and cleanup decisions. Response operations for a major oil spill require detailed local information. In particular, shore-zone character data for cleanup operations is very site-specific and the description of the coastal environments is designed to provide an understanding of local processes and geology which can be used as the basis for local pre-spill information-gathering programmes.

RESUME

Les rives canadiennes des Grands lacs ne comptent que pour moins de 5% de l'ensemble des côtes du, Canada, mais elles font partie des régions les plus densément peuplées du pays. Un déversement massif d'hydrocarbures y aurait, par conséquent, un effet désastreux. En vue de la planification des mesures d'urgence en cas de déversement, il a fallu définir et décrire 32 milieux côtiers dans le présent exposé statique et dynamique de cette région. Il existe un contraste frappant entre les caractéristiques des rives des lacs Ontario, Erié, Sainte-Claire et du sud du lac Huron, et les régions situées plus au nord. Les rives y sont surtout rectilignes, constituées de falaises de moraine de fond qui s'érodent rapidement et de vastes formes sédimentaires isolées. Les sédiments sont relativement abondants à cause de l'érosion des falaises, et les rives y évoluent très rapidement. Cette règion se caractérise aussi par sa forte densité de population. De leur côté, les rives du bassin supérieur présentent des caractéristiques plus complexes. La longueur totale de la ligne de rive est constituée à plus de 50% par des îles. Le rivage y est constitué en majeure partie d'affleurements résistants de roche-mère, les sédiments y sont très rares à quelques exceptions près et les rives n'y évoluent que très lentement. La densité de la population y est faible et elle comporte plusieurs secteurs inaccessibles par voie de terre. Comme le bassin des Grands lacs constitue une importante voie de navigation, nous en identifions les régions qui sont le plus exposées aux déversements, à l'aide de données portant sur la densité et les difficultés de navigation. C'est dans le lac Huron et l'ensemble des rivières Sainte-Claire et Détroit que la navigation est dense tandis qu'elle est la plus difficile dans la Sainte-Marie et la Saint-Laurent. Ces quatre régions arrivent en tête de liste pour ce qui est des risques d'accidents et de déversements.

La discussion portant sur la fragilité des rives, leur protection et leur nettoyage s'accompagne d'une série du listes de contrôle qui peuvent servir à déterminer quels sont les principaux renseignements nécessaires à la prise de décisions concernant la protection et le nettoyage. Le choix des mesures à prendre lorsque survient un important déversement dépend d'une masse de renseignements précis. Les données portant sur les caractéristiques des rives et qui sont nécessaires aux opérations de nettoyage sont liées très étroitement à l'emplacement précis du déversement, et la description du milieu côtier vise à expliquer l'évolution locale des rives et les caractéristiques géologiques qui serviront de fondement aux programmes locaux de collecte des renseignements en prévision de déversements.

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PART 1 - FOREWORD

1.1 INTRODUCTION

The Great Lakes system is one of the major shipping arteries of North America. The high traffic density on the waterways makes this a high risk area for a major oil spill. The region is also a high population density area, particularly the lower lakes (St. Clair, Erie and Ontario) so that the potential impact and damage from a spill is also high.

Contingency planning for an oil spill has many facets and requires a considerable effort in order to prepare for response operations. This report focusses on the protection of shorelines from spilled oil and the cleanup of shorelines upon which oil has become stranded. A knowledge of coastal processes and shoreline types is of fundamental importance for the assessment of the impact of an oil spill and for the selection of the correct protection and cleanup procedures. When an oil spill occurs, the relevant information and data to develop decisions should be at hand. The opportunity to undertake detailed shoreline surveys or to compile data is minimal so that preparedness is a critical factor. Information pertinent to the assignment of protection priorities should be immediately available to the On-Scene Commander following implementation of the spill-response operation.

It is not practical in this report to provide a detailed description of the entire shore zone of the Canadian Great Lakes to the level that is necessary for an actual, site-specific spill response. This information can only be obtained at the local level. The information and checklists on coastal processes and shoreline types presented in this report are intended as a basis for further local information gathering and to provide the framework for describing the important characteristics of the shore zone. There is considerable variability in the geographic distribution of available information on the Great Lakes coasts. In general, the amount of information is directly proportional to the regional population density, so that the available information base for the upper lakes is poor when compared to the lower lakes.

The report was prepared from: (a) information gathered during a series of aerial reconnaissance surveys of almost the entire Canadian Great Lakes coast (only the section in Lake Huron from Parry Sound to central Manitoulin Island was not surveyed), (b) ground reconnaissance surveys at selected sites in the Great Lakes system, (c) a literature survey of published and unpublished information, (d) discussions with other workers who have studied the Great Lakes coasts or who have been involved with coastal oil spills or cleanup programmes, (e) experience gained by studies during previous major oil spills, and (f) a literature survey of the effects of previous spills and cleanup programmes in analagous coastal environments.

1.2 OBJECTIVES

The primary objectives of this report were as follows:

(1) To define and describe the major coastal environments of the Canadian Great Lakes,

(2) To explain the significant characteristics of shoreline types and coastal processes in each environment that are relevant to spill response operations,

(3) To discuss the expected behaviour, distribution and persistence of oil residues in the different coastal environments and on different shoreline types,

(4) To discuss the sensitivity of shoreline types to the expected impact of stranded oil,

(5) To assess available onshore protection and shoreline cleanup methods in terms of their applicability and effectiveness,

(6) To present guidelines and checklists for the development of decisions related to the definition of response priorities and to the selection of appropriate cleanup techniques for the different coastal environments, and

(7) To present a bibliography of relevant geological and cleanup information sources.

1.3 FORMAT

The first section (Part 2) consists of an outline of how the text material and checklists can be used prior to, and during, spills. The remainder of the report can be considered in two parts. The first (Parts 3 and 4) defines and describes the coastal environments of the Canadian Great Lakes, the second (Parts 5 to 8) discusses the impact and cleanup of stranded oil.

As an introduction to the examination of the coastal environments in detail, the process and geological characteristics of the Great Lakes shorelines and potential high spill risk areas are considered at the general level (Part 3). The coasts of the Great Lakes are then defined in terms of six basic regions. Each of the lakes and its adjacent waterways are taken as a single region with the exception of Lake Huron which is considered as two distinct systems. Within each of the regions the coastal character is discussed within the framework of 32 subdivisions. These subdivisions are defined on the basis of discrete shore-zone sediment transport systems (Part 4).

In the second section, the relevant properties of oil and the processes of oil degradation and persistence (Part 5) and the characteristics of shoreline processes and shoreline types (Part 6) are related to the expected impact and the sensitivity of different shoreline sections (Part 7). Priorities and methods of onshore protection and of shoreline cleanup are discussed both in terms of the applicability, effectiveness and potential effects of the techniques and of guidelines for the implementation of available methods (Part 8).

The bibliography provides a reference to information sources used in the text and an appendix defines terms used in this report.

PART 2 - SCOPE AND ORGANIZATION

INTRODUCTION

Although environmental pollution results from a wide range of man's activities, major oil spills are dramatic events that attract a great deal of public attention and concern. Effective spill-response operations require considerable planning. The range of problems that are usually addressed encompasses organization, responsibility, environmental impact assessment and scientific follow-up studies. This report focusses on only one facet of oil spills: that which deals with coastal environments, shoreline types and the impact of stranded oil on the coasts of the Canadian Great Lakes.

ORGANIZATION

The description of the coastal processes and shoreline types for each of the six regions and 32 coastal environments is designed to provide basic material that can be used to understand the shore-zone character. In order to be adequately prepared for a spill, a programme of local information gathering on shoreline types is recommended. The necessary shore-zone information base for spill-response decisions is very site specific and those coastal processes and shoreline characteristics that are of direct relevance to spills are discussed in Part 6 (p.169). Table 24 (p.188) provides a checklist of the relevant information. Collection of this information at the local level on a systematic basis would provide data for immediate decisions on protection and cleanup priorities in the event of a spill.

The sensitivity of a section of shoreline is a function of the volume and type of oil, the shore-zone character and the timing of the spill. With an adequate data base on the character of the oil (Table 19, p. 167), on the character (geological and biological) of the shore zone (Table 24), and information on the spill, an assessment can be made using the checklist given in Table 27 (p. 201). These three checklists, when completed, provide in a summary format the basic information that is necessary for first-phase spill response decisions related to the impact and persistence of stranded oil.

The evaluation of shoreline protection priorities and of the feasibility of protection operations is discussed in Part 8.1. The major factors in this phase of the spill response are summarized as a series of questions in Table 28 (p. 206).

The question whether or not to clean a section of shoreline can be summarized as a series of questions (Table 31, part B, p. 215). In addition to assessing the desirability for cleanup of the stranded oil, it is also necessary to determine the practicality (or feasibility) of cleanup methods and the effect that these may have on the biological and geological stability of the shoreline section (Table 31, parts C and D).

The series of checklists and questionnaires is designed to familiarize users with the types of information and decisions that relate to shoreline protection and cleanup operations. The text discussion with the accompanying summary tables and figures provide material for understanding the relevance and the importance of each of the factors used in the decision-making process. The discussion is necessarily brief and further information can be obtained from the cited references.

USE OF THE CHECKLISTS FOR A HYPOTHETICAL SPILL

To demonstrate the use of the report and the checklists, a hypothetical spill situation has been developed. The "spill" has occurred in late May in western Lake Erie as the result of a collision between two ships (a tanker carrying Bunker C fuel oil and a freighter). The oil drifted for 5 to 6 days before becoming stranded on the southwest coast of Point Pelee (Photo 29, p. 117). For this exercise, in part (iv) (shoreline protection) below, the scenario is changed slightly to a situation where the oil is still on the lake surface but is expected to become stranded on the same shoreline section within 24 hours.

The relevant data has been used to complete the checklists, which are given on pages 11 to 16.

(i) Spill Information

The collision between a tanker and freighter in western Lake Erie in late May resulted in a spill of 500,000 U.S. gallons of Bunker C oil. The oil remained on the water surface for 5 to 6 days before being stranded, and the weathering of the oil resulted in a loss of light fractions by evaporation. This weathering combined with cold water temperatures and cool air temperatures changed the character of the oil from a potentially flammable, low-viscosity fluid to a relatively safe, highly viscous (semi-solid) substance.

On the section of shoreline in question, which is a sand beach, the oil coated the entire length of the section.

Penetration of the oil into the sand was low, because of the viscous nature of the oil and because sand grains are relatively closely packed, leaving little space for oil to migrate down.

A rough estimation of the oil volume on the beach is obtained by multiplication of (i) the width of the zone of stranded oil (3 m); (ii) the average thickness of the stranded oil (approximately 3.5 cm); and (iii) the length of the shoreline section (3 km). This gives an approximate volume of 80,000 U.S. gallons, or 2,000 U.S. barrels.

(ii) Shore-Zone Character

Information given in Parts 3 and 4 of this report states that the shore zone is a sand beach backed by sand dunes and is in a National Park. From a pre-spill information-gathering survey by local authorities, it is known that the debris cover is generally low (<10%), beach width is approximately 5 m, and the berm height is about 2 m above lake level at this time of year.

In terms of shoreline exposure and wave-energy levels, data in Parts 3 and 4 indicate that the prevailing winds during May are onshore and that the fetch is 75 km. The coast is straight and open, and from Table 20 (p. 182) this section is classified as a moderately-high wave energy shoreline (category 8). No ice is present on the lake or the shore and the seasonal wave-energy level is intermediate (p. 191).

(iii) Shore-Zone Sensitivity

The weathered Bunker C oil on the shore is not expected to persist for a long time as this section is exposed to waves and the oil is stranded on the beach within the zone of wave action.

The sand beach is a zone of low biological sensitivity according to a biologist who has visited the area and who was consulted during the pre-spill information-gathering programme. The section is within a National Park and is intensely used during the summer months so that the beach is highly sensitive in terms of man's activities.

(iv) Shoreline Protection

(Note: In this part of the scenario only, it is assumed that the oil is on the lake but that it is expected to wash ashore within 24 hours.)

The oil on the beach would be removed by normal wave action within about a year. However, due to the high-intensity recreation use during summer months this rate of natural cleaning is too slow and the oil would have a severe impact on man's activities.

No biological damage is expected but large-scale sediment removal could endanger beach stability so that shoreline protection is preferable to cleanup. Insufficient time is available to mobilize an offshore containment and removal operation, therefore a decision is made to use onshore protection methods. The beach has good access to vehicles and equipment is available locally to implement a protection operation. Based on this information it is decided to construct a ditch/dyke system along the endangered section. The ditch would contain and collect the oil for removal by vacuum trucks and the dyke would prevent oil from reaching backshore areas. Two trench-cutting machines are available and can complete the operation with the time available. As a back-up, bulldozers will be moved to the beach to build a dyke in the event of a mechanical breakdown to one or both of the trench-cutters.

(v) Shoreline Cleanup

The decision to implement a cleanup programme is taken on the basis that the level of contamination is unacceptable, the rate of natural recovery is too slow, and that recreational shoreline use would be severely affected. Immediate cleanup is necessary as the oil could become buried within the beach. If this situation occurred then large-scale sediment removal could endanger beach stability.

Graders and self-propelled elevating scrapers are locally available, the beach is accessible to the equipment and the equipment can operate on the beach so the decision is made to mechanically remove the stranded oil. The method is expected to achieve the operational objective that the beach can be cleaned effectively and efficiently for subsequent recreational use. The removal operation is not expected to endanger beach stability if the cleanup is undertaken before the oil is buried and if the recommended procedures for operation of the equipment are followed.

(vi) Discussion

This case study outlines only some of the decisions and data that are necessary for a spill response. To fully address the scenario would be lengthy and would only repeat the discussion given in the text of Parts 5 to 8. This type of exercise can be used for familiarization with the checklists and can be a useful training tool.

TABLE 19. SPILL INFORMATION CHECKLIST

1. OIL ON WATER

Source of Spill: SHIP COLLISION - TANKER/FREIGHTER

Is oil still being spilled?

YES - Spill Discharge Rate: ____

- Estimated Duration of Spill: ____

- Estimated Final Spill Volume: ____

[✓ NO] - Volume of Spill: APPROX. 500,000 U.S. GALLONS

Type of Oil: BUNKER C - WEATHERED ON LAKE FOR 5-6 DAYS

Is oil flammable or otherwise hazardous to personnel? [✓ YES]/NO

Will the oil be stranded? [✓ YES]/NOT KNOWN/NO

*Where will the oil be stranded? WEST BEACH POINT PELEE

*Requires spill movement prediction information not contained in this report.

2. OIL ON SHORE

Has the spill ceased? [✓ YES]/NO

Is there a danger of more oil being washed ashore? YES/[✓ NO]

Oil Viscosity: Low (fluid) ____ Moderate ____ High (semi-solid) XX

Oil Flammability: Very Dangerous ____ Potentially Flammable ____ Low Risk XX Inert ____

DO THIS FOR EACH SECTION

Section Name or Identification: WEST COAST POINT PELEE

Surface Area Covered by Oil: 100 %

Thickness of Surface Oil: 2 TO 5 cm

Distribution Across Shore Zone: ON BEACH FACE BELOW BERM

Depth of Oil Penetration: 1 TO 2 cm

Volume of Stranded Oil on Beach: APPROX. 80,000 U.S. GALLONS (2000 U.S. BARRELS)

Shoreline Exposure: (see Part 6.4, p. 180) OPEN COAST, FETCH 75 KM

Wave Energy at Shoreline: (see Part 6.4, p. 180) MODERATELY HIGH

TABLE 24. SHORE ZONE CHARACTER CHECKLIST

1. BEACH SEDIMENTS AND MORPHOLOGY

	Substrate	Sediment Size(s)
Lower Beach	SAND	SAND
Upper Beach	SAND	SAND
Backshore	SAND	SAND

Sediment Sorting: Good XX Poor ____

Angularity of Sediments: Rounded XX Angular ____ Sharp Edges ____

Debris: Cover on lower beach <10 % On upper beach 10-20 %

Beach Width: 5 m

Maximum Berm or Ridge Height (above lake level): 2 m

2. SHORELINE EXPOSURE AND ENERGY LEVELS (for the Great Lakes)

Maximum Fetch (km) >200 ____ 50-200 XX <50 ____

Predominant Winds: Onshore XX Offshore ____

Coastline Straightness: Straight XX Irregular ____ Indented ____

Degree of Exposure: Open XX Partly Sheltered ____
Completely Sheltered ____

Presence of Ice Foot: Absent XX Present ____

Relative Exposure/Energy Level: (from Table 20, p. 182) 8

Seasonal Energy Level: (see text, p. 191) High ____
Intermediate XX Low ____

3. SHORELINE ACCESS (see Table 23, p. 187)

Heavy Vehicles: Land Access: Existing XX Required ____
Seaborne Access: YES/NO

Light Vehicles: Land Access: Existing XX Required ____
Seaborne Access: YES/NO

Pedestrians: Land Access: [✓ YES]/NO
Seaborne Access: YES/NO
Aerial Access: YES/NO

TABLE 27. SHORE-ZONE SENSITIVITY CHECKLIST

IMPACT FACTORS

Type of Oil: WEATHERED BUNKER C

Is oil on shore?

[✓ YES] - Volume Stranded (from Table 19, p. 11): 2000 U.S. BARRELS

NO - Volume of Spill: ___

Expected Persistence of Oil: Days ___ Months XX Years ___ Decades ___

Month of Year: MAY

Can cleanup be effective? (from Table 31, p. 15) [✓ YES]/NO

Would cleanup have an impact? (from Table 31, p. 15) [✓ YES]/NO

If YES, describe: COULD CAUSE EROSION IF TOO MUCH BEACH SEDIMENT REMOVED

SHORE ZONE CHARACTER

Shoreline Type (from Table 21, p.184): SAND BEACH

Rare or Endangered Biological Species: Absent XX Present ___

Natural Biological Recovery Potential: <1 Yr. XX Years ___ Decades ___

Natural Geological Recovery Potential: <1 Yr. XX Years ___ Decades ___

Recreational Use of Shore Zone:
None ___ Low ___ Moderate ___ High ___ Very High XX

Commercial Use of Shore Zone:
None ___ Low XX Moderate ___ High ___ Very High ___

Biological Impact of Oil:
None ___ Low XX Moderate ___ Severe ___ Critical ___

Impact of Oil on Rare or Endangered Species:
None XX Low ___ Moderate ___ Severe ___ Critical ___

Biological Impact of Cleanup:
None ___ Low XX Moderate ___ Severe ___ Critical ___

Geological Impact of Cleanup:
None ___ Low ___ Moderate XX Severe ___ Critical ___

TABLE 28. SHORELINE PROTECTION CHECKLIST

	YES	NO
1. Will the oil become stranded?	X	
2. Would the shoreline be cleaned naturally in an acceptable period of time?		X
3. Would the section of shore zone be seriously affected by the impact of oil?	X	
IMPACT OF STRANDED OIL		
4. Would the oil seriously endanger flora or fauna?		X
5. Would the impact on flora and fauna be long-term?		X
6. If shoreline cleanup is necessary, would this affect beach stability (*e.g.*, by sediment removal)?	X	
7. Would the presence of the oil affect man's use of the shore section?	X	
8. Would protection be more effective than cleanup?	X	
PROTECTION FEASIBILITY		
9. Is sufficient time available to implement the protection operation?	X	
10. Would the method(s) be effective?	X	
11. Are sufficient equipment, materials and manpower available?	X	

METHODS

12. What is (1) the most applicable method? OFFSHORE CONTAINMENT AND REMOVAL

(2) the most applicable alternative? DITCH/DYKE SYSTEM

TABLE 31. SHORELINE CLEANUP INFORMATION CHECKLIST

A. OIL AND THE SHORE ZONE

Type of Oil: WEATHERED BUNKER C

Depth of Penetration: UP TO 2 CM

Volume of Stranded Oil (from Table 19, p. 11): 2000 U.S. BARRELS

Shoreline Type (see Table 21, p.184): SAND BEACH

Shore-Zone Sediments (see Table 24, p. 12): SAND

Shore-Zone Exposure and Wave-Energy Levels (see Table 24, p. 12):
EXPOSED MODERATELY HIGH ENERGY

Is ice present in the shore zone? YES/[✓ NO]

B. CLEANUP OR NATURAL RECOVERY?

Expected Persistence of Oil:
Days ____ Months XX Years ____ Decades ____

Would continued presence of oil be undesirable in terms of?

(a) Biological Processes YES/[✓ NO]

(b) Recreational Activities [✓ YES]/NO

(c) Commercial Activities YES/[✓ NO]

Is the level of contamination unacceptable? [✓ YES]/NO

Would oil migrate onto other shoreline sections? [✓ YES]/NO

Is immediate cleanup necessary? [✓ YES]/NO

What is the most effective/efficient cleanup method for the shoreline section? GRADERS AND ELEVATING SCRAPERS

C. CLEANUP FEASIBILITY

Are satisfactory equipment and sufficient manpower available? [✓ YES]/NO

Is the shoreline accessible for equipment and/or personnel? (see Table 24, p. 12) [✓ YES]/NO

TABLE 31 (Cont'd)

Can the equipment operate effectively in the shore zone? [✓ YES]/NO

Would the degree of cleanup be satisfactory? [✓ YES]/NO

If the most preferred cleanup method is unfeasible or would incur damage (see "D" below), what is the next suitable alternative method?

N/A

D. CLEANUP DAMAGE (see Section 8.5)

Would the level of biological damage be acceptable? [✓ YES]/NO

Would the level of geological damage be acceptable? [✓ YES]/NO

Impact of Cleanup on Unique Cultural Features:

None XX Low ____ Moderate ____ Severe ____ Critical ____

Impact of Cleanup on Recreational Activities:

None XX Low ____ Moderate ____ Severe ____ Critical ____

Impact of Cleanup on Commercial Activities:

None XX Low ____ Moderate ____ Severe ____ Critical ____

NOTES:

PART 3 - THE GREAT LAKES REGION

SYNOPSIS

The Great Lakes system is comprised of a series of large lakes connected by narrow channels and rivers. Shoreline processes are limited by short fetch distances, and wave heights >2 m are rare. A marked seasonal change in the wave climate is characterized by relatively calm conditions during summer months and higher wave-energy levels in winter which are associated with the passage of storms across the region. Shoreline processes are greatly modified in winter by the presence of ice for periods up to four months on most coasts and up to five months in sheltered areas.

Lake levels vary due to the effects of storms and these short-term fluctuations are superimposed on seasonal and long-term lake level changes. Short- and long-term fluctuations are generally less than 1 m but can be as much as 2 m.

The Great Lakes system was formed by erosion along the margin of the Canadian Shield. Those coasts where resistant Shield rocks outcrop in the shore zone are complex, with many islands and embayments and few beach sections. To the south of the Shield where less resistant rocks or unconsolidated sediments overly the Shield, the coasts are generally straight and are characterized by beaches and low-lying, relatively unresistant cliffs.

The lake system is a major shipping artery for the U.S. and Canada. Ship traffic is concentrated in the sections between the St. Mary's River and Lake Erie, and is particularly dense in the St. Clair-Detroit region. The ship traffic is characterized by relatively small vessels travelling between ports within the Great Lakes system.

3.1 INTRODUCTION

The Great Lakes system is an extensive inland network of freshwater lakes and interconnecting waterways. The dimensions of the individual lakes vary considerably (Table 1), but as a unit they form a step-like sequence that drains into the Atlantic Ocean through the St. Lawrence River (Fig. 1).

The Canadian shoreline of the Great Lakes is about 9,500 km long which represents 3.7% of Canada's total coastline (Table 2). One of the primary features of the shore zone is that approximately 46% of the coastline is comprised of islands.

TABLE 1. Dimensions of the Great Lakes System

	Area (km^2)	Volume (km^3)	Max. Length (km)	Max. Width (km)	Max. Depth (m)
Lake Superior	821,000	12,100	563	257	405
St. Mary's R.	230		113		
Lake Michigan	57,800	4,920	494	190	281
Lake Huron	59,600	3,540	332	295	229
St. Clair - Detroit R.	1,270	4*	42*	39*	6*
Lake Erie	25,700	484	388	92	64
Niagara R.	60		60		
Lake Ontario	18,960	1,640	311	85	244
St. Lawrence R.	492		808		

*Lake St. Clair

Source: Canada-U.S., 1977

This section presents a general summary of the relevant physical factors that contribute to the shoreline character and to the processes that operate in the shore zone of the Great Lakes system within Canada.

3.2 COASTAL PROCESSES

The character of the shore zone and the rates at which the shoreline morphology changes are related directly to inputs of mechanical energy. These energy inputs are a function of winds, waves, ice, and water level changes. Each of these major factors

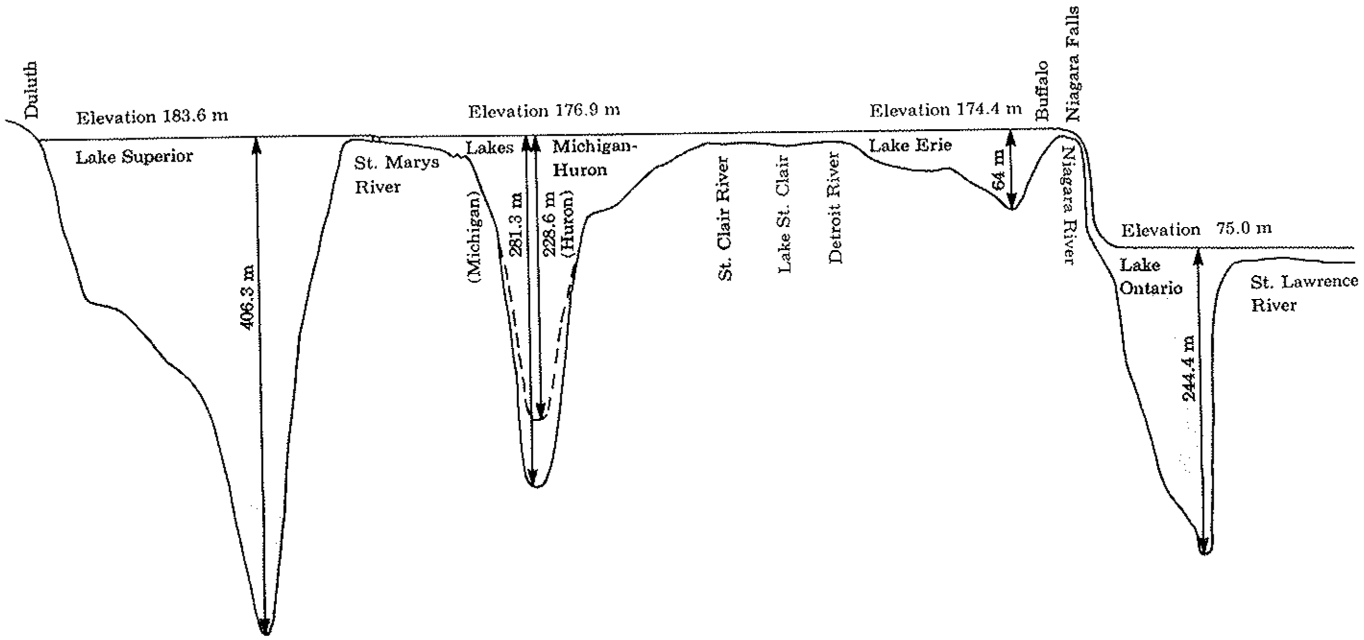


Figure 1. Idealized profile of the Great Lakes to illustrate their relative depths and elevations (note that the horizontal and vertical scales are considerably distorted) (from Ragotzkie, 1974).

is described briefly in terms of their geographic variability within the Great Lakes region. The actual role of each factor in terms of shore processes, geomorphology, and oil is discussed further in sections 5.3 and 5.5.

Winds

Winds are a major factor in shoreline processes as they provide energy for the generation of waves and currents, and they are a prime force in the patterns of ice movement on the lake surface. The Great Lakes are under the dominant influence of prevailing westerly winds throughout the year, but significant seasonal variations are evident on a regional basis (Figs. 2 and 3).

TABLE 2. Shoreline Lengths (in kilometres)

	Total Length	Length in Canada
Lake Superior	4,385	2,380
St. Mary's River	397	207
Lake Michigan	2,633	-
Lake Huron	6,157	4,810
St. Clair-Detroit River	726	340
Lake Erie	1,402	639
Niagara River	171	58
Lake Ontario	1,146	618
St. Lawrence River*	765	419
	17,782 km	9,471 km

*Above Iroquois Dam

Source: Canada-U.S., 1977

Total Length of Canada's Coasts = 253,507

Great Lakes segment = 3.74%

Total Length of Canadian Great Lakes Mainland Coast = 5,095 (54%)

Total Length of Canadian Great Lakes Island Coast = 4,376 (46%)

In western Lake Superior winds are predominantly from the west to northwest in winter months, and from the east in summer (Thunder Bay, Table 3), whereas, the reverse condition prevails at Sault Ste. Marie on the eastern shore of the lake. Prevailing winds on Lake Huron and Georgian Bay are generally from west

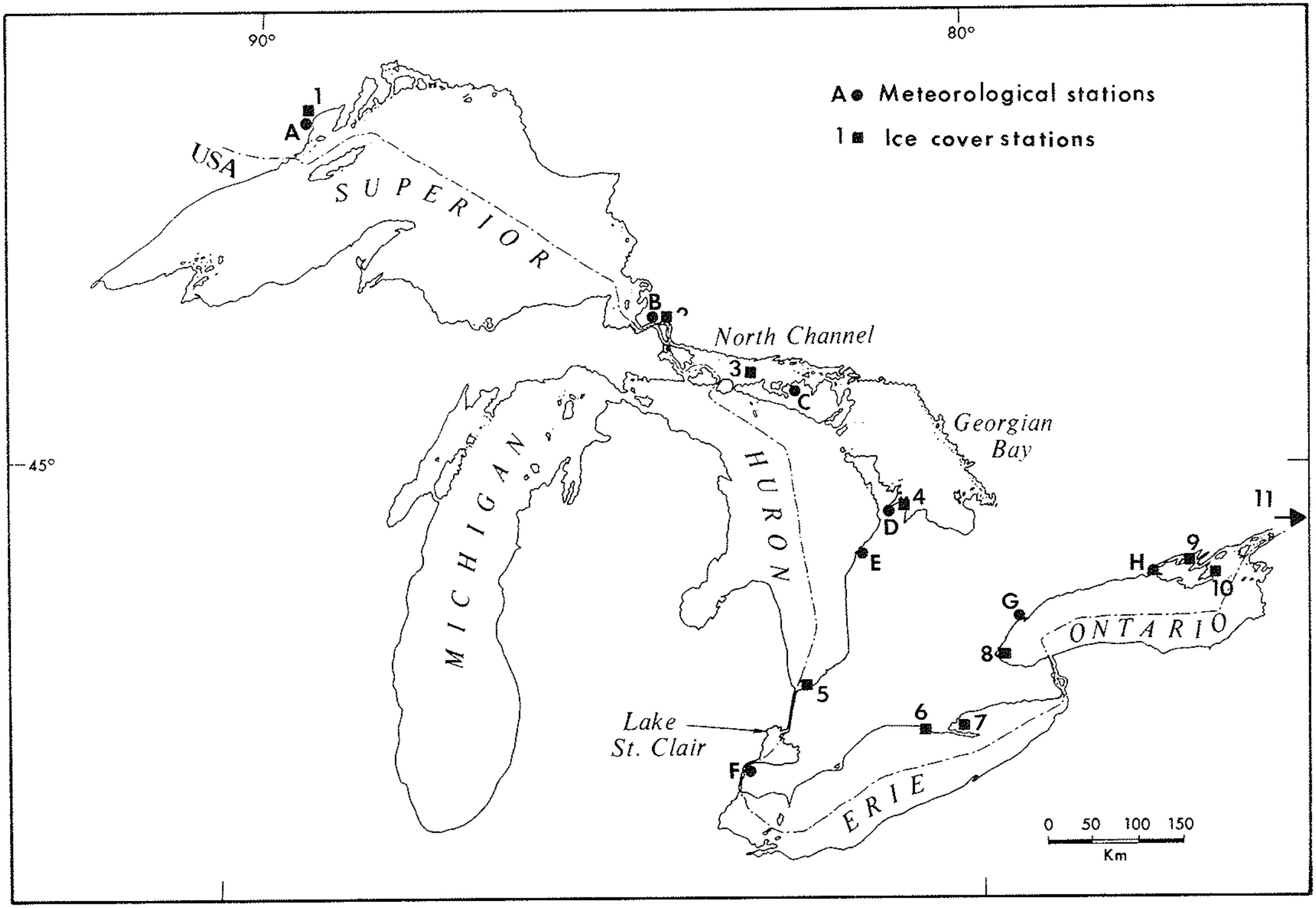
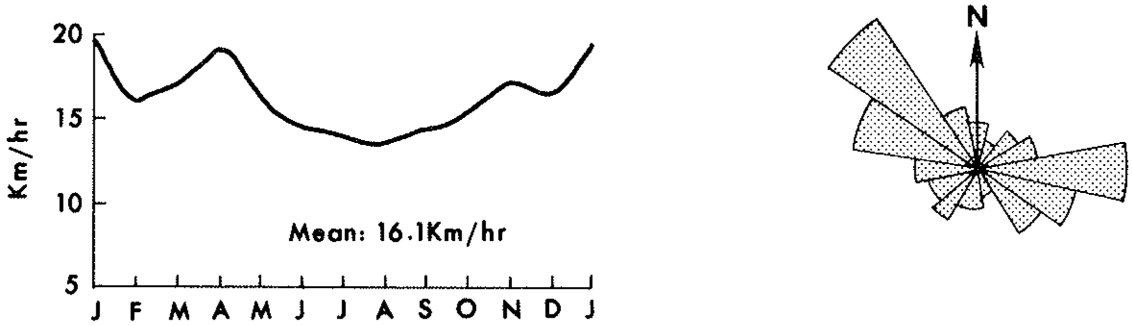
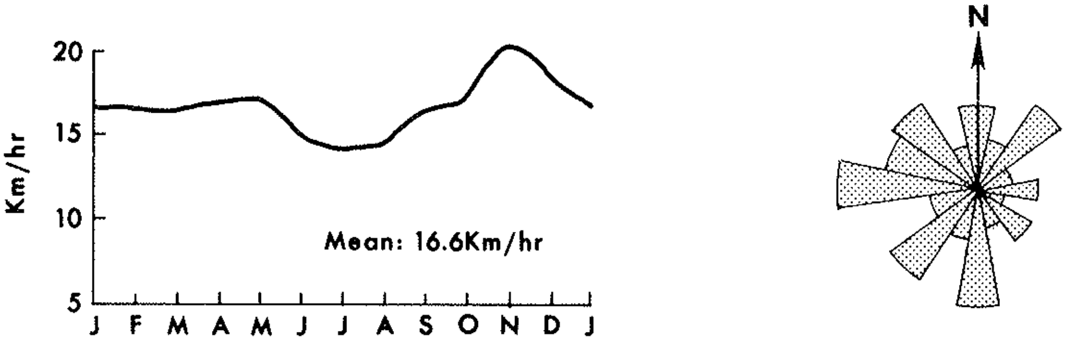


Figure 2. Location of meteorological stations (Figs. 3 and 5; Table 3) and ice-cover stations (Fig. 7).

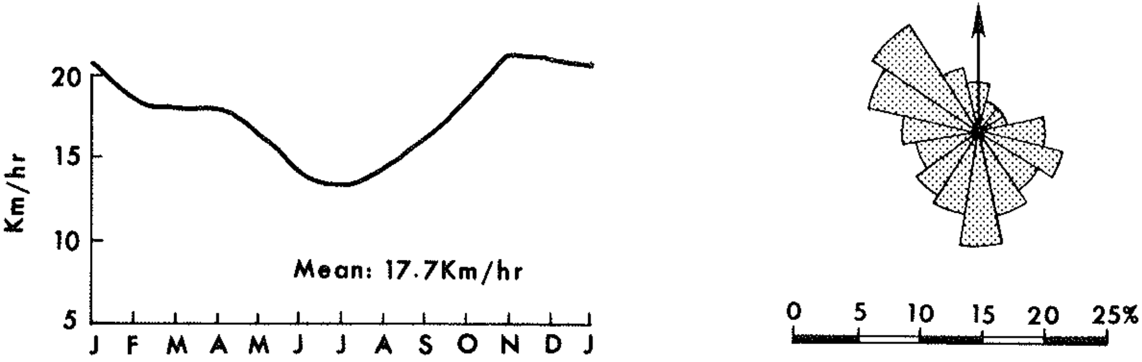
A. THUNDER BAY



B: SAULT STE. MARIE

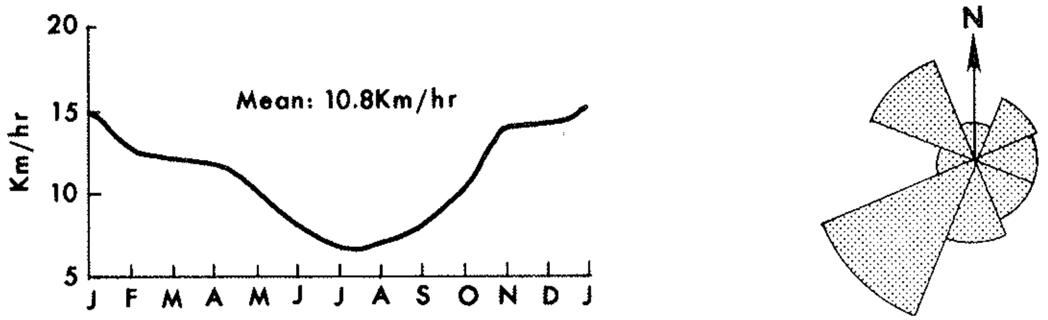


C. GORE BAY

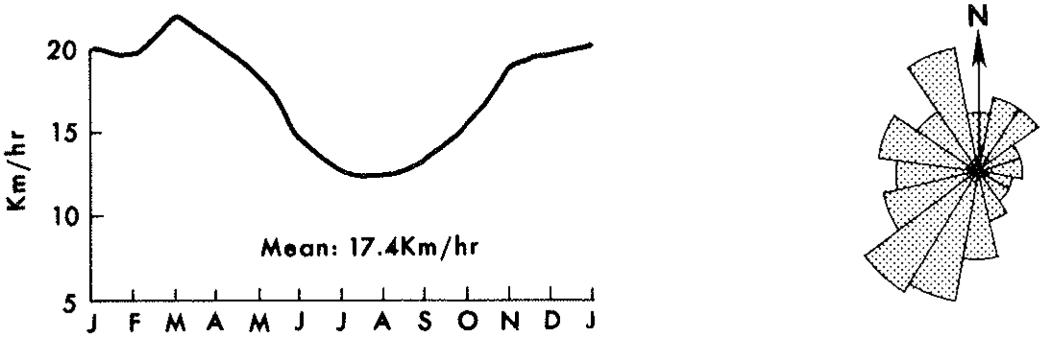


D. WIARTON

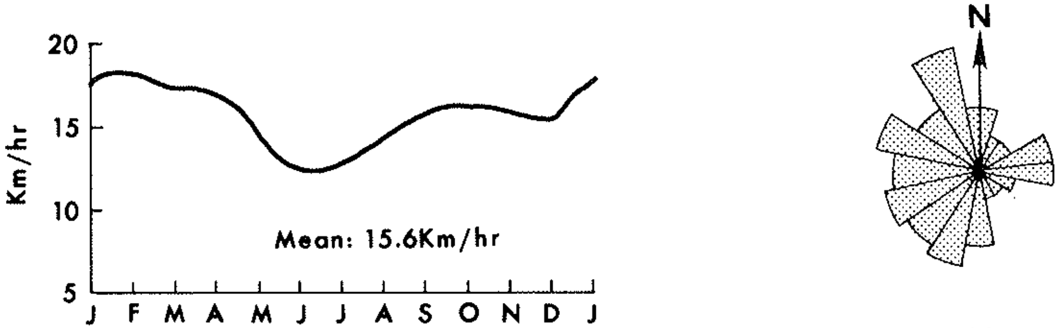
Figure 3. Mean monthly wind velocity and annual frequency of winds by directions. Stations located on Figure 2 (data from Canada, Dept. of Transport, 1968).



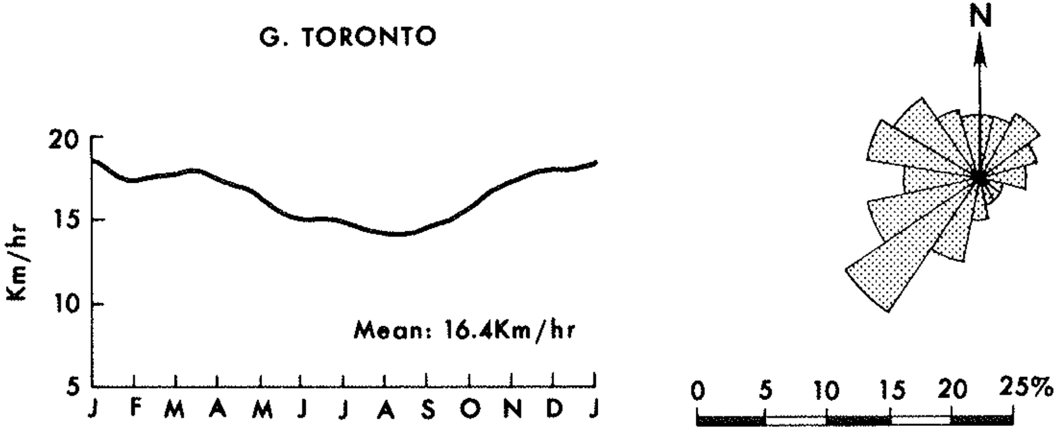
E. SOUTHAMPTON



F. WINDSOR



G. TORONTO



H. TRENTON

Figure 3 (Cont'd)

TABLE 3. Mean monthly wind velocity (a) and direction (b). Stations are located on Figure 2 (data from Canada, Dept. of Transport, 1968).

	LOCATION		JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
A	Thunder Bay	a.	14.6	14.5	13.8	15.9	15.9	12.9	11.9	11.6	12.9	13.8	16.1	15.5	14.2
		b.	W	W	W/SW	E	E	E	E/W	E/W	W	W	W	W	W
B	Sault Ste. Marie	a.	18.3	16.4	17.1	18.3	16.4	14.6	14.0	13.5	14.6	15.3	17.2	16.4	16.1
		b.	E	NW	WNW	NW	NW	NW	NW	NW	E/NW	E/NW	E/NW	E	NW
C	Gore Bay	a.	16.6	16.6	16.3	16.7	16.9	14.8	14.2	14.5	16.6	17.4	20.3	18.3	16.6
		b.	NE/NW	NE/NW	NE	W	S/W	S/W	S/W	WSW/S	S	S	W	NE/W	W
D	Wiarton	a.	20.6	18.5	18.0	17.9	16.6	14.2	13.5	14.5	16.3	18.3	21.1	20.9	17.7
		b.	NW	WNW	NE	WNW	SW	SW	WSW	S/W	S	S	S	S	S
E	Southampton	a.	14.8	12.9	12.2	11.8	10.0	8.1	7.1	7.2	8.1	10.0	14.0	14.2	10.8
		b.	SW	SW	E/NW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW
F	Windsor	a.	20.1	19.8	21.7	20.4	18.3	14.5	12.7	12.6	13.5	15.6	18.8	19.5	17.4
		b.	SW	SW/WNW	NNE/WNW	SW	SW	SSW	SW	SW	SSW	SSW	SSW	SW	SW
G	Toronto	a.	17.7	18.0	17.4	16.9	13.8	12.4	13.5	14.6	16.1	16.1	15.8	15.6	15.6
		b.	SW	WSW	E/NW	E/NW	NNW	S/NW	S/NW	S/NW	SW/NW	WSW	WSW	WSW	SW
H	Trenton	a.	18.5	17.4	17.9	17.4	16.3	15.0	14.8	14.2	14.5	15.9	17.5	17.1	16.4
		b.	NW/NE	WNW	WNW/ENE	SW	SW	SW	SW	SW	SW	SW	SW	NE/WSW	SW

with a seasonal shift to the south and southwest in summer and fall. The prevailing winds on Lakes Erie and Ontario approach from the southwest, roughly parallel to the long axes of the lakes (Windsor, Toronto: Table 3).

In general, wind speeds are at a maximum in spring and autumn months when cyclonic activity in the region is greatest (Fig. 3, Table 3). An important factor in utilizing wind data collected at on-land stations is that measured speeds at these sites are generally lower than those that occur over water. The ratio between overland and overwater wind speed is in the order of 1.7 but varies daily and seasonally. Monthly ratios range from a low of 1.2 in summer to a high of 2.1 in winter months (Derecki, 1976).

During summer months, when wind speeds are generally at a minimum, the effects of onshore and offshore lake breezes can be important. An offshore breeze (from the land to the lake) occurs when the water is warmer than the land, and an onshore breeze occurs under the reverse conditions. Although these breezes are a common feature of the wind systems in the shore zone, the wind speeds are low.

Waves

Fetch (q.v.) distances are limited in the Great Lakes so that wave heights are relatively low (generally <2 m) and wave periods are short (<7 seconds). As wave generation is a direct result of wind action wave heights vary seasonally and are lowest during summer months. During winter months significant wave heights (q.v.) in the order of 0.8 to 1.7 m are common in all but sheltered areas, whereas, in summer months significant wave heights are usually between 0.1 and 0.6 m.

Few sets of long-term wave data exist for most of the lakes and much of the available information is based on hindcast or predicted values. Figure 4 presents an indication of the percent time that the significant wave height is expected to exceed the given values. For example, on Lake Ontario in January waves

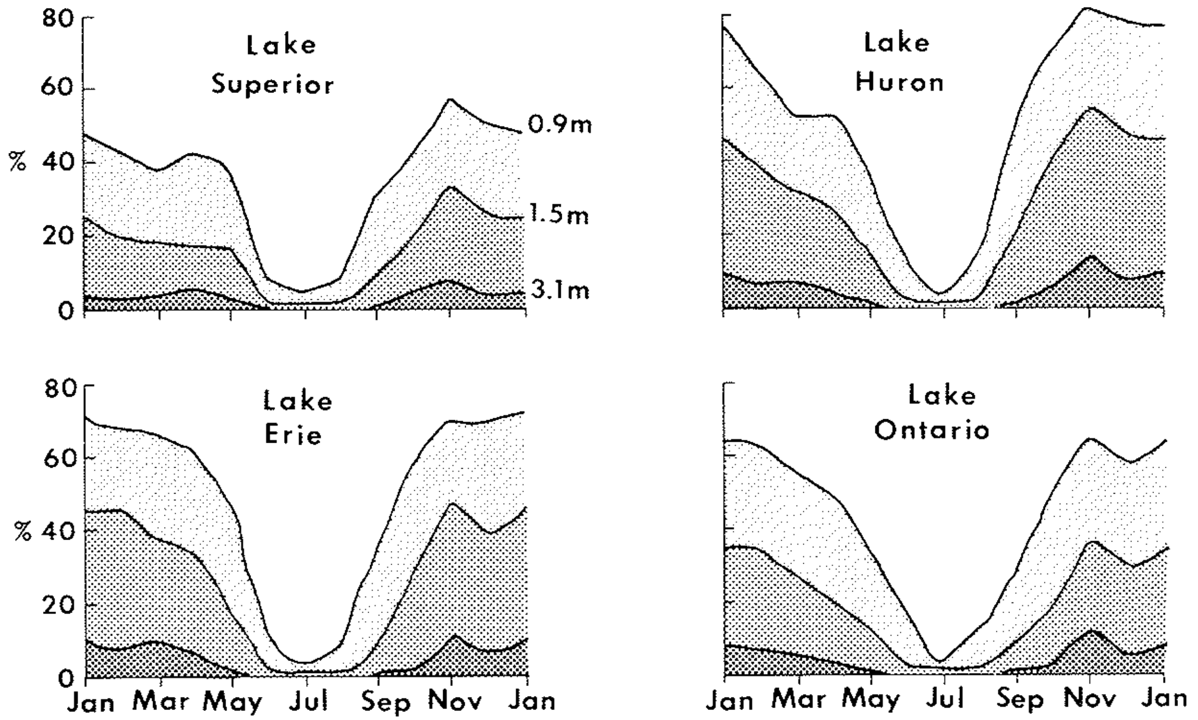


Figure 4. Computed frequency of significant wave heights for each lake (values computed for 170 km fetch) (Richards and Phillips, 1970).

greater than 0.9 m (3 feet) are to be expected 64% of the time; those greater than 1.5 m (5 feet), 35% of the time; and waves greater than 3.1 m (10 feet) for 8% of the time. These computed wave values indicate the general wave climate for each lake; the close correspondence between seasonal changes in wind speed and wave heights is evident.

Wave energy at the shoreline varies geographically depending on fetch distances and the orientation of the coast with respect to the direction of wave approach. For example, with winds out of the southwest crossing the long axes of Lakes Erie and Ontario, low energy conditions could be expected on the sheltered southwest coasts with high energy levels on the northeast coasts.

Ice

Ice plays an important role in reducing the ability of winds to generate waves or in dampening existing waves during winter months, a time when wind speeds are relatively high. Air temperature data (Fig. 5) indicates that all parts of the Great Lakes system have mean daily temperatures below freezing for at least two months each year. The actual air temperatures, however, are not the only important factor in ice growth as those lakes with a large water volume can retain heat through the winter months and this effect can delay or prevent ice growth.

Ice forms initially in December in sheltered shallow areas, such as the Bay of Quinte, Lake St. Clair, North Channel, and Thunder Bay. Figure 6 indicates the dates and extent of the maximum ice cover for the major lakes. Only Lake Erie freezes over regularly, although during heavy ice years each of the other

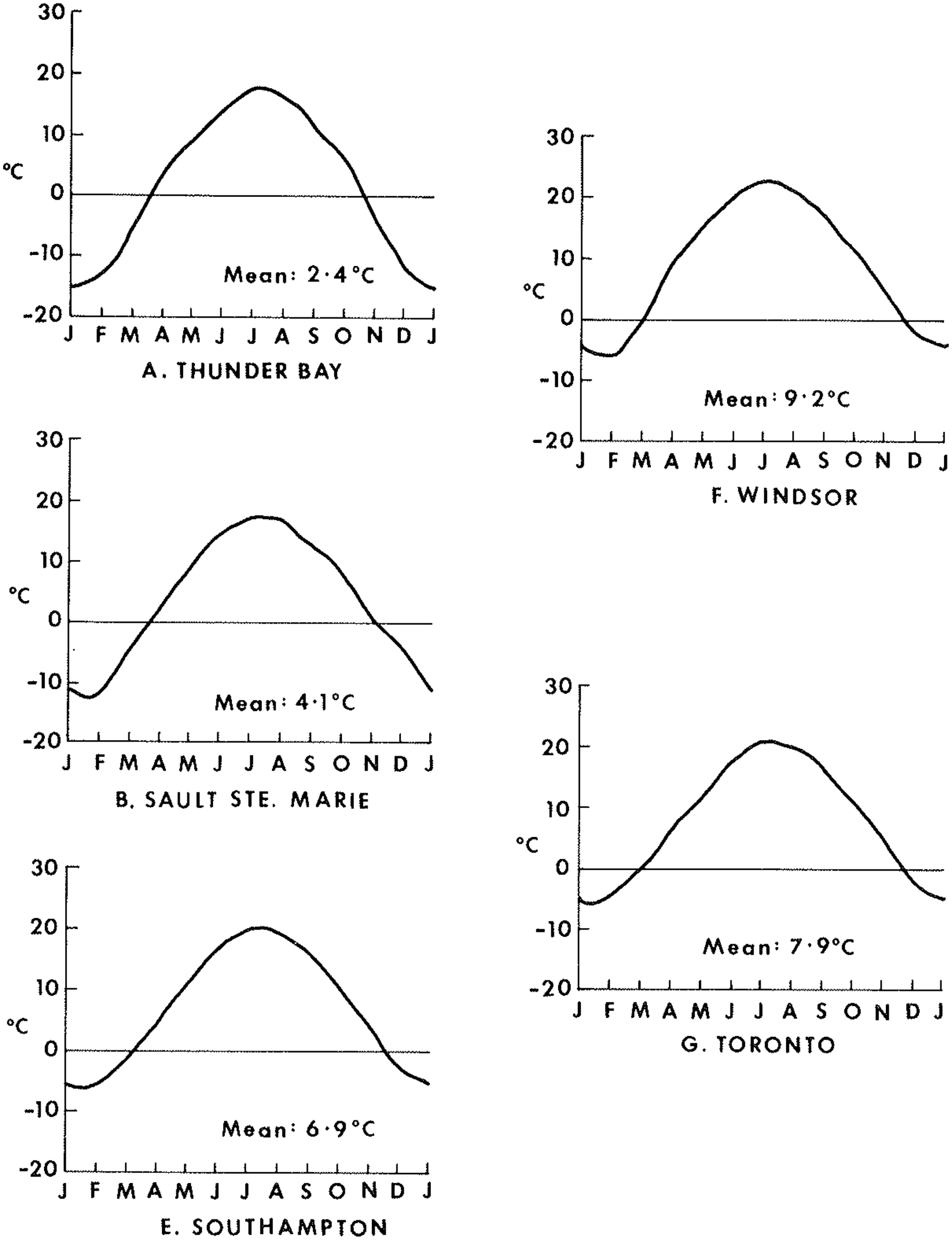


Figure 5. Mean daily air temperatures (Environment Canada, 1973). Stations are located on Figure 2.

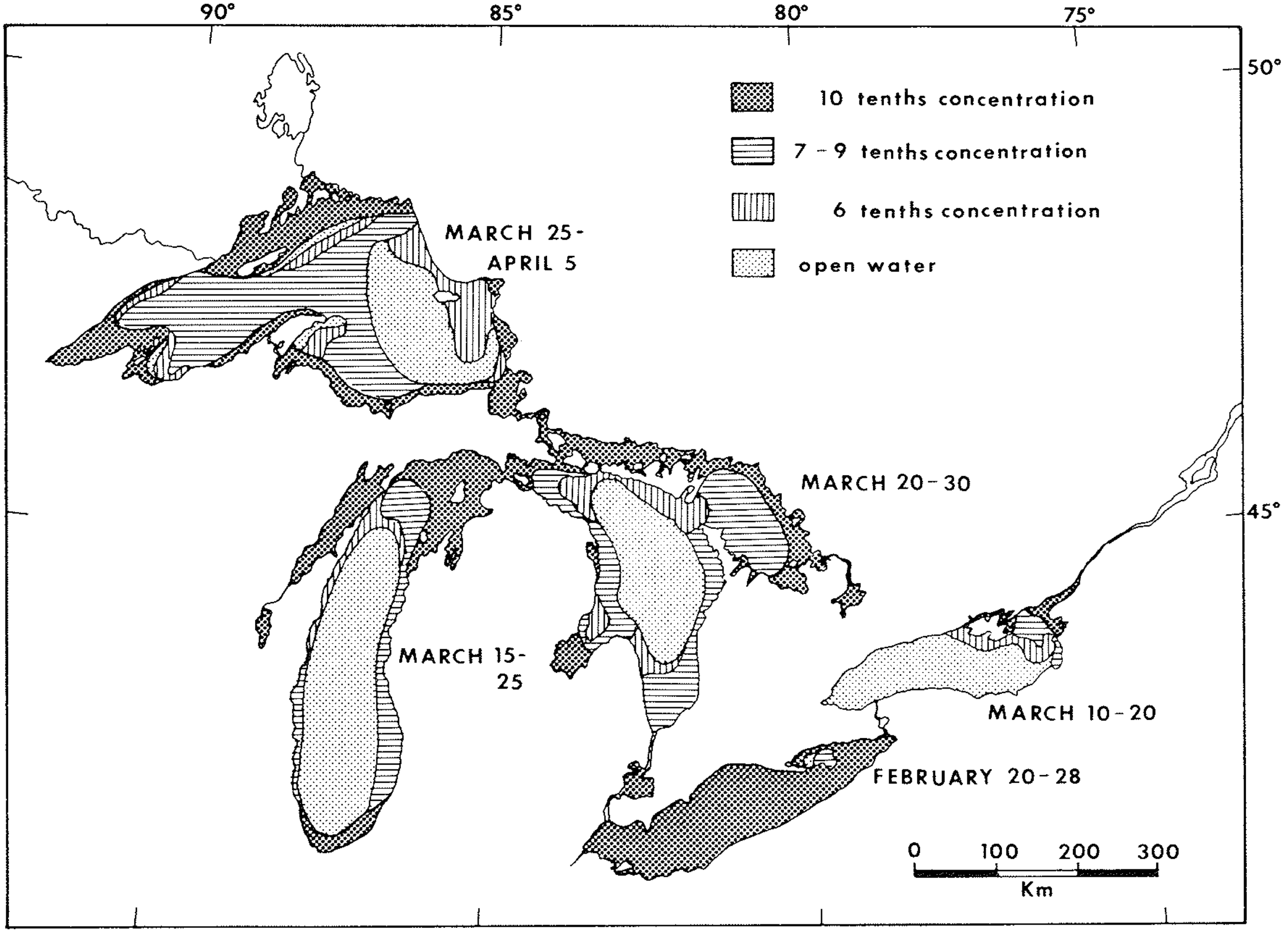


Figure 6. Maximum average ice distribution, with dates of maximum average cover (Rondy, 1976).

Canadian lakes has had a 10/10 cover for short periods of time. Although Lake Ontario has frozen over twice in the last century, the normal maximum ice cover is 60% and the average is only 15-20%. Lakes Huron and Superior usually have a 40-50% cover, with occasional periods of 80-100% cover.

An indication of ice cover duration in the shore zone is given in Figure 7. All areas are affected by ice from January to the end of March. Even though the lake surface may be clear of ice or have only a low percentage ice cover, ice is usually present in the shore zone. This ice effectively protects the shore from any wave action (Photo 1).

Photo 1. Ice foot on the south shore of Lake Ontario near Burlington (January 1968). The ice foot is approximately 1 m high and protects the entire shore zone.

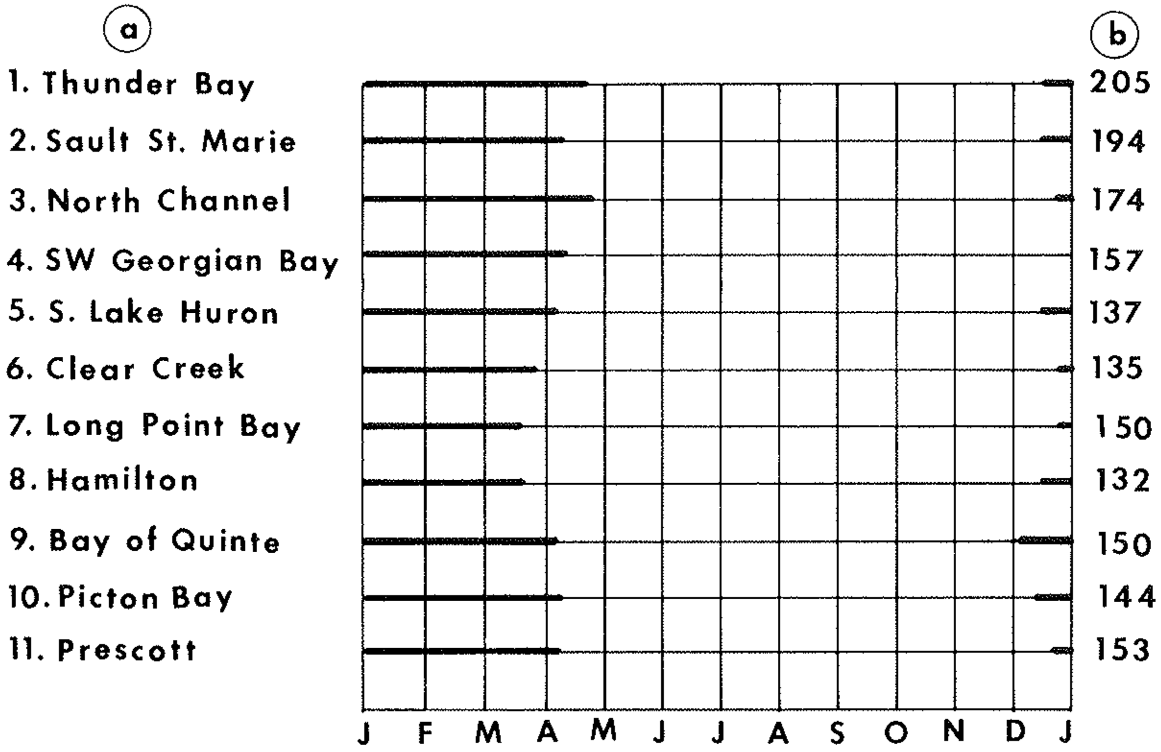


Figure 7. (a) Duration of ice on beaches or in nearshore zones during average year (data from Allen, 1964). (b) Number of days/year with frost (from Environment Canada, 1973). Stations are located on Figure 2, p. 21.

Water Levels

The Great Lakes system can be compared to a large river in which natural dams have created lakes that interrupt the normal flow of water (see Fig. 1). The level of the water in each lake varies continuously (seasonally and annually) depending on the amount of water that enters each lake (from rainfall, rivers, and from the lake above) and the amount that leaves (by outflow and evaporation). Superimposed on the natural balance of these factors is man's regulation of lake levels by controlling outflow volumes. In addition, short-term (hourly and daily) fluctuations within lakes can result from wind action piling water against the shoreline.

Long-period and seasonal variations are indicated in Figure 8 and Table 4. The variability for Lakes Erie and Ontario is greater than for Lakes Superior and Michigan/Huron because the two lower lakes are affected by the cumulative effects of the outflow from the upper lakes. Lake levels are generally at a maximum in spring and early summer, and lowest in early winter (Environment Canada, 1975).

TABLE 4. (a) Monthly lake level extremes, and
(b) annual variability of lake levels.

	Superior	Huron	Lake Clair	Erie	Ontario
(a) Monthly Lake Elevation					
Maximum	183.5 m	177.4	175.5	174.6	75.6
1860-1970 Average	183.0	176.3	174.7	173.8	74.6
Minimum	182.3	175.4	173.1	173.0	73.6
(b) Annual Lake Level Variability					
Maximum	0.58 m	0.67	1.01	0.82	1.07
1860-1970 Average	0.34	0.34	0.49	0.46	0.55
Minimum	0.12	0.03	0.27	0.15	0.21

Source: Great Lakes Basin
Commission, 1975a

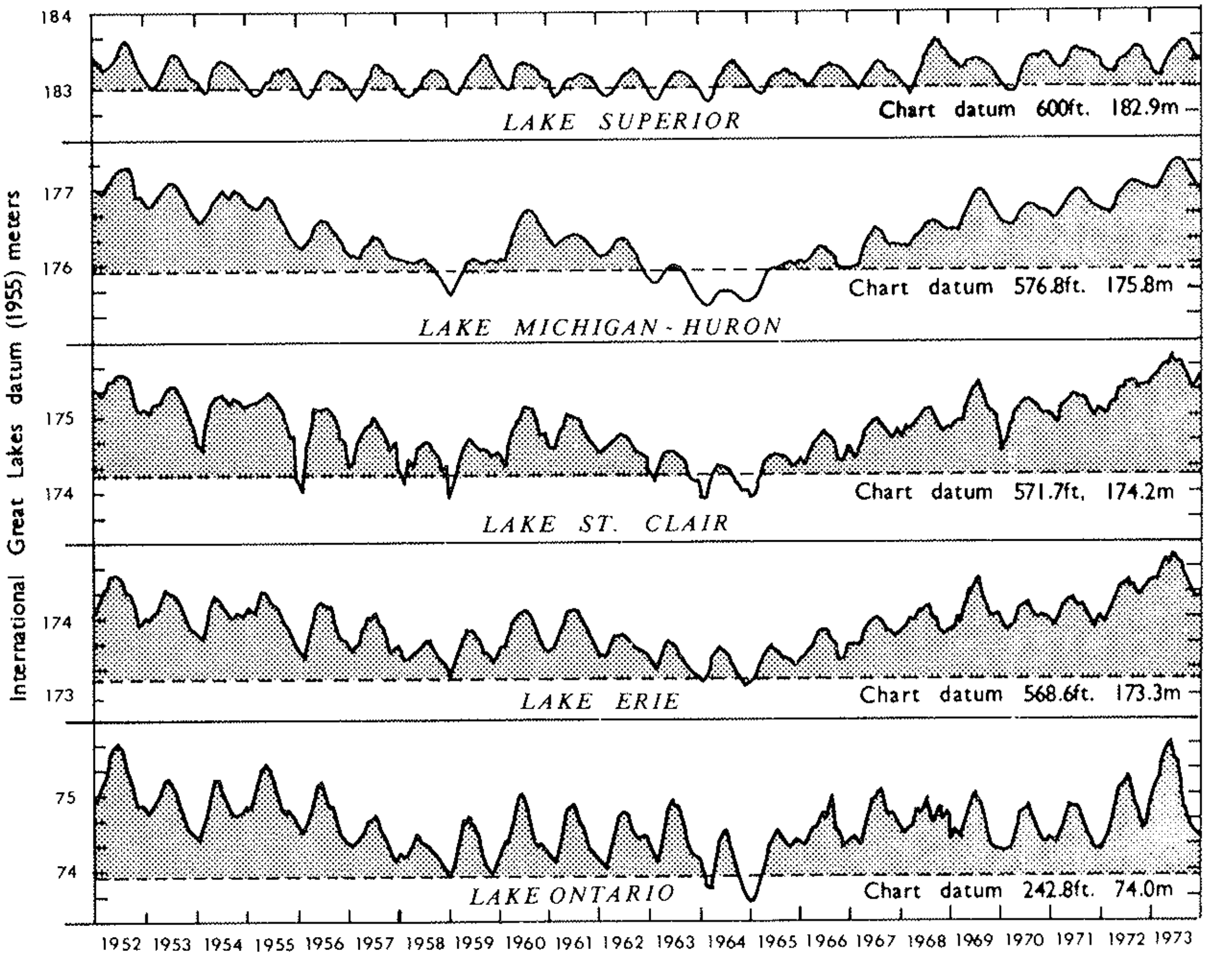


Figure 8. Hydrographs of mean monthly Great Lakes water levels, 1952-1973 (after Boulden, 1975).

Short-term fluctuations caused by meteorological effects are usually small (<1 m) but can be as much as 3 m in extreme cases. A storm in Lake Erie during February 1967 caused the water level at Buffalo to rise 2.4 m above the normal lake level; at the same time, the level dropped to 1.7 m below normal at the opposite end of the lake at Toledo (Clemens, 1976). This set-up and set-down led to a seiche effect (q.v.) of alternating high and low water levels at Buffalo and Toledo. Figure 9 illustrates a similar situation as an equilibrium condition was restored following a major storm surge.

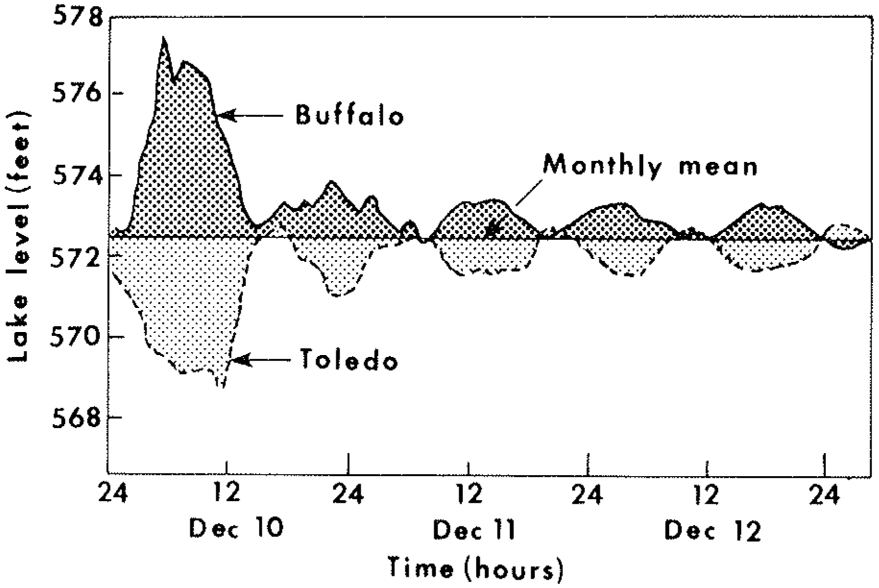


Figure 9. Water levels at Buffalo and Toledo, Lake Erie, showing storm surge followed by seiche (q.v.) (from Ragotzkie, 1974).

3.3 SHORELINE FACTORS

The form of the shore zone and the types of sediment that occur there result from the combined nature of the coastal processes and the local geology. The important geological shoreline factors in this region are primarily the large-scale bedrock distribution pattern, relief and the sediment supply. In this section these major factors are considered briefly and a summary of the general coastal geomorphology is presented.

Geology

The Great Lakes region can be divided broadly into two geological units: (a) the Canadian Shield (Fig. 10), and (b) the less resistant sedimentary rocks to the south. The Shield rocks are very resistant to erosion and where they outcrop in the Sault Ste. Marie area and at the eastern end of Lake Ontario they act as bedrock dams that form Lakes Superior and Ontario. The less resistant rocks that outcrop to the south of the Shield have been folded into large basins that contain all of the lakes except for Superior. Lakes Michigan, Huron and Erie are at approximately

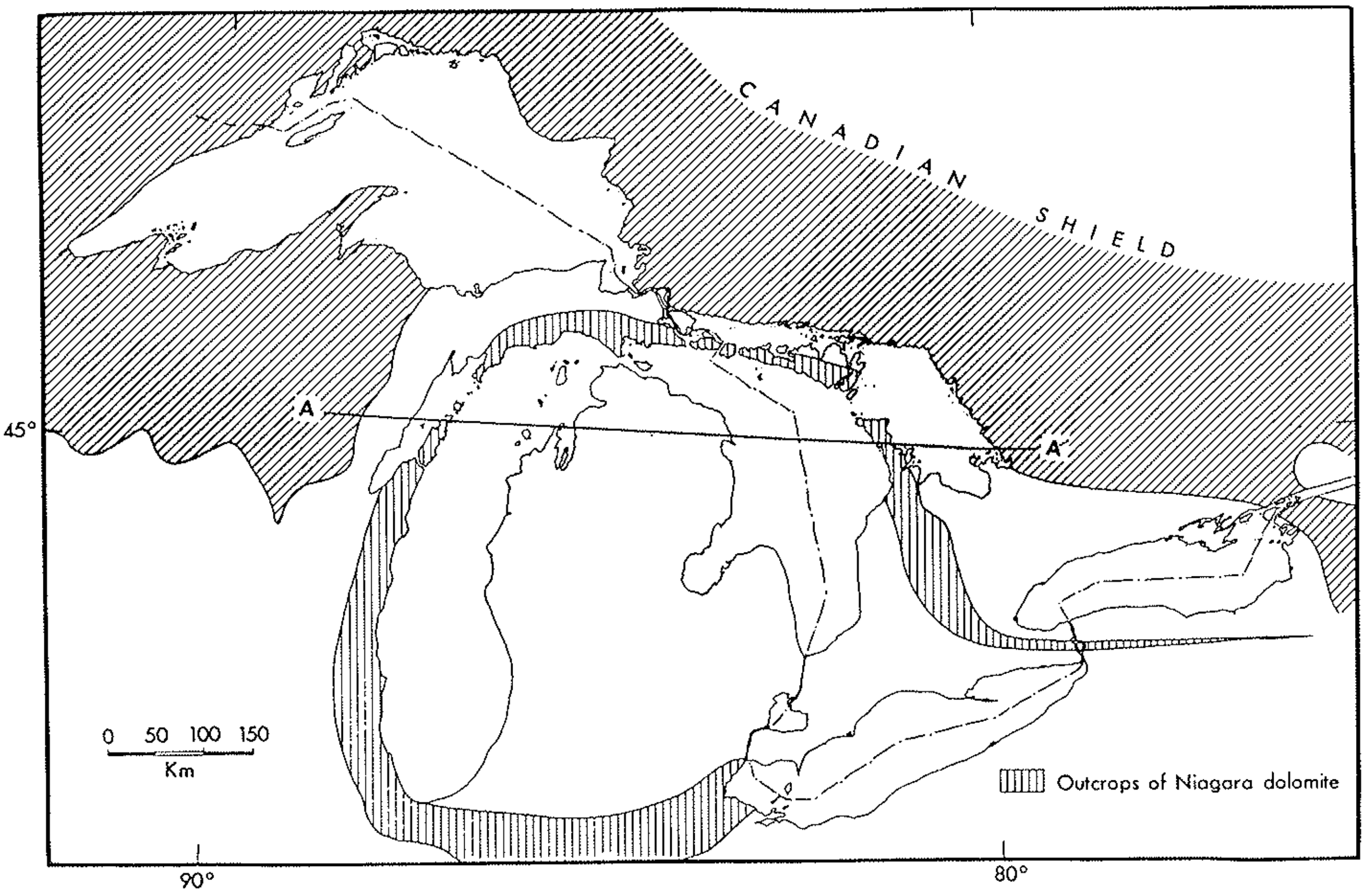


Figure 10. Simplified geology of the Great Lakes region to show the distribution of Shield rocks and the Niagara dolomite outcrops. The cross section A-A' is given in Figure 11.

the same elevation (Fig. 1), and Erie is separated from Ontario by a resistant limestone outcrop, the Niagara Escarpment, which acts as a natural dam. The Niagara Escarpment has formed as the result of erosion of adjacent less resistant rocks (Fig. 11), and is a major feature of the geology and relief. From the Niagara Peninsula the Escarpment extends north and west through the Bruce Peninsula and Manitoulin Island to separate North Channel and Georgian Bay from Lake Huron. From Manitoulin, it then trends west and then south to form the northern and western margins of Lake Michigan.

The basins now occupied by the Great Lakes were formed as ice sheets scoured along pre-existing valleys during the advances and retreats of the Pleistocene glaciation. The lakes began to form at the margins of the retreating ice, approximately 15,000 years ago, and by 2,000 years ago had achieved their present form (Hough, 1968).

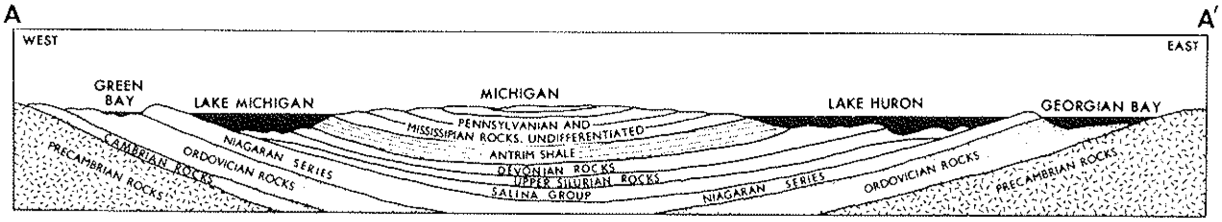


Figure 11. Cross section across the Michigan Basin (located on Fig. 10). The escarpment formed by the Niagara dolomite separates Georgian Bay from Lake Huron (the Bruce Peninsula) and Green Bay from Lake Michigan (the Door Peninsula) (from Pincus, 1962).

South of the Shield, the glacial ice deposited large volumes of sediments that in most areas cover the bedrock outcrops. This mantle of unconsolidated sediments was deposited not only by the ice itself, but also by lakes and rivers associated with the constantly changing landscape. The character of these sediments varies greatly and includes all sizes of material from mud to boulders.

Most of the Great Lakes region is characterized by low relief, with a maximum elevation of 680 m near the northwest coast of Lake Superior. Elsewhere local relief is generally less than 50 m above lake level except where the Niagara Escarpment is adjacent to the shore.

Coastal Geomorphology

The local character of the shore zone varies considerably depending on the shoreline factors and the coastal processes. One major characteristic of the entire system is the absence of astronomical tides, other than this the coastal processes are the same as those that operate on open ocean coasts. The lakes are relatively small in area, so fetch (q.v.) distances are limited and, therefore, wave-energy levels at the shoreline are relatively low.

The supply of sediments to the coasts of Lake Superior, North Channel, Georgian Bay and the Bruce Peninsula is limited due to the resistant rocks and to the general absence of overlying unconsolidated sediments. In these areas, beaches are frequently absent and are only well-developed in embayments where there is a local source or where sediment that is moved alongshore can be trapped. These northern and western regions, therefore, tend to be characterized by rocky shorelines with some sections of cliffed coasts.

In the lower Great Lakes bedrock outcrops are rare and the shore is composed for the most part either of cliffs that have been cut into unconsolidated sediments or of sand beach systems. The cliffs are generally low (< 10 m), but rise locally to as much as 100 m. As this part of the lakes region has shorelines of sand or easily erodible cliffs, rates of change can be rapid. Sand systems can be drastically altered by the effects of large storms and cliff erosion rates in excess of 1 m/year are not uncommon in some sections. This is in marked contrast to the northern and western areas where changes on the rocky coasts are imperceptibly slow.

3.4 SHIPPING TRAFFIC PATTERNS AND DISTRIBUTION OF SHORE-ZONE OIL FACILITIES

The two sources for potential oil spills are accidents on the lakes or accidents on land. As the Great Lakes system is a major shipping artery for the U.S. and Canada, spills on the waters of the lakes must be expected. Land-based oil-handling facilities can be either refining plants or local fuel depots.

Shipping

The volume of ship traffic in the Canadian Great Lakes varies considerably from one part of the system to another. The largest volume of shipping in terms of cargo is concentrated on the waters of Lake Huron, the St. Clair-Detroit waterway, and Lake Erie (Table 5). Information on the volume of cargo traffic

TABLE 5. Total Traffic by Volume (Million Tons)

	1960	1970	Projected 1995
Lake Huron	126.0	141.3	-
Lake Erie	114.9	142.7	-
Detroit River	111.2	125.6	203.4
St. Clair River	97.2	109.2	178.7
St. Mary's River	86.6	81.1	156.0
Lake Superior	81.8	78.8	-
Welland Canal	21.7	45.7	82.3
Lake Ontario	22.1	45.1	-
St. Lawrence River	12.0	30.9	77.7

Source: Great Lakes Basin
Commission, 1975b

can be used as one factor in determining high-risk spill areas, as the likelihood of shipping accidents increases in proportion to shipping density.

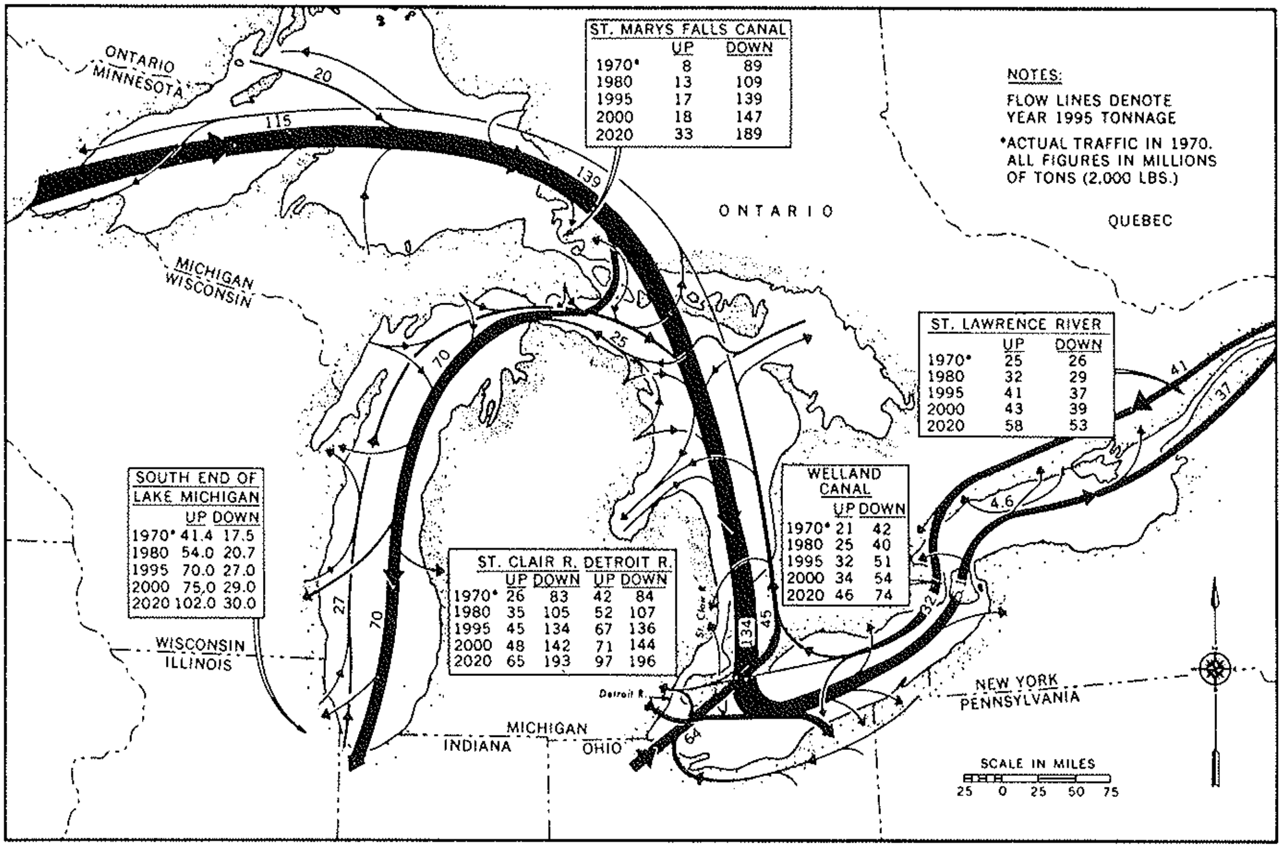
In terms of traffic through man-made channels the St. Mary's River has the largest number of vessel transits (Table 6). This waterway ranks fourth behind Lake Huron, Lake Erie and the St. Clair-Detroit waterway in terms of traffic density (Fig. 12).

An important aspect in spill-risk analysis of shipping is the identification of the major petroleum-handling ports in the Great Lakes. When this factor alone is considered the St. Clair-Detroit region has the highest volume of oil carried by ship and ranks above the Toronto-Buffalo area (Table 7).

TABLE 6. Total Traffic Through Man-Made Channels
(Number of Vessels)

	1960	1970	Projected 1980
Sault Ste. Marie	22,151	12,712	19,200
Welland Canal	7,536	6,768	6,900
St. Lawrence Seaway	6,869	5,936	7,100

Source: Great Lakes Basin Commission, 1975b



ST. MARYS FALLS CANAL

	UP	DOWN
1970*	8	89
1980	13	109
1995	17	139
2000	18	147
2020	33	189

NOTES:
FLOW LINES DENOTE YEAR 1995 TONNAGE
*ACTUAL TRAFFIC IN 1970. ALL FIGURES IN MILLIONS OF TONS (2,000 LBS.)

ST. LAWRENCE RIVER

	UP	DOWN
1970*	25	26
1980	32	29
1995	41	37
2000	43	39
2020	58	53

SOUTH END OF LAKE MICHIGAN

	UP	DOWN
1970*	41.4	17.5
1980	54.0	20.7
1995	70.0	27.0
2000	75,0	29.0
2020	102.0	30.0

WELLAND CANAL

	UP	DOWN
1970*	21	42
1980	25	40
1995	32	51
2000	34	54
2020	46	74

	ST. CLAIR R.		DETROIT R.	
	UP	DOWN	UP	DOWN
1970*	26	83	42	84
1980	35	105	52	107
1995	45	134	67	136
2000	48	142	71	144
2020	65	193	97	196

Figure 12. Projected total traffic flow, 1995 (from Great Lakes Basin Commission, 1975b).

TABLE 7. Major Ports (1970)-Shipping and Receiving (Millions of Tons)

A. PETROLEUM	
Sarnia	2.4
Toronto	1.1
Hamilton	0.7
Clarkson	0.6
Buffalo	0.6
Sault Ste. Marie	0.4
Windsor	0.4
Thunder Bay	0.4
Detroit	0.4

Source: Great Lakes Basin Commission, 1975b

B. ALL CARGO	
Chicago	41.9
Duluth-Superior	41.4
Detroit	30.0
Toledo	25.2
Thunder Bay	20.9
Cleveland	20.9
Buffalo	13.7
Hamilton	12.7
Sarnia	6.3
Toronto	5.2
Sault Ste. Marie	4.6
Clarkson	2.3
FOR COMPARISON	
New York	195.1
New Orleans	144.2
Vancouver	30.8
Montreal	22.0

The size of the Great Lakes tankers is relatively small when compared to ocean-going tankers, and only 33% of those registered in the Great Lakes have a capacity greater than 5,000 tons. This size restriction is due to the draught limitations in many of the harbours or to the size of locks in the man-made waterways (Great Lakes Basin Commission, 1975b).

On a regional basis with traffic density as the primary criteria, the high risk areas for on-lake spills can be ranked as: (i) Lake Huron, (ii) the St. Clair-Detroit waterway, (iii) St. Mary's River, (iv) Lake Erie, and (v) western Lake Ontario. Superimposed on this initial ranking are factors related to navigation. The risks of an accident increase greatly in sections of narrow, winding, rocky channels when compared to open lake or to narrow, straight channels without rocky outcrops. Using these additional navigation factors, the St. Mary's River area and the St. Lawrence River, particularly the Thousand Islands section, rank high in terms of potential accidents and spills.

Shore-Zone Facilities

Oil is imported into the Canadian Great Lakes region primarily by pipeline. The large oil-handling and oil refining facilities on the lakes' shores are associated with this pipeline and are concentrated in Sarnia, eastern Lake Erie, and western Lake Ontario (Oilweek, 1978a) (Tables 7 and 8). These areas are the high-risk onshore locations, particularly if the facilities are associated with the major petroleum ports.

TABLE 8. Ontario Refinery Capacities (1978)
(in barrels per day)

	Crude Capacity	No. of Refineries
Sarnia	469,000	4
Oakville	123,000	2
Nanticoke	95,000	1
Clarkson	79,100	1
Port Credit	48,000	1

Source: *Oilweek*, 1978b

Onshore fuel depots are found in all of the harbours in the Great Lakes system. The spill risk is high for all ports whether they are major shipping centres or local harbours with relatively little traffic; therefore, ranking of specific locations is not practical.

PART 4 - COASTAL ENVIRONMENTS OF THE CANADIAN GREAT LAKES

SYNOPSIS

The Great Lakes system has been divided into 6 regions (Fig. 13) that are related to the geography of the lake basins. Each lake system is treated as a single region except for Lake Huron which is divided into two regions due to the separation of North Channel and Georgian Bay from the main body of the lake by the Niagara Escarpment. The coastal processes and geology of each region are reviewed.

The regions have been subdivided into 32 coastal environments on the basis of shore-zone sediment transport systems. Each of the coastal environments is described and the primary characteristics identified. The major process factors and morphological characteristics for the coastal environments within each region are summarized as a series of tables and then summarized at the regional level in the final section.

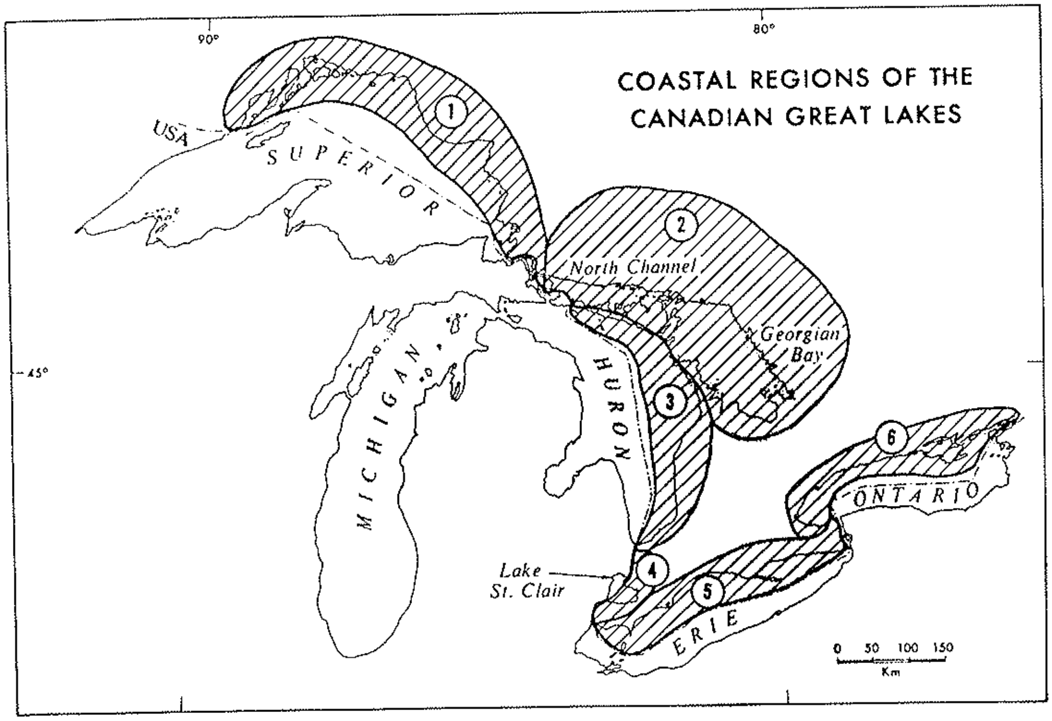


Figure 13. Division of the coast of the Canadian Great Lakes into six regions.

4.1 LAKE SUPERIOR REGION

Summary

This region lies astride the resistant Canadian Shield and the coast is characterized by low, resistant rock outcrops with few areas of sediment accumulation. The northwest and southeast sections of the coast have complex shorelines due to erosion of relatively unresistant outcrops that has produced a series of large, sheltered embayments. The remaining coastline is relatively straight with only small bays and headlands. Although backshore relief is high in many areas, there are few sections of cliffed coast in the region. The shore-zone character is primarily that of a low, rocky coast with occasional sections of cliffs at headlands and with beaches in embayments, usually adjacent to river mouths. Beaches are scarce due to the resistant nature of the rock outcrops and to the general lack of surficial sediments.

The exposed coasts are high wave-energy environments; maximum fetches are in the order of 500 km. On these coasts, pebble-cobble beaches have well-developed storm ridges and log debris lines over 4 m above lake level are evident at many locations. Along the north and east coasts, transport systems converge at the heads of large reentrants (Marathon, Michipicoten Harbour and Agawa Bay), but sediment transport along the adjacent shores is interrupted by the presence of numerous small bays and headlands. In the sheltered embayments of the northwest and southeast coasts the transport systems are very localized. Within the embayments, the shore-zone character is very mixed, with rock outcrops, sand, pebble, cobble and boulder beaches and marshes. Although sediments are more common in the shore zone of the embayments (particularly in the southeast) than on the exposed coasts, the supply of material is nevertheless scarce. Throughout the region rates of shoreline change are very slow; on exposed coasts because of the resistant rock outcrops and in sheltered areas due to the low levels of wave energy.

4.1.1 Coastal Processes and Geology

Winds

The prevailing wind direction over Lake Superior is from the west and northwest (Fig. 3, p. 22). Superimposed on this basic pattern is a secondary seasonal variation with winds out of the east during April to August in western areas (see Thunder Bay) and during September to January in eastern areas (see Sault Ste. Marie: Table 3, p. 24). Wind velocity maxima occur between November and May (Fig. 3).

Waves

Maximum fetch distances on the north and east coasts of the lake vary between 300 and 500 km. Due to the dominance of winds out of the westerly quadrant there is a distinct increase in wave heights towards the east, particularly during winter months when wind velocities are at a maximum (Table 9). The seasonal variability in wave heights is clearly evident in Figure 4 (p. 26) which indicates that waves greater than 0.9 m occur for less than 5% of the time in summer, but for approximately 40-50% of the time in winter months.

TABLE 9. Measured Median Significant Wave Height (m) 1965-1967 (from Ploeg, 1971)

Station	Sept. 15	Sept. 15-30	Oct. 1-31	Nov. 1-End	Mean
North Superior (West Coast)	0.3	0.6	0.5	0.7	0.4
Battle Island (North Coast)	0.4	0.6	0.7	0.7	0.5
Eagle Harbour (South Coast)	0.5	1.1	0.9	1.1	0.6
Grand Marais (Southeast Coast)	0.4	0.8	1.0	0.8	0.6

Ice

The formation of ice in sheltered areas, particularly Thunder Bay, Black Bay, Nipigon Bay, and Whitefish Bay, begins in early December (Marshall, 1967). The maximum lake-ice cover occurs in mid-March and varies between 40 and 60% (Fig. 6, p. 29), but may briefly reach 100% at times. The shore zone ice cover can persist for up to 150 days each year (Rondy, 1976), and persists in the sheltered bays until the end of April or even early May (Fig. 7,

p. 31). The lake ice is generally about 1 m thick and the actual distribution is controlled largely by the action of storm winds that continuously break up the ice cover.

Water Levels

The water outflow from the lake has been controlled at the Sault since 1921. Seasonal variations in water levels are usually in the order of 0.3 m (Fig. 8, p. 33), but maximum and minimum monthly variations of +0.5 and -0.7 from the long-term average have been recorded (Table 4, p. 32).

Geology and Coastal Transport Systems

The entire Canadian coastal zone of Lake Superior is comprised of ancient, resistant, igneous, metamorphic and sedimentary rocks of the Shield that have been subjected to folding and faulting. The north coast to the west of Terrace Bay is comprised predominantly of igneous, sedimentary and metasedimentary rocks, whereas, a complex system of metamorphic rocks dominate the coast to the east (Sloss, *et al.*, 1960). This two-fold division of the north coast is particularly reflected in the greater complexity of the coastline in the western section which is in marked contrast to the relatively straight coastline in the eastern section. Thunder, Black and Nipigon Bays are separated from the main body of the lake by resistant rocks that have a northeast-southwest structural trend.

In the Sault Ste. Marie area, south of Batchawana, resistant sedimentary rocks of Cambrian age act as a natural dam that has been cut by the St. Mary's River to provide the narrow outflow for the lake. These sedimentary rocks rest on older, igneous Shield rocks that also outcrop along this section of the Superior coast. The greater shoreline complexity in Whitefish Bay again reflects a geological change similar to that found in the region to the west of Terrace Bay, with resistant Shield rocks forming headlands and less resistant sedimentary rocks having been eroded to form shallow embayments.

Relief in the coastal zone of the region is generally low, less than 100 m above lake level. However, the shore has a rugged character in many sections due to the absence of a sediment cover on the Shield rocks. Glacial or old lake sediments are largely confined to river valleys and low-lying embayments. Due to the scarcity of surficial sediments over much of the coastal region, little material has been supplied to the shore zone for reworking by wave action. Beach and nearshore sediments are restricted largely to the areas adjacent to river mouths or to low-lying embayments where unconsolidated sediments are eroded by wave action.

Within the embayments of the northwest and southeast coasts, the shore-zone transport systems are very localized, depending primarily on shoreline orientation. On the straighter, exposed coasts the form of the coast has produced three large reentrants that have formed natural transport systems. In each case, the large-scale angular form of the reentrant has led to an easterly transport on the south-facing coast and to a northerly transport on the west-facing (or northwest-facing) coast (Fig. 14). The subdivision of this region is based on the overall transport systems; the two adjacent similar systems of the northeast coast are treated as a

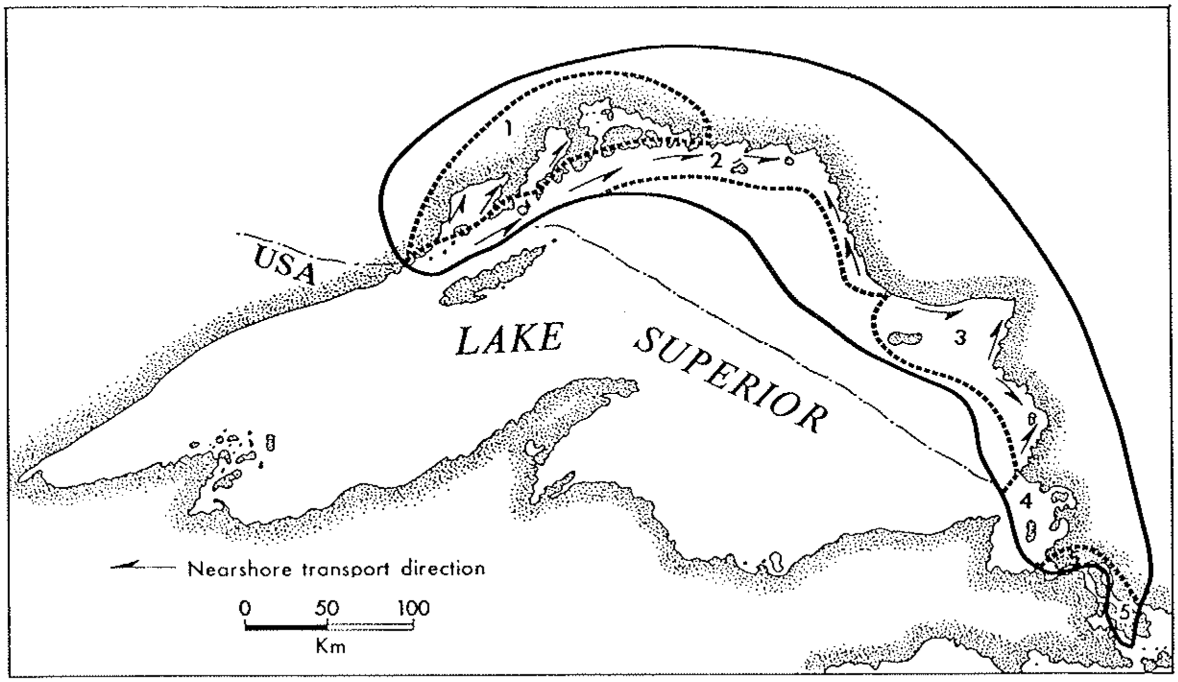


Figure 14. Coastal environments and primary shore-zone transport directions - Lake Superior region.

single environment and the St. Mary's River section is treated separately as this is a riverine unit. Each of the subdivisions outlined in Figure 14 is described separately in the text and the main features of each subdivision are summarized in Table 10.

4.1.2 Coastal Environments of Lake Superior

1. Northwest Bays

The three large embayments of Thunder Bay, Black Bay and Nipigon Bay are separated from the main body of Lake Superior by a series of islands and peninsulas that outcrop along a northeast-southwest structural trend. Thunder and Black Bays are separated by the Sibley Peninsula that is a high, resistant outcrop with a steep, west-facing scarp which rises inland to 200 m above lake level. The rocks of the Sibley Peninsula dip towards the east to produce a low shore on the Black Bay coast. A low peninsula of

TABLE 10. COASTAL ENVIRONMENTS OF LAKE SUPERIOR

		COASTAL ZONE			
SUBDIVISION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	BEACH CHARACTER	FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
1. Northwest Bays	Resistant Shield rocks eroded to form 3 large bays: backshore relief high in some areas	Upland coasts of low rocky shores with many bays and islands: few beaches or marshes: large delta at mouth of River Kaministikwia	Absent or narrow, predominantly poorly sorted, coarse sediments	Low energy coasts: fetch <50 km: shore-zone ice up to 5 months/year	Sediments generally very scarce: some local accumulations adjacent to rivers: local transport systems
2. North Coast	Resistant Shield rocks outcrop in shore zone: southwest-northeast structural trends in western areas form narrow peninsulas, islands and bays; elsewhere high backshore relief (up to 100 m) in many sections	Relatively straight coasts, except in western areas, with predominantly rocky shore zone but cliffs not common: few beaches	Absent or narrow, restricted to bays: sediments generally pebble-cobble-boulder: where present, beaches have high storm ridge and log debris lines	Exposed, high energy coast: fetch distances up to 500 km: some local sheltering due to headlands and bays: shore-zone ice up to 5 months/year	Sediments very scarce: transport directions converge near Marathon but system interrupted by numerous small bays and headlands that act as local traps
3. Northeast Coast	Resistant Shield rocks outcrop in shore zone: high backshore relief in many sections	Relatively straight coasts, but few cliffs despite high backshore relief: few beaches, predominantly rocky shore zone	Absent or narrow in most areas: beaches have developed at heads of reentrants and, where present, usually have coarse sediments with high storm ridge and log debris lines	Exposed, high energy coast: maximum fetch up to 500 km: shore-zone ice up to 5 months/year	Sediments very scarce: two separate transport systems converge in Michipicoten and Agawa Bays: transport discontinuous due to numerous small headlands and bays
4. Whitefish Bay	Resistant Shield rocks and less resistant sedimentary rocks outcrop in shore zone: less resistant rocks eroded to form large bays: generally low relief	Indented coast with rock headlands and large bays: some beach and marsh development in bays: delta at Goulais River	Absent or narrow on exposed sections: wide sand or pebble-cobble beach in some bays: sand beaches backed by low dunes and have parallel bars in nearshore zone	Some exposed headlands but predominantly sheltered, low energy coasts with fetches <50 km: shore-zone ice up to 5 months/year	Generally scarce but locally abundant in some sections: local transport systems
5. St. Mary's River	Resistant Shield and sedimentary rocks outcrop in shore zone: low relief	Riverine coast with channels, islands and linear lakes: mixed character of low, rocky coast or narrow coarse-sediment beaches with extensive marshes in shallow areas	Beaches narrow and predominantly poorly-sorted sand to boulder size sediments	Very low energy levels: predominantly riverine environment: shore-zone ice up to 5 months/year	Sediments scarce: general transport direction follows river channels into Lake Huron

resistant rocks mantled by clays and sands separates Black and Nipigon Bays. When compared to other sections of Lake Superior, this subdivision has a complex shoreline that has resulted from the folding of metasedimentary and sedimentary rocks.

Each of the three bays is a sheltered wave-energy environment with Nipigon Bay being the most protected due to a continuous chain of islands across the southern margin of the embayment. Although Thunder Bay is more open to the lake than the two other embayments, it is protected offshore by Isle Royale. The coasts of the bays are low wave-energy environments with maximum fetches of less than 50 km. Shore-zone ice forms early in December in these sheltered embayments and persists until mid- or late April.

In most sections little sediment is supplied to the shore zone from erosion due to the resistant nature of the rock outcrops. The primary exceptions are the west coast of Thunder Bay, north of the Kaministikwia Delta, the north coast of Black Bay, near Wolf River, and Gravel Bay on the east coast of Nipigon Bay. Each of these major exceptions results from the supply of material to the shore zone from river systems. Other beaches occur locally and are predominantly pebble-cobble sediments, but are restricted in extent due to the limited supply of sediments.

The predominant character of the coast in this subdivision is that of a sheltered, low, resistant, rocky shore zone. Backshore relief is high on the west coast of the Sibley Peninsula, and a few sections of this coast have low cliffs. Elsewhere cliffs are not common and the shore zone is predominantly rock or pebble-cobble sediments. Marshes are common at the mouth of the

Kaministikwia Delta (Burwasser, 1977) and in very sheltered sections where sediments have been supplied to the shore zone (c.f. Photo 8b, p. 60).

2. North Coast

The most westerly section of the north coast of Lake Superior is characterized by northeast-southwest trending resistant ridges. Formed by the erosion of adjacent, less resistant rocks, these ridges of folded sedimentary and intrusive rocks produce a complex series of peninsulas and islands along the coast between the U.S. border and Schreiber Channel (the eastern margin of Nipigon Bay) (Photo 2). To the east of Schreiber Channel, as far as Marathon,

Photo 2. Vertical air photograph near Pigeon River adjacent to the U.S. border. Scale is approximately 1 cm to 1 km (from Pye, 1969).

the coastal zone changes to a less complex shoreline of small bays and headlands. Offshore, the Slate Islands are a group of eight islands formed by the impact of a meteor (B.A.M. Phillips, pers. comm.). The final section of this subdivision from Marathon to La Canadienne Point is a straight coast of predominantly resistant metamorphic rocks.

Although this subdivision includes a long section of coast, it is considered a single unit in terms of the shore-zone processes that generate a west-to-east transport system along the north coast and south-to-north transport along the west-facing section. The actual transport of material within the shore zone is discontinuous due to the numerous small and large embayments and headlands, however, the entire unit forms a single transport system that converges in the area of Ashburton Bay and Marathon.

This subdivision is an exposed, high wave-energy coast with fetches up to 500 km to the southwest. As the prevailing winds are out of the west and southwest, and therefore predominantly offshore in western sections, wave heights increase to the east (Table 9, p. 47). There is a distinct wave-height maximum during autumn, but despite high wind velocities in the spring, wave generation is restricted by the presence of ice. Shore-zone ice is present for up to 5 months each year, and persists longest within the numerous small bays. As on all coasts that border the Canadian Shield, shore-zone sediments are scarce. A few beaches have developed, for example in Neys Provincial Park, adjacent to the Little Pic River (Ontario, 1977a), and these indicate the general shore-zone transport directions shown in Figure 14 (p. 50).

The shore-zone character is predominantly that of an exposed, rocky coast. Although backshore relief is high in some sections, cliffs are not common (Photo 3). Beaches are composed predominantly of pebble, cobble, and boulder sediments and are generally restricted to isolated embayments. Sand beaches, where present, are frequently adjacent to river mouths (B.A.M. Phillips, pers. comm.). In some sections, particularly in the vicinity of Marathon, logs have accumulated to form extensive debris lines along the shoreline at the highest wave-action levels.

3. Northeast Coast

From La Canadienne Point to Mamainse Point the northeast subdivision consists of two large reentrants that are separated

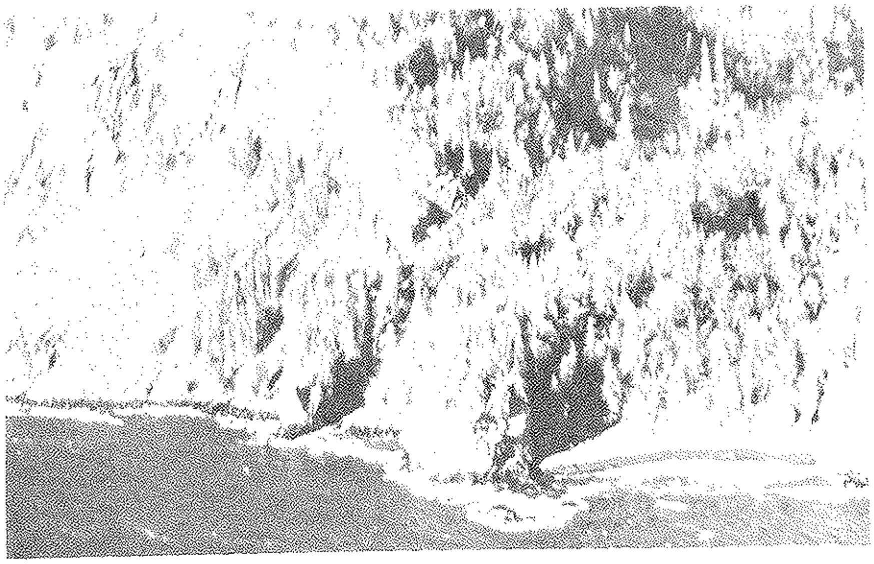


Photo 3. Steep coast, just to the west of Terrace Bay. Although backshore relief is extremely steep, the shore zone is an alternating sequence of low, rock outcrops and small cobble or boulder beaches (29 October 1978)

by the headlands of Cape Gargantua. In both reentrants the transport systems converge at the heads of the embayments (Fig. 14), Michipicoten Bay in the north and Agawa Bay in the south. This section is characterized by a relatively straight coastline of upland relief and resistant Shield rocks.

The coast is exposed to high wave-energy conditions, with a maximum fetch to the west of 500 km. Evidence of the west-to-east increase in wave heights in Lake Superior is given by log debris lines which are over 4 m above (the October 1978) lake level on exposed sections of this coast (Photo 4).

This high energy coast has many sections of high backshore relief but, as elsewhere in Lake Superior, cliffed sections are not common. This subdivision is characterized by predominantly low, resistant, rock outcrops (Photo 5) with occasional short

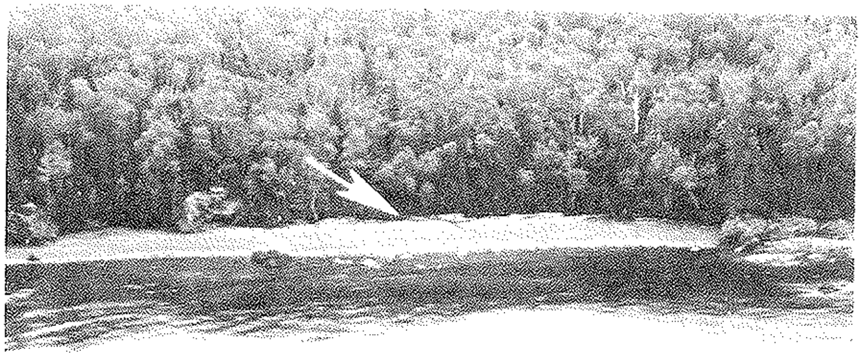


Photo 4. Cobble beach with log debris in Alona Bay, just to the southwest of Montreal River. The log lines (indicated by the arrow) on this section were observed on the ground to be over 4 m above lake level (30 May 1978).

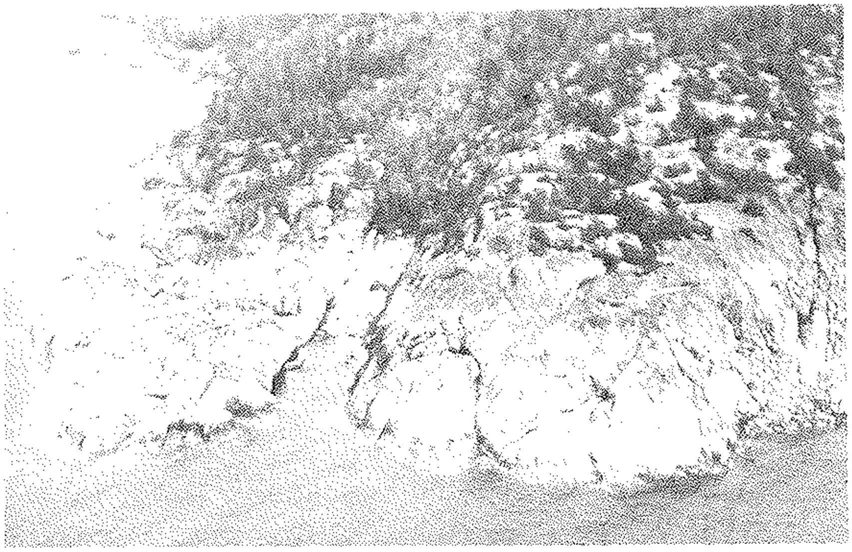


Photo 5. Low, exposed rocky coast near Theane Point (30 May 1978).

sections of cliffs (Photo 6). Beaches are scarce except towards the heads of the reentrants and are generally of pebble-cobble or boulder material. The beaches at the convergence of the transport

Photo 6. Vertical cliffs and rocky shore zone, Agawa Rock (from Pye, 1969).

systems are also adjacent to rivers and several extensive sand beaches with low backshore dunes (up to 5 m in height, Ontario, 1977b) have developed, for example, at Michipicoten Bay, Old Woman Bay, Sand River and Agawa Bay.

4. Whitefish Bay

South of Mamainse Point, to Gros Cap at the entrance to the St. Mary's River, the character of the coastal zone changes to a series of large bays separated by resistant headlands. The bays were formed by erosion of less resistant sedimentary rocks that are of a younger age than the resistant Shield rocks that form the major headlands. By comparison with other sections of the Superior coast, this section has a relative abundance of shorezone sediments and several extensive sand beaches have developed (Photo 7).

Photo 7. Pancake Bay Provincial Park. The wide sand beach is backed by low dunes that rarely exceed elevations greater than 1 m above the spring maximum lake levels (15 October 1978).

The northward extension of the south (U.S.) shore of Lake Superior and the indented nature of the coastline results in considerable sheltering for most of the coasts of this subdivision. Although some sections are open to a fetch of 300 km to the northwest, and therefore exposed to high wave-energy levels, most coasts have fetches less than 50 km and are low wave-energy environments. Within the bays, local sediment transport directions vary considerably depending on local exposure to waves and to shoreline orientation. The nearshore zones of the bays adjacent to beaches in sheltered areas are characterized by shallow depths and by multiple nearshore bars that parallel the shoreline (Mothersill, 1970).

The shore zone of this subdivision has considerable variety, with no one shoreline type predominating. The headlands are generally low, rocky shores with shallow, rock platforms in the nearshore zone. In more sheltered locations, beaches of sand (Photo 7) or mixed sediments (Photo 8) predominate. Within Goulais Bay a small delta has formed at the mouth of the Goulais River.

5. St. Mary's River

The St. Mary's River cuts across a low, natural dam to act as the outlet for Lake Superior into North Channel and then into Lake Huron. The upper reach is a single channel but beyond the rapids and navigation locks at Sault Ste. Marie, the river separates around Sugar Island and St. Joseph Island into a series of channels, islands and lakes. This is a riverine environment in which the long, narrow lakes are relatively shallow and dominated by

Photo 8. (a) Low-energy coast south of Mamainse Point. The shore zone is characterized by sediments that range in size from sand to boulders, with occasional rock outcrops (15 October 1978).

(b) Very sheltered beach near Chippewa Falls, with poorly-sorted sand to boulder sized sediments, logs, and marshes in the shallow nearshore zone (15 October 1978).

riverine rather than by lacustrine processes. St. Joseph Island lies to the south of the Canadian Shield rocks, which dip below less resistant limestones and dolomites. These sedimentary rocks are part of the formation that is associated with the northern rim of the Michigan Basin (Figs. 10 and 11, p. 35 and p. 36). The areas to the north of St. Joseph Island are more resistant Shield or Cambrian sedimentary rocks.

In this riverine environment, shore-zone energy levels are very low. Within the shipping channels the wind-generated waves are supplemented by the effects of waves generated by ships' wakes, but these are also small in size when compared to open-lake waves.

The shore zones of this subdivision are a mixture of low, rock outcrops; narrow, mixed sediment beaches (c.f. Photo 8), and marshes. A few isolated sections of sand beaches occur but these are very restricted in length. Marshes are extensive in many areas, for example, Lake George, where water depths are shallow and where fine-grained sediments have accumulated in the shore zone.

4.2 NORTH CHANNEL - GEORGIAN BAY REGION

Summary

The coastal zone of the North Channel-Georgian Bay has a high degree of uniformity although there is considerable internal variation in the geology and in wave-energy levels. The north and east coasts of the region are an area of resistant Shield rocks, whereas the south coast of North Channel and the Bruce Peninsula coast are part of the Niagara Escarpment that arches through Lake Huron to bisect the lake basin into two separate regions. Although fetch distances in Georgian Bay are much greater (up to 200 km) than in North Channel, there is considerable local sheltering

due to the complex shoreline configuration.

The shore zone throughout the region is dominated by bedrock outcrops. Except in Nottawasaga Bay, beach sediments are very scarce and, where present, are characterized by a thin layer of mixed sand and/or coarse material resting on bedrock. In southeast and northeast Nottawasaga Bay wide beach-dune systems have developed due to the local availability of abundant sand-size sediments. The coasts of southern Georgian Bay have a shallow, nearshore, bedrock platform in many sections. These platforms are several hundred metres wide in places and are strewn with boulder-size sediments.

The shoreline throughout the region is complex, with many islands, headlands and embayments providing a high degree of sheltering to the mainland coast. The only straight sections of shoreline are in Nottawasaga Bay.

4.2.1 Coastal Processes and Geology

Winds

Prevailing wind directions at the two stations in this unit (Gore Bay and Wiarton: Fig. 3, p. 22; Table 3, p. 24) are more variable than in other regions. This may be due in part to local topography and to the location of the stations rather than to a major change in the wind direction patterns. Despite the variability, the predominant wind directions are out of the westerly quadrant and the south. There is a seasonal change, with northerly and westerly winds being more characteristic at Gore Bay from November to April, and southerly or westerly winds prevailing during the summer months. At Wiarton, northerly or westerly winds prevail from January to July and southerly winds from August to December. Wind velocities are at a maximum from October to March (Table 3).

Waves

No wave data are available for this region. North Channel is a very sheltered environment with fetch distances less than

30 km in most areas and reaching a maximum of 100 km on the long axis. Wave-energy levels in Georgian Bay are higher as fetches are in the order of 50 to 200 km. As with all other areas of the Great Lakes, wave heights are at a maximum from November to April.

Ice

Ice begins to form in the sheltered parts of North Channel and northeast Georgian Bay during late November to mid-December. During even the mildest winters, North Channel freezes over completely and Georgian Bay has an 80% ice cover (Richards, 1964) (Fig. 6, p. 29). The ice persists until mid-April and may remain until early May in North Channel and eastern Georgian Bay (Rondy, 1976). Due to warmer air temperatures in southern areas, ice in the shore zone forms later and melts earlier than in North Channel (Fig. 7, p. 31).

Water Levels

The lake level changes in these two water bodies follow those of Lake Huron (Fig. 8, p. 33). Seasonal variations at Collingwood are in the order of 0.3 m with maxima and minima of +1.3 and -0.4 m with respect to lake level.

Geology and Coastal Transport Systems

The unit straddles the southern margin of the Canadian Shield with the resistant Shield rocks forming the north coast of North Channel and the north and east coasts of Georgian Bay (Fig. 10, p. 35). To the south and west, these resistant rocks are overlain by a series of more recent sedimentary rocks that form the eastern margin of the Michigan Basin (Fig. 11, p. 36). North Channel and Georgian Bay were formed by the erosion of relatively unresistant sedimentary rocks that outcrop between the Shield and the Niagara Escarpment. The escarpment separates this region from the main part of Lake Huron and forms the backbone of the Bruce Peninsula and Manitoulin Island, then continues west through Cockburn Island into Michigan (Fig. 10).

The Shield coast of this unit can be subdivided into two distinct regions associated with the rock types. The coast of North Channel between Blind River and Killarney is a series of folded sedimentary, metasedimentary, intrusive and volcanic rocks that trend east-west along the coast and give a complex archipelago shoreline of islands and narrow headlands. Elsewhere the Shield rocks are predominantly metamorphic, similar to those on the northern and eastern coasts of Lake Superior. The sections of coast that have outcropping metamorphic rocks can be further subdivided into: (i) a straight but indented shoreline that is characterized by numerous islands and long, narrow inlets in Georgian Bay, and (ii) a straight shoreline in northwest North Channel. Surficial sediments on the Shield coast are scarce and are confined to valleys and low-lying embayments so that little or no material is present in the shore zone, except adjacent to river exits or at the heads of inlets and shallow bays.

North Manitoulin Island and the Bruce Peninsula are steep coasts of sedimentary rocks associated with the Niagara Escarpment that have been deeply indented to give a complex shoreline with many deep bays. Unconsolidated sediments are more common than on the Shield but are not plentiful, and beach sediments are generally scarce. The major exceptions to this pattern are St. Joseph and Cockburn Islands in the northwest and Nottawasaga Bay in the southeast, where glacial deposits have been eroded by wave and river action to provide sediments to the shore zone.

Relief in the coastal zone is generally low in the regions of Shield rocks, whereas, the steep east- and north-facing Niagara Escarpment rises up to 150 m above lake level, with local backshore relief over 300 m above lake level in southern Nottawasaga Bay.

Shore-zone transport systems are localized throughout the region due to the very irregular shoreline configuration. The only extensive transport system is in Nottawasaga Bay, which has relatively straight shorelines. The subdivision of the region into six coastal environments (Fig. 15) is based primarily on geology and fetch, except for Nottawasaga Bay which has a well-defined transport system. The main characteristics of each subdivision are summarized in Table 11.

4.2.2 Coastal Environments of North Channel and Georgian Bay

1. North Coast of North Channel

This very sheltered section of coast (Fig. 15) is underlain by resistant Shield rocks. Relief is generally low and the coast is characterized by numerous, small, rock islands and reefs. The complexity of the coast increases to the east of Blind River where relatively uniform metamorphic rocks give way to a folded

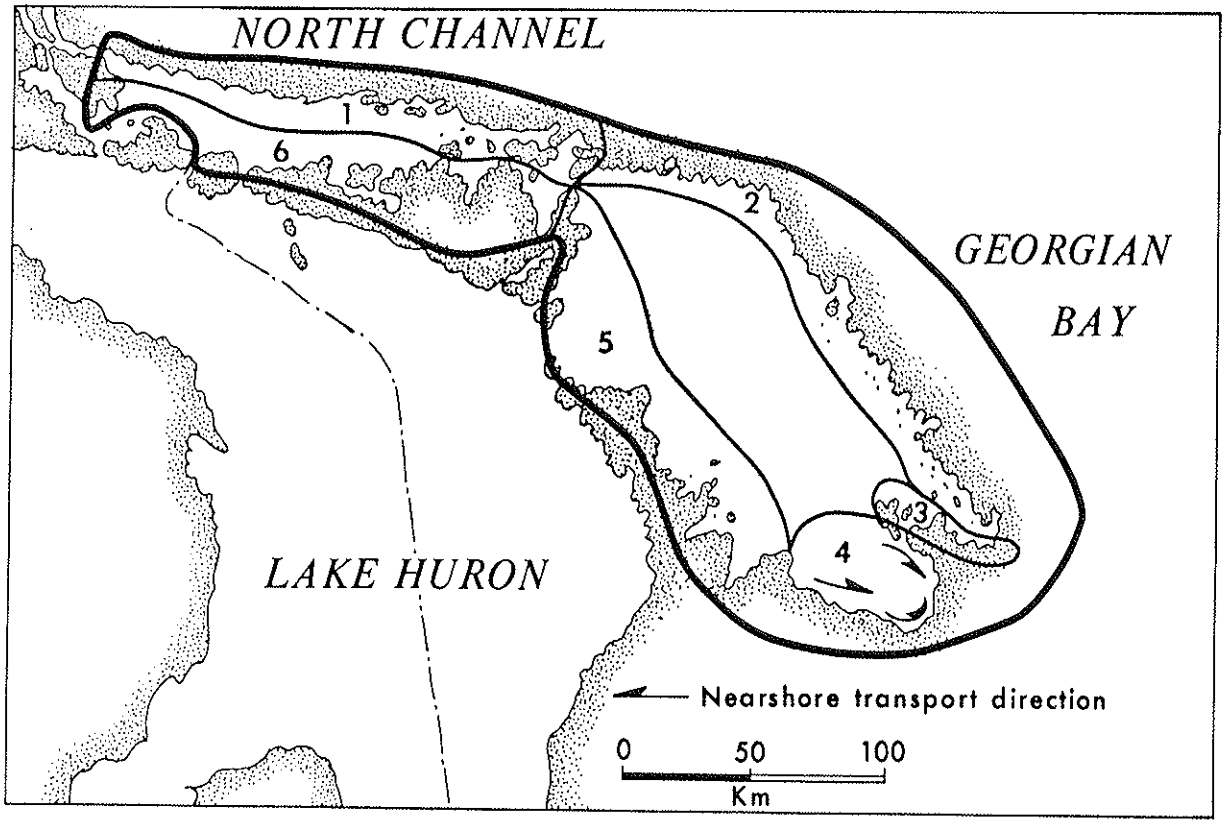


Figure 15. Coastal environments and shore-zone transport directions - North Channel-Georgian Bay region.

sequence of sedimentary, metamorphic, intrusive and volcanic rocks that have structural trends oriented west-east. In extreme eastern sections of this unit (Frazer Bay and Killarney Bay), the structural trends are southwest-northeast and a series of long, narrow islands, headlands and bays characterize the shore zone. The areas of McGregor Bay and Bay of Islands have an extremely complex system of small islands and channels (Robertson and Card, 1972) that is in contrast to the relatively straight coast to the west of Blind River.

Sediments are very scarce throughout this subdivision and low bedrock outcrops characterize the shore zone. Sand and clay

TABLE 11. COASTAL ENVIRONMENTS OF NORTH CHANNEL - GEORGIAN BAY

		COASTAL ZONE			
SUBDIVISION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	BEACH CHARACTER	FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
1. North Coast North Channel	Resistant Shield rocks outcrop in shore zone: low relief	Complex shoreline of bedrock outcrops, islands and bays: some beaches and marshes in bays	Absent or narrow pocket beaches of poorly-sorted sand and coarse sediments	Very sheltered coast, maximum fetch 100 km: very low wave-energy levels: shore-zone ice up to 5 months/year	Sediments generally very scarce, restricted to river mouths and low-lying embayments: local transport systems
2. North and East Georgian Bay	Resistant Shield rocks outcrop in shore zone: low relief	Extremely complex shoreline of bedrock outcrops, islands and bays: few beaches	Absent or narrow pocket beaches of sand and coarse sediments	Fetch distances up to 200 km: outer coasts exposed but considerable local sheltering: shore-zone ice up to 5 months/year	Sediments very scarce, restricted to river mouths and low-lying embayments: local transport systems
3. East Christian Island Peninsula	Relatively resistant sedimentary rocks outcrop in shore zone:. low relief	Irregular shoreline with boulders on shallow, nearshore bedrock platforms	Predominantly cobble-boulder beaches: some pocket sand beaches	Fetch distances <50 km: most of the coast very sheltered, low wave-energy environments: shore-zone ice up to 5 months/year	Sediments scarce, where available predominantly boulders with some sand: local transport systems
4. Nottawasaga Bay	Embayment formed by erosion of less resistant sedimentary rocks that outcrop in a northwest-southeast trend: low relief, maximum cliffs heights are 10 m: extensive barrier beach in the southeast	Large beach-dune system with nearshore bars adjacent to the beach at head of bay: bedrock exposed as headlands in northeast and as straight coast with boulder-strewn, shallow, nearshore platform in the west	Predominantly wide, sand beach, with some pebble sediments in southeast: elsewhere narrow beaches of poorly-sorted sand, pebbles, cobbles and boulders	Maximum fetch of 200 km to northwest: exposed coast: shore-zone ice up to 4 months/year	Abundant sand-sized sediments in southeast from erosion of former beach and lake deposits: elsewhere locally abundant but not sediment-rich coasts: transport to south on east and west coasts, to east along south coast
5. East Bruce Peninsula and East Manitoulin Island	Niagara Escarpment of resistant sedimentary rocks: high backshore relief with cliffs up to 100 m in north: high backshore but low shore zone relief in south and on Manitoulin	Upland coast with bedrock cliffs in north and Manitoulin, unconsolidated cliffs in south: irregular coast except in most northerly sections: usually steep nearshore slopes	Sand and pebble-cobble beaches in south adjacent to sediment sources: few, small coarse-sediment beaches in the north: on Manitoulin coarse-sediment beaches narrow or absent except in Smith and James Bays	Fetch distances up to 200 km to north and east, but not high wave-energy levels as winds are predominantly offshore and many sections of the coast are sheltered: shore-zone ice up to 4 months/year	Some material available in the south: very scarce in north and on Manitoulin, except in Smith and James Bays: local transport systems
6. South Coast North Channel	Niagara Escarpment of resistant sedimentary rocks: backshore relief up to 150 m in east, decreases to low relief in the west	Indented coast of predominantly bedrock outcrops with few beaches and cliffs: marshes in bays	Few beaches except on St. Joseph and Cockburn Islands: usually poorly-sorted coarse sediments	Maximum fetch of 100 km: very sheltered coast, very low wave-energy levels: shore-zone ice up to 5 months/year	Very scarce in west: more abundant on St. Joseph and Cockburn Islands: local transport systems

sediments occur in the coastal zone to the west of Thessalon and to the east of Spanish, but form only a thin cover and do not constitute a major source for beach sediments (Ontario, 1965). Where beaches are present, they are usually characterized by poorly-sorted, mixed sand and coarse sediments. Marshes are common in sheltered bays. Wave-energy levels are low throughout the unit due to the short fetches and to the high degree of sheltering provided by islands and headlands.

The shore zone of this unit can be defined as a low-energy environment of bedrock outcrops and few sections of sediments.

2. North and East Georgian Bay

This coast is a continuation of the previous subdivision in terms of the geological setting, but is more exposed to waves generated across Georgian Bay. Fetch distances for the exposed outer coastline range between 80 and 200 km and the coast faces the south and west, the prevailing wind directions. There is a considerable difference in local wave-energy levels between the exposed outer coasts and the very sheltered inner shorelines.

This unit has the most complex coastline of any section in the Great Lakes system, with the exception perhaps of the Thousand Islands region of the St. Lawrence. The regional name, Thirty Thousand Islands, is an apt description of the shore zone character (Photo 9). The coast is generally low-lying and is underlain by resistant metamorphic Shield rocks. Structural trends, where evident, are perpendicular to the coast and this has a marked effect on the coastal character in the French River

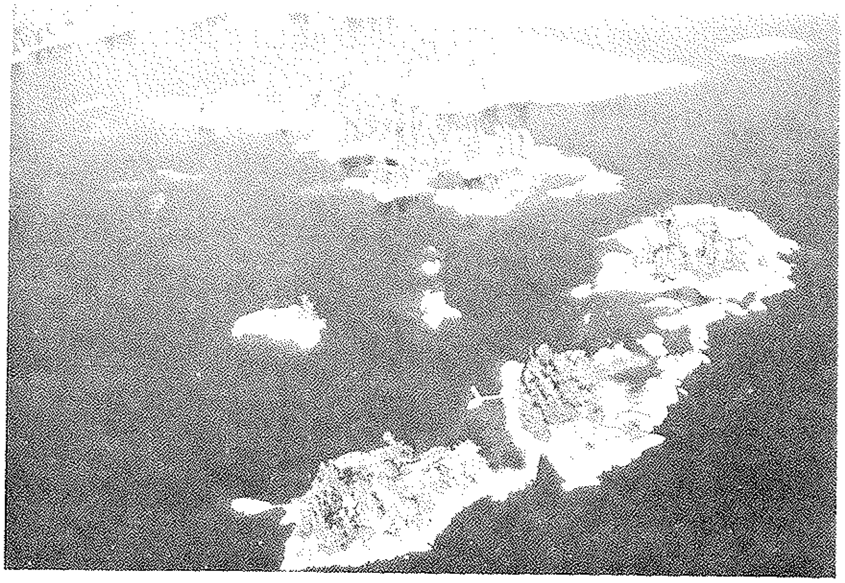


Photo 9. Small, low rocky islands near Muskosh Channel in the south of the Thirty Thousand Islands region (27 May 1978).

and Parry Sound areas where long, narrow inlets extend inland up to 20 km.

Surficial sediments are extremely scarce throughout this unit and, where present, they form only thin deposits (Chapman and Putnam, 1972; Chapman, 1975). Isolated pocket beaches of sand and/or coarse sediments occasionally occur where material is locally available. One example of this is the Whitchelo Point-Killbear Provincial Park area at the northern entrance to Parry Sound, where river and wave erosion have provided sediment for the development of several small beaches. Apart from a few localized exceptions, the shore zone character is dominantly that of a rocky coast with no shore zone sediments (Photo 9).

3. East Christian Island Peninsula

The east coast of this northwest-trending peninsula

(Fig. 15, p. 66) and its associated offshore islands represents a relatively resistant outcrop of sedimentary rocks that was formed by the erosion of less resistant rocks to the northeast and southwest. The coastline is indented by several large bays that follow the lines of river systems which have eroded back into the peninsula. The bedrock is mantled by sand and boulder deposits (Chapman, 1975) which provide a sediment source for reworking by wave action. The coasts are open to waves generated over short fetches to the north and northeast, and much of this unit is a sheltered, low wave-energy environment.

The coastal zone is characterized by steep backshore relief up to 30 m locally, but there are no cliffed sections. The shore zone is predominantly a boulder beach that rests directly on bedrock. Wide, shallow, boulder-strewn bedrock platforms make boat access difficult (Photo 10) on the seaward margin of the shoreline. Sand beaches have developed at Bar Point on Christian Island, in the central part of Beckwith Island, and in Thunder Bay, but these are exceptions to the general shore zone character. Some marshes have developed in sheltered river exits, such as at the mouths of the Coldwater and North Rivers in Matchedash Bay, but these also are restricted to small areas. The character of this coast is dominated by bedrock outcrops which are locally mantled by boulder-size sediments.

4. Nottawasaga Bay

The bay was formed by erosion along a northwest-southeast geological trend between two relatively resistant outcrops (the

Photo 10. Boulder-cobble beach with wide, shallow nearshore zone near Thunder Bay (27 May 1978).

Bruce Peninsula and the Christian Island Peninsula). Relief in the backshore is low, except along the south coast, and the bay is shallow. At times during the glacial period this corridor provided a river exit for the Upper Lakes towards the southeast (Chapman and Putnam, 1966). The deposition of fluvial and lacustrine sediments in the low-lying areas of this subdivision has provided material for subsequent river and wave erosion to form the present-day beach and dune complexes along the southeast and northeast shores of the bay. Bedrock outcrops at a few locations in the shore along the north coast as a series of headlands, such as Yarwood Point and Spratt Point. Between the headlands a series of sand beach-dune systems have developed and sediment transport in the shore zone is predominantly to the southeast, with local reversals in the lee of some headlands.

From New Wasaga Beach to Brocks Beach a large, straight, sand barrier system backed by dunes extends uninterrupted for 10 km. The Nottawasaga River runs parallel to the barrier before entering the bay, having been deflected to the northeast by the growth of the present-day beach system (Photo 11). The sand beaches are wide (up to 25-30 m) and backed by modern dunes that extend up to 6 m above lake level. In the shallow nearshore zone a series of sand bars parallel the shoreline. Although the beach sediments are predominantly sand-size, some pebble and cobble material are present, particularly on the upper parts of the beach. Martini (1975) reports that the sands are well-sorted, which indicates that the beaches are exposed to wave action, and that the beaches are subject to erosion and deposition cycles associated with storm-wave activity. Along this section shore-zone sediment transport is towards the northeast.

The west coast of the bay from Brocks Beach to Cape Rich is in marked contrast to the east coast. The shore zone has

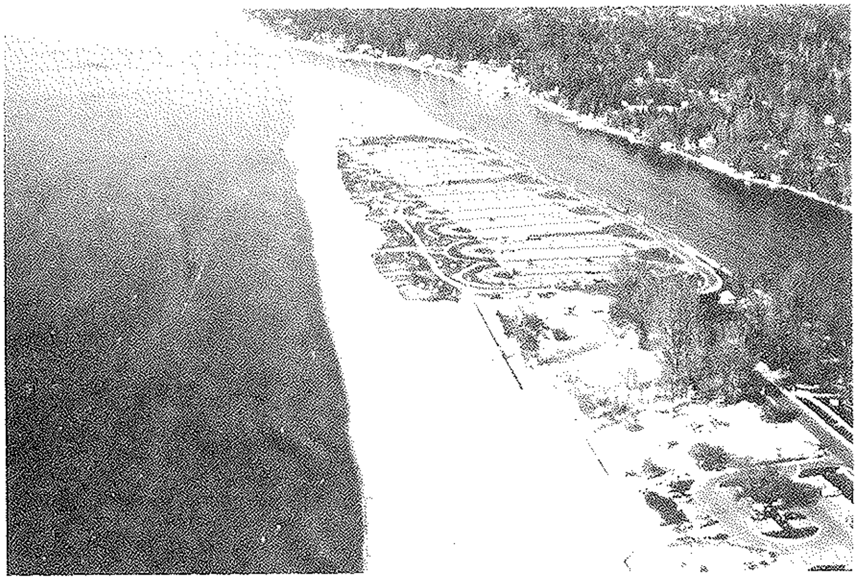


Photo 11. The mouth of the Nottawasaga River which has been deflected to the northeast by the growth of a bay-head barrier-spit system (27 May 1978).

relatively little sediment and bedrock outcrops in many sections. Relief is high inland (up to 300 m above lake level) and the backshore slopes frequently rise steeply from the coast, although the shore zone is low-lying except in the section between Thornbury and Meaford and at Cape Rich where friable, shale bedrock cliffs are being eroded by wave action (Photo 12).

The unit is exposed to waves out of the north and these waves generate a northwest to southeast sediment transport in the shore zone. This transport process has provided material for the development of Wasaga Beach and has resulted in a depletion of fine-grained sediments on this coast.

The shoreline is virtually straight and is bedrock controlled following the northwest-southeast structural trends of the outcrops. The only indented section is in the Collingwood area and here marshes have developed where fine sediments have been trapped in sheltered sites.

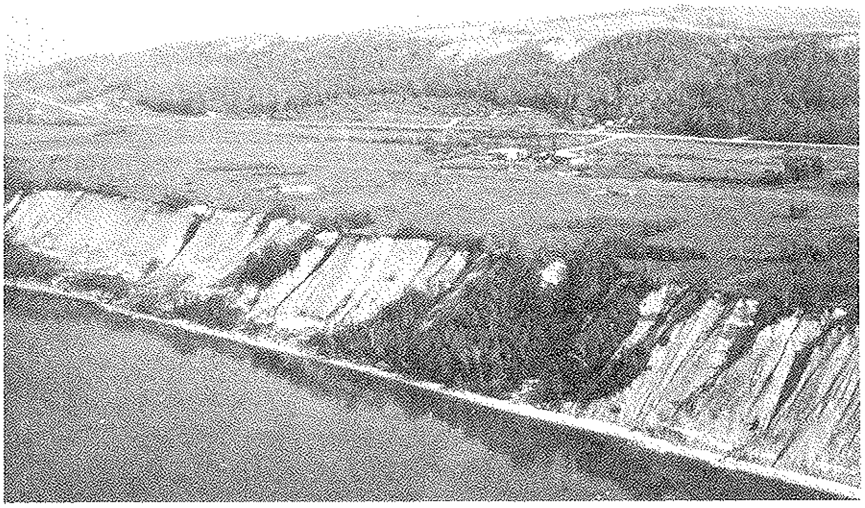


Photo 12. Eroding cliffs of unresistant sedimentary bedrock to the east of Meaford (27 May 1978).

The gently dipping limestone bedrock exposed in the shore zone often gives a shallow, wide rock platform in the nearshore zone (Photo 13) that is frequently mantled by cobbles and boulders. Sediments are more plentiful adjacent to local deposits of unconsolidated material but, in general, boulder beaches and bedrock outcrops characterize this section of Nottawasaga Bay.

5. East Bruce Peninsula and East Manitoulin Island

This upland coast has formed along the margin of the Niagara Escarpment. The resistant Niagara rocks dip towards the centre of Lake Huron and the edge of the outcrop forms the 40 to 60 m-high, steep, east-facing escarpment that is the backbone of the Bruce Peninsula. The escarpment forms part of the coastal zone north of Colpoys Bay (Photo 14), but active marine cliffs are found only in the most northerly section of the peninsula.

The coastline is deeply indented except on Manitoulin due to river erosion during the post-glacial period. Although the

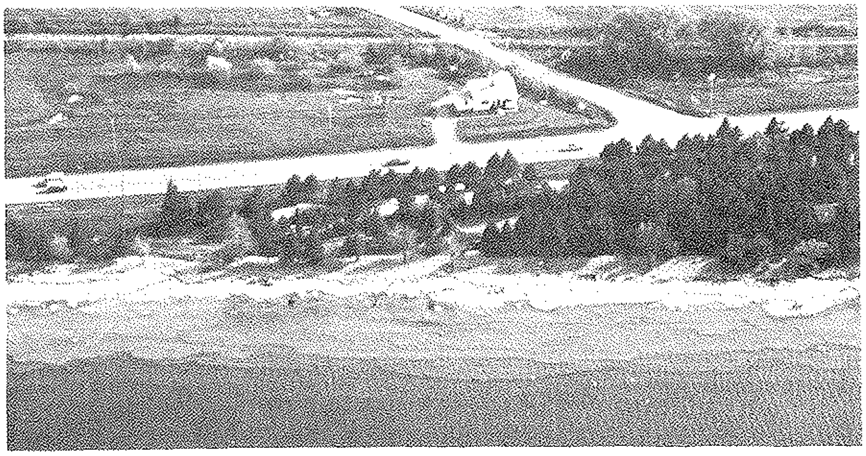


Photo 13. Wide shore-zone bedrock platform near Craigleith, to the west of Collingwood (27 May 1978).

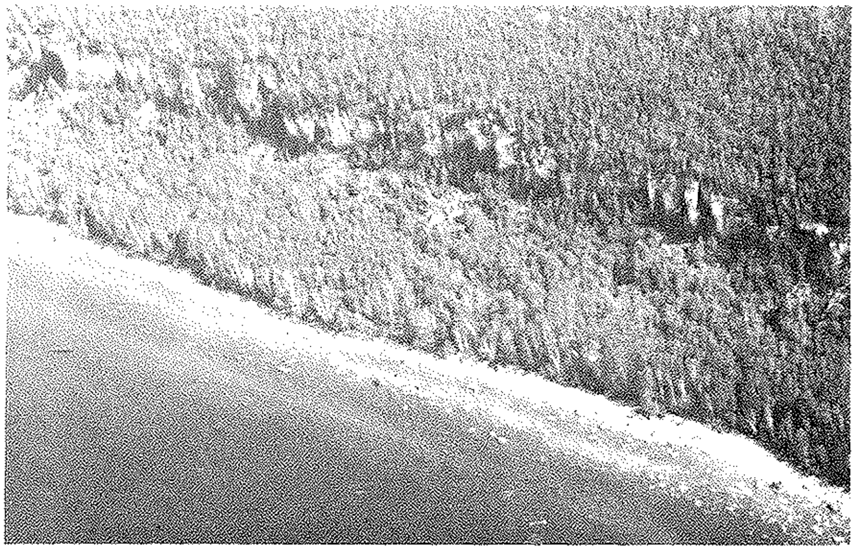


Photo 14. North shore of Colpoys Bay near Wiarton. The Niagara Escarpment provides high backshore relief but the shore-zone is a low, poorly-sorted, cobble-boulder beach (27 May 1978).

nearshore zone is wide and shallow in areas to the south of Colpoys Bay, offshore slopes are steep and the bays are deep.

The eastern Bruce Peninsula can be subdivided into two zones. The first zone is between Cape Rich and Melville Sound where unconsolidated sediments mantle the bedrock and provide coarse sediments to the shore zone. Narrow boulder and pebble/cobble beaches and wide, shallow, boulder-strewn, nearshore bedrock platforms are common (Photo 15). Sand and pebble/cobble pocket beaches have developed adjacent to local sediment sources, for example, near Leith in Owen Sound. The second zone is from Melville Sound to Cape Hurd where the shore zone is predominantly bedrock outcrops that form cliffs in the northern extremities of the peninsula, rising to 100 m at Cabot Head. Small pocket beaches have formed in a few sheltered embayments, but, in

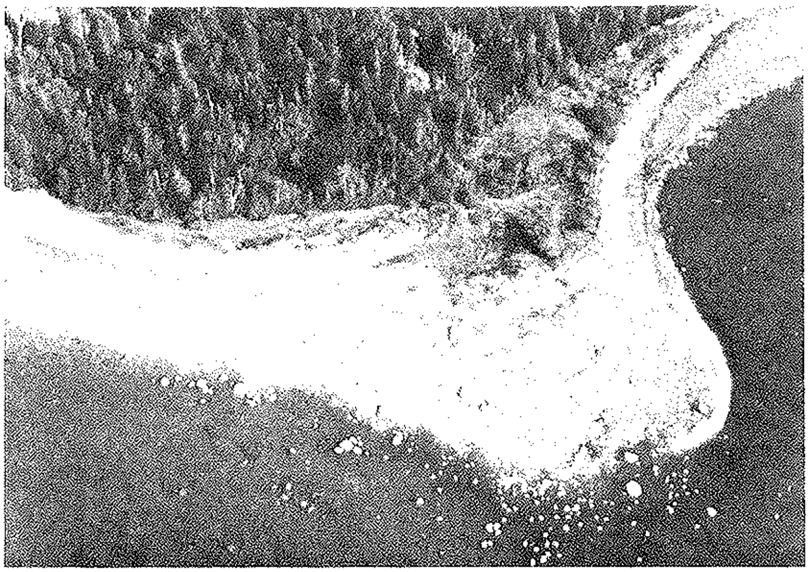


Photo 15. Cobble-boulder beach with wide, shallow, boulder-strewn nearshore zone, near Vail Point to the west of Cape Rich (27 May 1978).

general, this coast is devoid of sediments as erosion of the bedrock outcrops produces very fine-grained sediments that are removed in suspension from the shore zone.

The shore zone of the Bruce Peninsula is characterized by bedrock outcrops that are wide in the south but very narrow in the north. Beach sediments are coarse, often in the boulder size range, and occur in the south where unconsolidated sediments are available for erosion. The shore zone in the north is steep and sometimes cliffed.

The east coast of Manitoulin Island, including the islands north of Main Channel, is exposed to a fetch of 200 km to the southeast and has relatively high wave-energy levels in winter months.

The coast is generally low and sediments are scarce.

Bedrock outcrops in the shore zone and forms a wide, shallow nearshore zone. The only extensive cliffed section is on the north shore of Owen Channel from Owen Island to Tamarack Point. Beaches are restricted to Smith Bay and James Bay where local unconsolidated sediments are available for reworking by wave action. Elsewhere beaches are a thin deposit of coarse sediments that rest directly on the shore zone bedrock.

6. South Coast North Channel

This very sheltered section (Fig. 15, p. 66) is an extension of the Niagara Escarpment on the edge of the Michigan Basin (Fig. 10, p. 35). The escarpment faces towards the north and has been deeply indented in Manitoulin Island by river erosion in the post-glacial period. Relief is highest in the east (up to 150 m above lake level) and decreases markedly to the west.

A few sections of the coast are exposed to waves that can be generated across the long axis of North Channel, but for the most part, the coasts of this unit are very sheltered environments. The coastal zone is frequently steep and sediments are absent or scarce on Manitoulin Island (Hoffman, *et al.*, 1959) so that beaches have developed in only a few restricted areas. To the west, on Cockburn and St. Joseph Islands, sand and clay sediments provide source material for beach development. In these sections mixed sand and coarse-sediment beaches are usually poorly-sorted and rest on bedrock outcrops in the shore zone. Marshes are common in the shallow embayments where fine-grained sediments have accumulated.

This entire unit is characterized by low-energy coastal environments with bedrock outcrops in the shore zone. Relief increases and sediment becomes scarcer to the east on Manitoulin Island, which has a complex coastline of bays and islands.

4.3 CENTRAL LAKE HURON REGION

Summary

The coasts of this region are predominantly bedrock in the north and beaches or narrow beaches with retreating cliffs in the south. Although the coast is exposed in all sections, local sheltering is of great importance in northern areas where bedrock headlands and islands give the coast a complex shoreline. The resistant sedimentary rocks that outcrop in the shore zone dip gently towards the centre of the lake basin and shore-zone relief is low. By contrast, relief increases to the south, the shorelines are straight and only a few sections are sheltered from wave action. Sediments are scarce in the north, whereas cliff erosion and the reworking of former beach deposits has led to the development of extensive beach-dune systems along the southern coast. In this area beaches are generally wide where backshore relief is low, but are narrow where cliffs are present in the backshore.

Shore-zone sediment transport in the southern half of the region is to the south, except between Clark Point and the Sauble River where the transport direction is to the northeast. In the north the transport system is discontinuous due to the very irregular shoreline configuration, but a net northwest to south transport direction is evident.

4.3.1 Coastal Processes and Geology

Winds

The prevailing winds for this region are out of the westerly quadrant. The data for Southampton is representative of this region (Fig. 3, p. 22; Table 3, p. 24) and indicates the dominance of southwesterly winds throughout the year with a distinct velocity maximum from November to April. An important feature of the winds is a secondary prevailing direction out of the northwest (Fig. 3).

Waves

The entire shoreline of this region is an exposed windward coast. Fetch distances range from 70 to 300 km and onshore winds prevail throughout the year. Data collected in 1973 from Cove Island at the northern tip of the Bruce Peninsula indicate significant wave heights of 0.4 to 0.5 m from May to August; 0.7 to 0.9 m for September and October respectively; and 1.7 m for November, with a mean for the open-water season of 0.7 m (Environment Canada, undated). In general, wave heights do not exceed 3 m except for brief periods in winter months (Richards and Phillips, 1970). The seasonal variability of wave heights is evident from Figure 4 (p. 26) and Cole (1971) notes that computed wave height values exceed 2 m for approximately 1% of time in June, but for approximately 10% in November.

Ice

Ice begins to form along the coast by mid-December and persists until early April (Fig. 7, p. 31). The ice cover forms first and persists longest in the south of the lake and in the northwest, adjacent to the Straits of Mackinac (Rondy, 1976). The lake ice cover is usually 4/10 to 6/10 with the maximum cover occurring in mid- to late-March (Fig. 6, p. 29). A 10/10 cover can occur briefly during very severe winters but storm winds usually break up the ice throughout winter months (Richards, 1964). One result of the wind factor is that ice is piled up against the eastern coasts of the lake.

Water Levels

The lake level has long-term fluctuations up to a maximum of 2 m (Table 4, p. 32). Seasonal variations are usually in the order of 0.3 m, but short-term wind-induced changes up to 1 m are possible. Freeman and Murty (1972) report data from a single storm in which the lake level was raised 0.6 m above normal at Goderich and 0.8 m above normal at Sarnia.

Geology and Coastal Transport Systems

This coastal region has a curved shape that is derived from the exposure of sedimentary rocks on the rim of the saucer-shaped Michigan Basin (Fig. 11, p. 36). The rocks dip below the lake at a low angle and the entire coastal region is characterized by low (<15 m) backshore relief. The resistant Niagara dolomite is exposed in the coastal zone of western Bruce Peninsula and southern Manitoulin Island and continues westward to form the north shore of the Mackinac Straits and Lake Michigan.

This region can be subdivided initially into two major units: the north coast where the Niagara dolomite is exposed in the shore zone, and the east and south coasts of the lake where bedrock exposures are relatively rare. The northeast coast is characterized by bedrock exposures as the outcrops are only occasionally covered by unconsolidated sediments. This lack of a sediment cover results in a scarcity of beaches. There is, nevertheless, a net transport towards the south on this coast.

In the southern half of the region the less resistant sedimentary rocks are mantled by thick (5 to 30 m) silt and sand-size deposits that provide abundant material to the shore zone. Local variation in shoreline types is related primarily to backshore relief. In low-lying sections, wide, sand-pebble beaches backed by dunes are the dominant characteristic. As relief increases, the backshore zones are characterized by actively eroding cliffs which in most areas have a narrow beach at their base. This southern section is further divided due to a reversal in the shore-zone transport direction between Clark Point and Sauble River. The limits of the subdivisions are indicated on Figure 16 and the main characteristics are summarized in Table 12.

4.3.2 Coastal Environments of Central Lake Huron

1. Northeast Coast

This long section of shoreline (Fig. 16) is relatively uniform in character and is predominantly a low rocky coast with very few sections of beach. The coast is exposed to the west and south to face the dominant winds and has a maximum fetch of 300 km to the south. Data from Cove Island, in the center of this subdivision, show that significant wave heights of 1 to 2 m characterize the open-water winter months (p. 79). Although wave-energy levels are relatively high and the coast has a straight form, the shoreline is, in fact, very irregular and indented so that many sections are sheltered from wave action. In particular, South Bay on Manitoulin Island is a long (25 km), narrow bay with a restricted entrance and is a very sheltered wave-energy environment. In addition, the nearshore areas have many small islands and reefs and are generally shallow due to

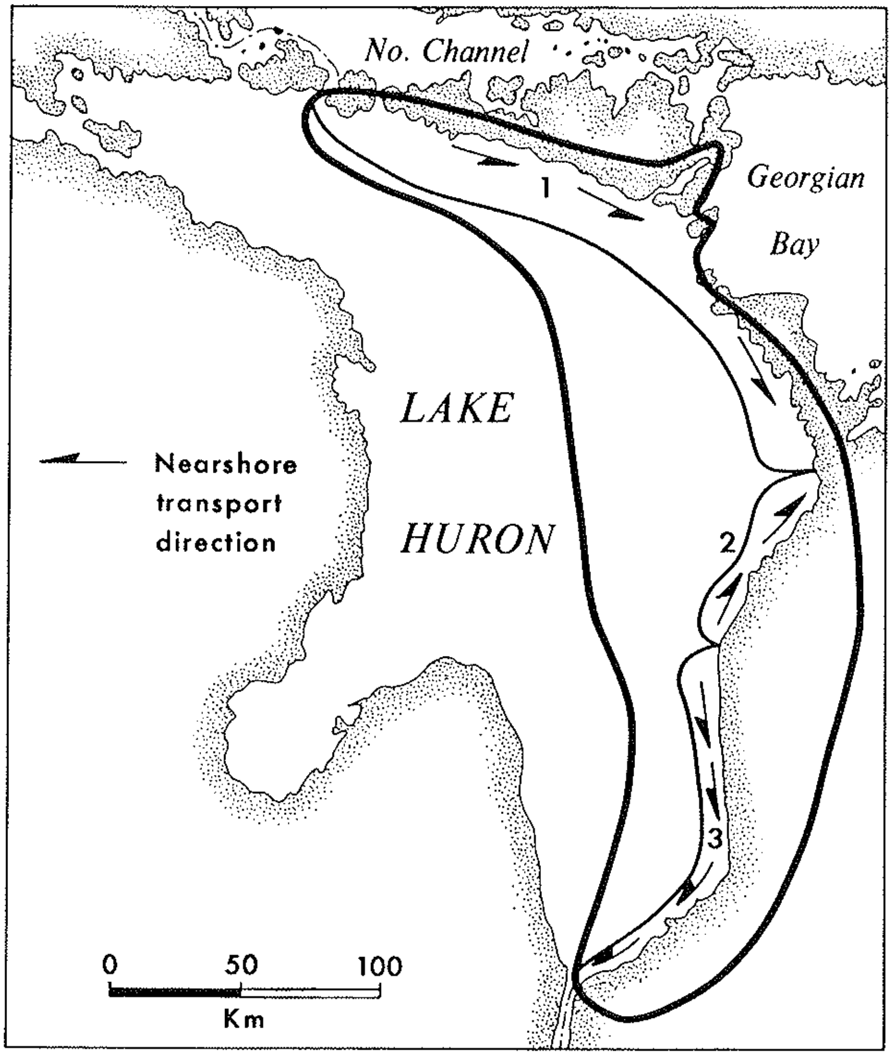


Figure 16. Coastal environments and shore-zone transport directions - Central Lake Huron region.

the low dip angle of the bedrock outcrops, so that energy is lost as the waves break before reaching the shoreline.

The resistant Niagara dolomite that outcrops throughout the shore zone of this subdivision provides little sediment for reworking by wave action as the rocks break down into very fine-grained sediments which are removed in suspension from the shore zone. Beaches have developed locally where occasional deposits of surficial material provide a source of sand and coarse

TABLE 12. COASTAL ENVIRONMENTS OF CENTRAL LAKE HURON

SUBDIVISION	RELIEF AND GEOLOGY	COASTAL ZONE		FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
		SHORE-ZONE CHARACTER	BEACH CHARACTER		
1. Northeast Coast	Resistant sedimentary rocks outcrop in shore zone and dip gently to the centre of lake basin: very low relief	Irregular shoreline with wide, shallow, boulder-strewn, rock platforms, many small islands and reefs: marshes in embayments and sheltered areas	Few beaches, where present usually coarse sediments and boulders	Fetch distances up to 300 km: exposed coast with many sheltered bays: shore-zone ice up to 4 months/year	Sediments very scarce: local transport systems with prevailing transport direction to the southeast
2. Central East Coast	Resistant sedimentary rocks dip gently to west: very low relief with a few sections of low (3 m) cliffs cut into backshore unconsolidated sediments	Two sections of extensive beach systems separated by section of wide, boulder-strewn, rock platforms with an irregular shoreline	Beach sections have sand with pebble sediments and low dunes: elsewhere predominantly coarse sediments with marshes in sheltered bays	Exposed coast with fetch distances up to 300 km: some sheltered bays: shore-zone ice up to 4 months/year	Sediments generally scarce but more abundant in southwest and northeast sections: transport to the northeast
3. Southeast Coast	Steep coast of unconsolidated sediments, cliffs up to 20 m: a few bedrock outcrops in shore zone in southern section	Straight coast of unconsolidated cliffs in north with two extensive beach-dune systems in the south: cliffed sections undergoing erosion and artificially protected in the south	Adjacent to cliffs beaches are narrow and predominantly sand and coarse sediments: beach sections have wide, sand, shore-zone backed by high (10 m) dunes	Exposed, high-energy coast: fetch distances up to 300 km: shore-zone ice up to 4 months/year	Sediments available from cliff erosion transported to the south and into St. Clair River: removal of material in erosion zones causes local scarcity with accumulation characteristic in most of the beach-dune systems

sediments. In areas where sediment is available, large boulders form a partial cover on the shallow, nearshore bedrock outcrops and pebbles, cobbles and boulders form a thin beach deposit at the shoreline (Photo 16). No large beaches occur on the western Bruce Peninsula but several short sections of beach have developed on southern Manitoulin Island (in Dominion, Providence and Michael Bays). Marshes have developed in embayments and in sheltered areas where fine-grained sediments have been trapped, such as Misery Bay in southwest Manitoulin Island.

The subdivision is characterized by high wave-energy levels but also by a high degree of sheltering due to the very irregular coastline and to the shallow, nearshore bedrock zone. The shore zone is basically rocky and, where present, beach sediments are very coarse.

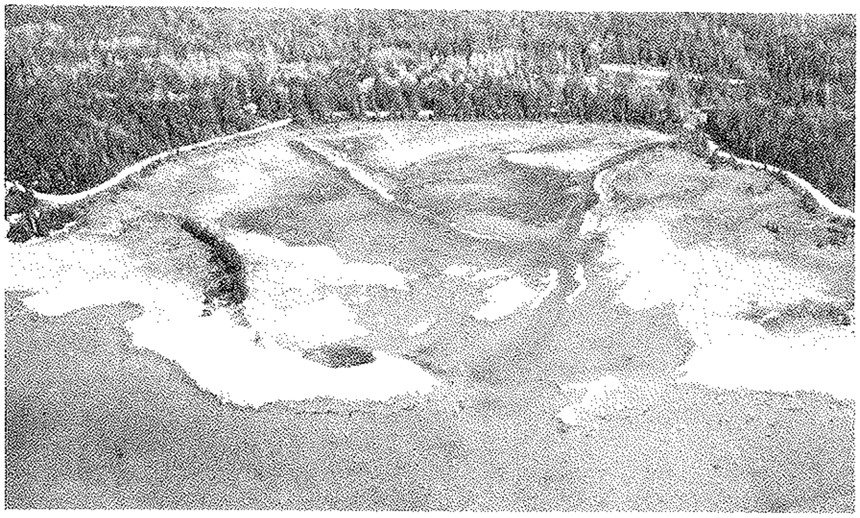


Photo 16. Small cove near Red Bay, southwest Bruce Peninsula. The sediments are predominantly cobbles and boulders, and the boulder-strewn, nearshore bedrock platform is shallow and wide (27 May 1978).

2. Central East Coast

This subdivision extends from the Sauble River to Clark Point (Fig. 16). This shoreline section combines two large sand-pebble beach systems that are separated by an irregular section of boulder-strewn bedrock. The coast faces towards the northwest and is a low-lying region where the bedrock is mantled by backshore sand and clay deposits that were formed during a period of higher lake levels following the retreat of the glaciers. The shore is exposed to waves out of the west and northwest and is a relatively high-energy environment. As the prevailing direction of wave approach is out of the westerly quadrant and the coast trends southwest-northeast, sediment in the shore zone is transported towards the northeast. There are some local reversals in this transport direction but along the large beaches the longshore drift is evidenced by the northeasterly deflection of the outlets of the Penetangore and Sauble Rivers.

The sections between the Sauble River and Frenchman Point (10 km) and between McRae Point and Clark Point (20 km) are characterized by low, wide beaches of sand and pebble material backed by dunes. The nearshore zones are shallow and have well-developed parallel bars in the Sauble beach section (Photo 17).

In the central section, bedrock outcrops in many places in the nearshore and shore zones. These outcrops dip very gently to the west below the lake and differential erosion has produced an irregular, crenulate shoreline with many small, sheltered embayments between Southampton and McRae Point (Photo 18). Where sediment is available, beaches or marshes have developed at the

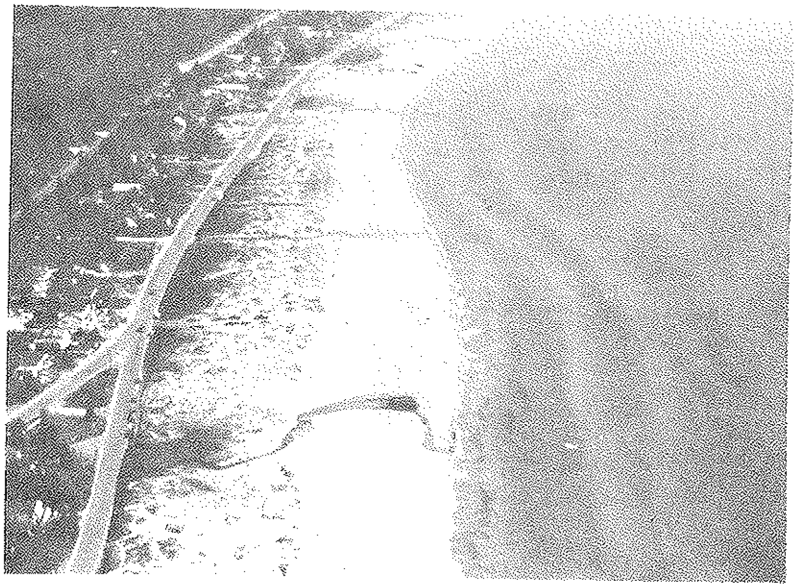


Photo 17. Sauble Beach. This wide sand beach is backed by low dunes and bars parallel the shore in the nearshore zone (27 May 1978).

Photo 18. Bedrock outcrops with a thin veneer of coarse sediments in the shore zone and backshore marshes; between Kincardine and Southampton (27 May 1978).

heads of the bays, depending on the size of the sediments and on the degree of sheltering. For example, Inverhuron Bay is exposed to waves and a beach has developed by the reworking of older beach deposits supplied from the Little Sauble River. Nearby, in Baie du Doré, erosion of finer-grained sediments and a more sheltered environment has led to the development of a marsh in this embayment.

This section is a very mixed environment with low bedrock outcrops, beaches, marshes and sections of low (<3 m) cliffs that cut into unconsolidated sediments. Erosion rates of the low cliffs are in the order of 5 cm/yr (over a 20-year period), whereas, some beach sections have retreated as much as 50 cm/yr during the same period, while others have undergone accretion (Boulden, 1975).

3. Southeast Lake Huron

The coast between Clark Point and Sarnia is a single sediment transport system that is composed of two geologic sections. In the north, the section of coast from Amberley to Grand Bend is characterized by a steep backshore of eroding cliffs and narrow basal beaches. The coast is only interrupted by a few small headlands and by the mouths of the Maitland and Bayfield Rivers. From Grand Bend to Sarnia the primary shore-zone character changes to an extensive beach-dune system which is interrupted by a section of cliffs to the west of Kettle Point.

This straight shoreline is a high wave-energy subdivision and is exposed to waves out of the west and northwest, with maximum fetches in the order of 75 and 300 km respectively. Wave data (Environment Canada, undated) for Goderich shows mean significant wave heights of 0.5 m for September, and 0.7 and 0.8 m for

October and November 1972. The wave-induced longshore drift of beach sediments is from north to south, as indicated by the accretion of sediments against the north jetties at Goderich and Bayfield and against groynes in the Sarnia area. Although winds from the southwest induce a south to north transport direction to the north of Grand Bend, the fetch distances to the northwest are greater and these waves are a more significant factor in shorezone processes and sediment transport.

Bedrock outcrops just below the present lake level throughout the subdivision and is exposed at a few locations in the nearshore zone. In northern sections the bedrock is mantled by a 5 to 30 m thick cover of unconsolidated glacial sediments, predominantly clays and silts with some sand and gravel sediments. The unconsolidated sediments are being actively eroded by waves in the shore zone and steep cliffs are characteristic of this section (Photo 19), except at the mouths of the Maitland and Bayfield Rivers.

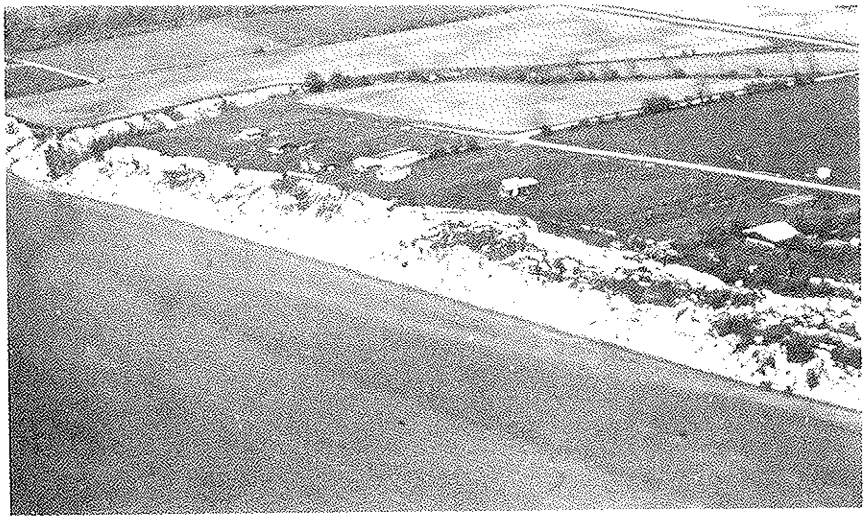


Photo 19. Eroding cliff section to the north of Goderich (27 May 1978).

Beaches at the base of the cliffs vary in width from 7 to 35 m (Quigley, *et al.*, 1974) and are composed of sand, pebble and cobble sediments. The beaches rarely extend more than 2 m above lake level and waves can erode the base of the backshore cliffs during storms. The beaches, therefore, provide protection to the cliffs only during periods of low or moderate wave-energy levels.

In most sections, the retreating cliffs are partially stabilized by a vegetation cover indicating slow erosion rates. In some locations, vertical cliffs are being actively eroded by storm-wave action as well as undergoing retreat as a result of slope failure processes (Photo 19). Cliff retreat rates vary considerably with maximum erosion up to 2.0 m/yr (during the period 1959-1973, Boulden, 1975) with a mean rate for the entire section in the order of 0.3 m.

This northern section is very uniform and is characterized by predominantly vegetated backshore cliffs, greater than 10 m in height with maxima of 30 m, and by narrow beaches of sand and pebble/cobble sediments. The coast is exposed to wave action and shore-zone sediment transport is predominantly to the south.

Between Grand Bend and the St. Clair River the coast resembles the Central East Coast subdivision. Two beach systems (Grand Bend to Kettle Point and Errol to Sarnia) are separated by a section of high, eroding cliffs. The two beach sections have developed in areas of sandy backshore sediments where former beaches, built at a time of higher lake levels, are now being eroded to provide sediment to the shore zone. The cliffed section in the central part of the subdivision is a region of unconsolidated clay and silt sediments that form vegetated cliffs over 10 m in height which have narrow beaches at their bases.

West of Grand Bend, the Little Sauble River was deflected approximately 15 km to the southwest but a man-made channel now connects the river to the lake at Grand Bend. This section of wide, sand beaches with some pebble/cobble sediments is backed by high dunes (Photo 20). The nearshore zone is shallow and parallel bars are common.

To the west of Kettle Point, a low bedrock outcrop, the shore zone is characterized by high (10-20 m), vegetated cliffs. The cliffs are retreating at rates that vary between 0.3 and 0.8 m/yr (Boulden, 1975). During the St. Patrick's Day storm of

Photo 20. Wide sand beach backed by extensive dune system, Ipperwash Provincial Park. Note the destruction of dune vegetation by off-the-road vehicles (27 May 1978).

1973, local retreat of up to 13 m was recorded on one section of these cliffs (Canada, 1973). The narrow beaches at the base of the cliffs do not provide protection from wave erosion during storms, but in some sections protection is provided by the shallow, boulder-strewn, nearshore platform.

To the west of Errol, the backshore, unconsolidated clay cliffs are low (<10 m). The shore zone is characterized by sand/pebble beaches with many sections of seawalls and groynes (Photo 21). These artificial structures provide protection to the backshore by reflecting waves or by sediment trapping to develop wide beaches. In non-protected sections, average cliff retreat rates are in the order of 0.2 m (Boulden, 1975).

Photo 21. Sand-pebble beaches, groynes and low (5-10 m), protected backshore cliffs of unconsolidated sediments near Brights Grove to the east of Sarnia (27 May 1978).

4.4 LAKE ST. CLAIR REGION

Summary

This region is an interconnecting waterway characterized by very low backshore relief; artificial protection structures or low cliffs; and marshes. The two river sections (the St. Clair and Detroit Rivers) are similar except for the sheltered, low section of wetlands adjacent to Fighting Channel. Elsewhere, the straight channel banks have narrow, coarse-sediment beaches and either very low cliffs or man-made structures.

In Lake St. Clair the marshes of the delta and the east coast have developed in shallow, low wave-energy environments. Sections of the marshes have been dyked but in most sections the coast is very irregular and unprotected. The south coast of the lake is composed of low cliffs, narrow beaches, and artificial structures. Sediment is scarce in this southern section and the nearshore zone is extremely shallow.

The St. Clair delta developed by the accumulation of material that was fed into the system from Lake Huron and deposited at the river mouth. The shoals at the mouth of the Detroit River developed in a similar manner but no delta has formed as relatively little sediment is fed into this system from Lake St. Clair.

4.4.1 Coastal Processes and Geology

Winds

The primary wind direction is from the southwest with a secondary prevailing frequency out of the northwest (Windsor: Fig. 3, p. 22; Table 3, p. 24). There is a distinct seasonal variation in wind velocities with a maximum between November and May (Fig. 3).

Waves

Within Lake St. Clair wave generation is limited by the small fetch distances (40 km). No wave data are available for this water body but it is expected that wave heights greater than 1 m would be rare. In addition, the lake is very shallow, generally less than 5 m, so that wave energy at the shoreline is reduced due to bottom friction in the nearshore zone. A seasonal variation in wave heights is expected due to the variation in wind velocity between summer and winter months.

Ship wakes are of greater importance than wave generation by winds in the St. Clair and Detroit Rivers (Photo 22). In cases where boats have been observed within 500 m of the channel margins, wave heights at the shoreline were in the order of 0.3 to 0.5 m. In this environment, wave-energy levels at the shoreline must be considered as a function of: (a) the proximity of the vessel to the channel margin, and (b) the frequency of passing vessels.

Ice

The formation of shore ice in Lake St. Clair begins in the

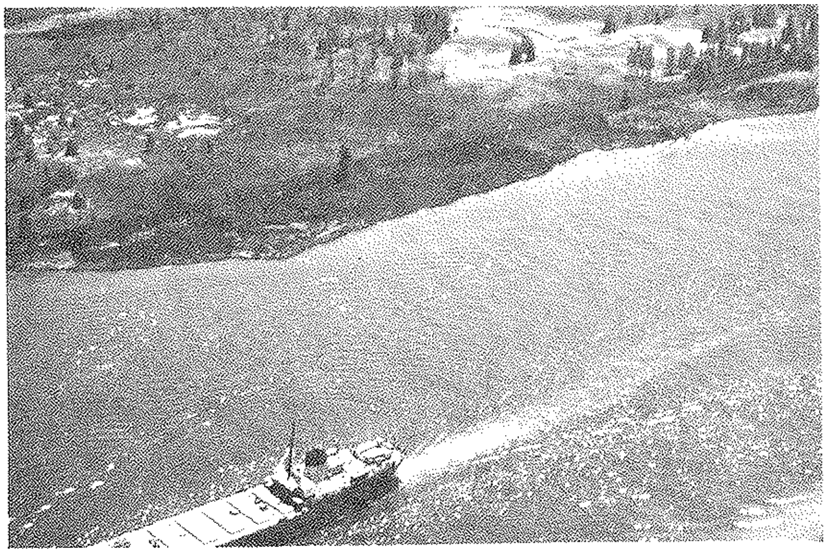


Photo 22. Waves generated by passing ships are the primary cause of shore erosion on this section of the lower St. Clair River, the northwest shore of Squirrel Island (photograph by N.A. Rukavina, 27 May 1978).

sheltered bays of the north and northeast coast during late December. In the eastern part of the lake, freeze-up is earlier and the ice persists longer due to the westerly winds that drive the floes into this part of the lake. The ice cover is 10/10 in most years; the maximum coverage is usually in late February (Fig. 6, p. 29), but may be as early as late January (Rondy, 1976). Breakup commences in early March and most of the lake is ice-free by April.

In the river channels the strong currents (up to 2 m/s) prevent ice formation in many sections, but in slack reaches, delta channels or bays, the period of ice cover is similar to that of Lake St. Clair. One important feature of the ice conditions in the channels is the formation of jams by drift ice. These ice jams or ice bridges form at the entrance to both the St. Clair and Detroit Rivers as floes enter the channels from the lakes upstream. The jams usually occur at narrows and constrictions, or where ice is prevented from leaving the channel at the downstream end by lake ice. These ice jams can retard the river flow and in the St. Clair River the ice retardation can reduce the flow by as much as 10%. This has an effect in upstream sections of the St. Clair River where river levels may rise as much as 1 m and in Lake St. Clair where water levels can be reduced by as much as 0.5 m each winter (Great Lakes Basin Commission, 1975a). Once a jam is broken, the failure of the dam can result in a surge of ice and water downstream. Although common in the Detroit River, the ice jams are a greater problem in the St. Clair River.

Water Levels

In Lake St. Clair the annual water level variability is in the order of 0.5 m but maximum variations up to 1.0 m have been recorded (Table 4, p. 32). The long-term fluctuations are in the order of 2 m. No data is available on wind-driven surges in Lake St. Clair, however, some water-level changes associated with storm winds would be expected due to the shallow nature of the basin.

The water levels in the river sections are controlled basically by variations in the upstream lake levels. For example, in the St. Clair River the flow rate has varied from a minimum value in February 1942 of 2,800 m^3/s to a maximum in June 1886 of 6,850 m^3/s (Great Lakes Basin Commission, 1975a), although the average monthly flow is approximately 5,300 m^3/s (Boulden, 1975). For both rivers the difference in normal monthly discharge between summer and winter months ranges from 20% to 50%.

The rise and fall of water levels in Lake Erie during wind-generated storm surges can be significant in the lower Detroit River. The river level has been known to be lowered by as much as 2 m in 8 hours as water levels have fallen in the western end of Lake Erie (see Fig. 9, p. 34).

Geology and Coastal Transport Systems

This low-lying region between Lakes Huron and Erie is mantled by unconsolidated material, and bedrock outcrops only in the river channels and at the southern end of the Detroit River. The region is a structural arch that forms the southeast margin of the Michigan Basin, although the arch sags in the area now occupied by Lake St. Clair (Sly and Lewis, 1972). The unconsolidated sediments are predominantly clays, but more sandy deposits occur on the eastern and southern margins of Lake St. Clair.

The St. Clair River is a narrow channel (up to 600 m wide) with depths generally in the order of 10 m. Currents are strong, 1 to 2 m/s in the main channel, and sediment derived from southern Lake Huron and channel-bank erosion is carried through into Lake St. Clair. Local relief is low, less than 10 m. This section can be considered as a river channel unit with few areas of sediment accumulation.

Backshore relief in the Lake St. Clair section is generally less than 2 m. The northern and eastern areas are dominated by deltaic and marsh environments respectively. The delta developed due to deposition as the sediment-laden current of the St. Clair River slowed upon entering the lake. The delta has a "bird-foot" morphology, typical of very low wave-energy environments. The lake is very shallow with depths less than 6 m except in dredged sections. Along the south coast the sediment transport is characterized by a divergence in the vicinity of Belle River (Fig. 17).

The Detroit River section is essentially similar to the St. Clair River, although in the lower (southern) half the channel widens up to 3 km. Bedrock outcrops below the river in this southern section have limited the water depths, thus causing the natural channel to widen (Sly and Lewis, 1972). Extensive shallow shoals have been formed on either side of the Detroit River

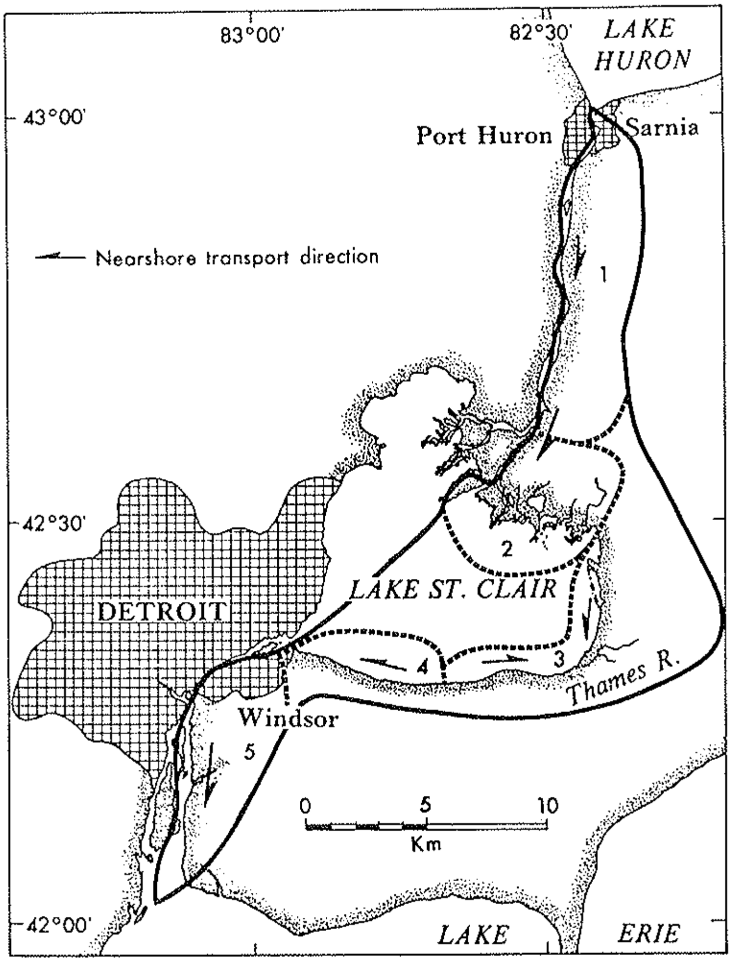


Figure 17. Coastal environments and shore-zone transport directions - Lake St. Clair region.

exit, but unlike the St. Clair River, no delta has been formed where the Detroit River discharges into Lake Erie. Backshore relief is again low, less than 10 m. The channel margins have been extensively modified by man as the cities of Detroit and Windsor developed.

The region is subdivided on the basis of the sediment transport systems (Fig. 17) and the primary characteristics of each subdivision are summarized in Table 13.

TABLE 13. COASTAL ENVIRONMENTS OF THE LAKE ST. CLAIR REGION

		COASTAL ZONE			
SUBDIVISION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	BEACH CHARACTER	FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
1. St. Clair River	Low relief with unconsolidated sediments: cliffs less than 5 m: no exposed bedrock	Straight river channel with vegetated cliffs, narrow beaches or artificial structures: marshes on Stag Island and in sheltered sites	Beaches are narrow and predominantly poorly-sorted coarse sediments	Very sheltered, narrow channel: ship-generated waves significant: strong river currents: shore-zone ice up to 4 months/year, ice jams form in channel	Sediments generally scarce: material fed in from Lake Huron transported through river into Lake St. Clair
2. St. Clair Delta	Very low relief, generally <3 m: deltaic environment	Complex shoreline: "bird-foot" shaped delta with many channels and shallow bays: predominantly a marsh environment with dykes and reclamation in northern sections	Beaches narrow or absent, predominantly fine-grained sediments: some channel-margin erosion adjacent to shipping lanes	Very low wave-energy levels: maximum fetch 40 km: shore-zone ice up to 4 months/year	Area of sediment accumulation
3. East and Southeast Lake St. Clair	Very low relief, <5 m: no exposed bedrock	Dyked and undyked marshes in east: low cliffs in the southeast with some narrow beaches west of Belle River	Where present, beaches are narrow and composed of sand-pebble sediments	Low wave-energy environment: maximum fetch 40 km and shallow nearshore zone: shore-zone ice up to 4 months/year	Fine-grained sediments in east trapped in marshes: sediments generally scarce in southeast and transported to the west
4. Southwest Lake St. Clair	Very low relief, <5 m: no exposed bedrock	Low, eroding cliffs protected by seawalls, beaches narrow or absent: considerable artificial protection	Beaches are low and narrow, predominantly sand-pebble sediments	Low wave-energy environment: maximum fetch 40 km and shallow nearshore zone: shore-zone ice up to 4 months/year	Sediments scarce: transported westward into the Detroit River
5. Detroit River	Low relief (<10 m) with unconsolidated sediments: bedrock outcrops in sections of the river bed, but not in shore zone	Straight river channel, eroding cliffs largely protected by seawalls: beaches narrow or absent: marshes in sheltered sites	Beaches are low and narrow: sediments in sand to cobble size range, generally poorly-sorted	Very sheltered, narrow channel: ship-generated waves significant: strong river currents: shore-zone ice up to 4 months/year, ice jams form in channel	Sediments generally scarce: material from Lake St. Clair transported through river into Lake Erie

4.4.2 Coastal Environments of the Lake St. Clair Region

1. St. Clair River

This narrow river channel (Photo 23) extends for 45 km between Lakes Huron and St. Clair, and has an elevation drop of about 1.7 m. The channel is narrow throughout the length of the section, so that wave generation by ships is an important factor in energy levels at the shoreline (Donnelly, 1968) (Photo 22).

The shore zone is uniformly characterized by low (1-5 m), vegetated cliffs (Photos 23 and 24) or artificial structures. A very narrow beach of sand and coarse sediments fronts the cliff bases in many sections. Elsewhere, short groynes or jetties and walls have been constructed to protect the cliffs from erosion. An area of marsh on the west coast of Stag Island and several

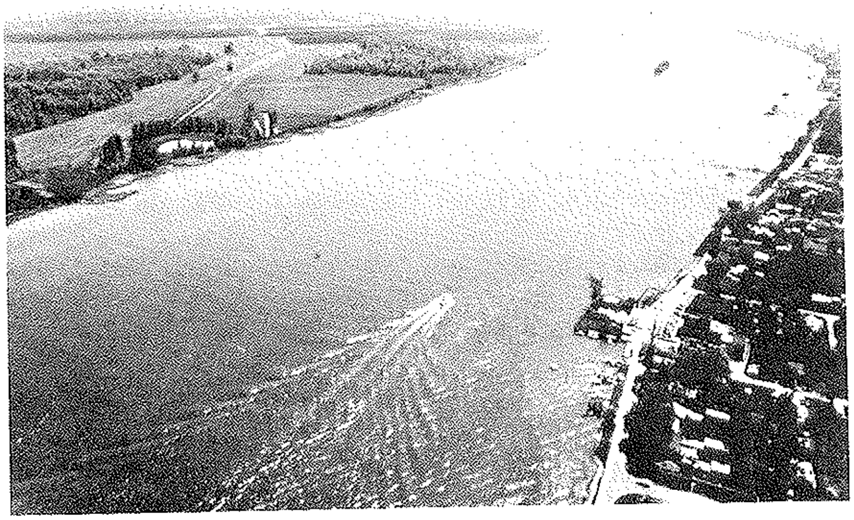


Photo 23. View to the south of the lower St. Clair River. This section is part of the delta and the river bifurcates at the top of the photograph into South and Basset Channels. Lake St. Clair is visible in the far background (photograph by N.A. Rukavina, 27 May 1978).

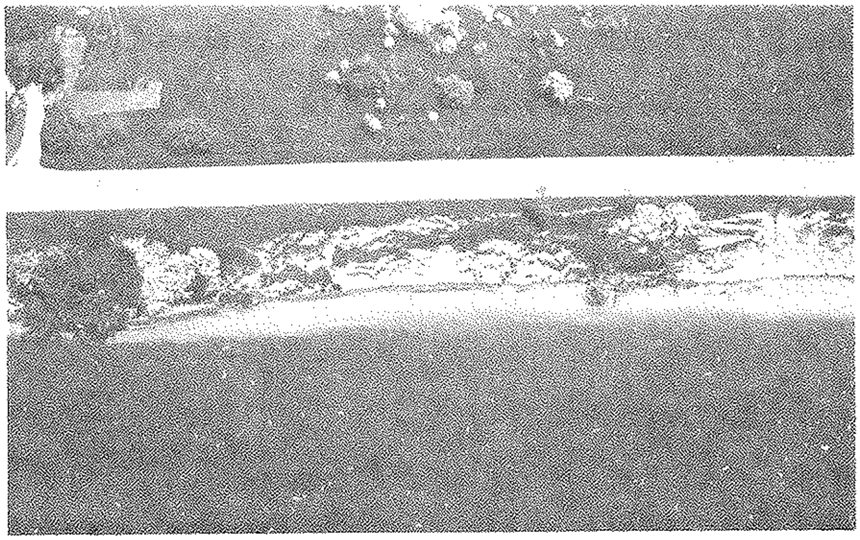


Photo 24. Low, eroding, cliffed section of the St. Clair River near Sarnia (27 May 1978).

small river channels are sheltered locations not affected by the river currents or by ship-generated waves.

2. The St. Clair Delta

Below Chematogan Channel the shore-zone character changes as the St. Clair River has built an extensive delta. Sediment carried downstream was deposited as the river current slowed upon entering the lake. The river separates into a series of distributary channels (Photos 23 and 25) and the delta morphology is characterized by natural channel-margin levees that give a "bird-foot" shape to the coast. The shallow bays between the channels have infilled and are now extensive marsh areas which, in the northern parts, have been dyked for agriculture.

A distinct difference exists between the channel or marsh shorelines adjacent to shipping lanes and those which are in more sheltered environments. As this is a very low-wave energy

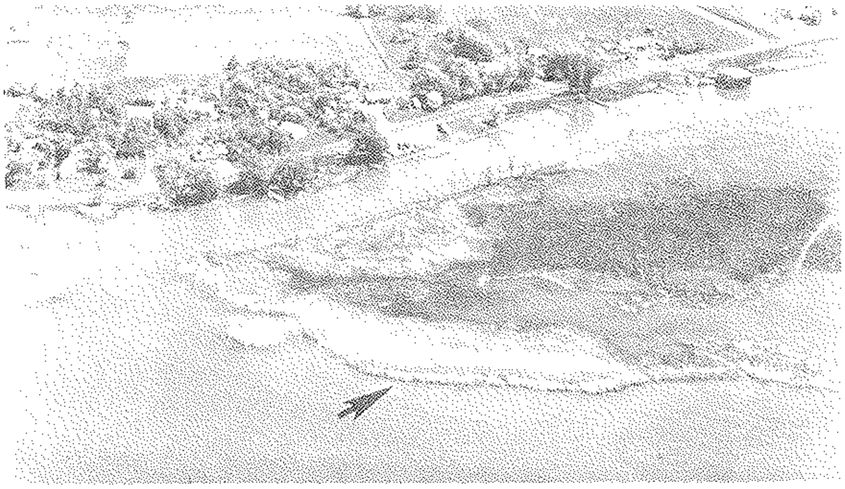


Photo 25. Main channel of the St. Clair River in lower part of photograph with the distributary Chematogan Channel in the upper part. Note the eroding marsh shoreline on the main channel shoreline, indicated by the arrow (27 May 1978).

environment the normal shoreline has a low slope on which marsh vegetation has developed. By contrast, boat-generated waves have eroded the shoreline adjacent to shipping lanes and the edges of the channels and marshes are marked by a low scarp, about 0.5 m in height (Photo 25).

The entire region is an extensive marsh environment with a very complex shoreline. The sediments are predominantly coarse silts and fine sands (Pezzetta, 1973) which have been trapped by the marsh vegetation that extends across the shore zone into the shallow, nearshore waters of the lake.

3. East and Southeast Lake St. Clair

The delta merges to the east into a low-lying coast that has a very irregular shoreline consisting of non-dyked marshes

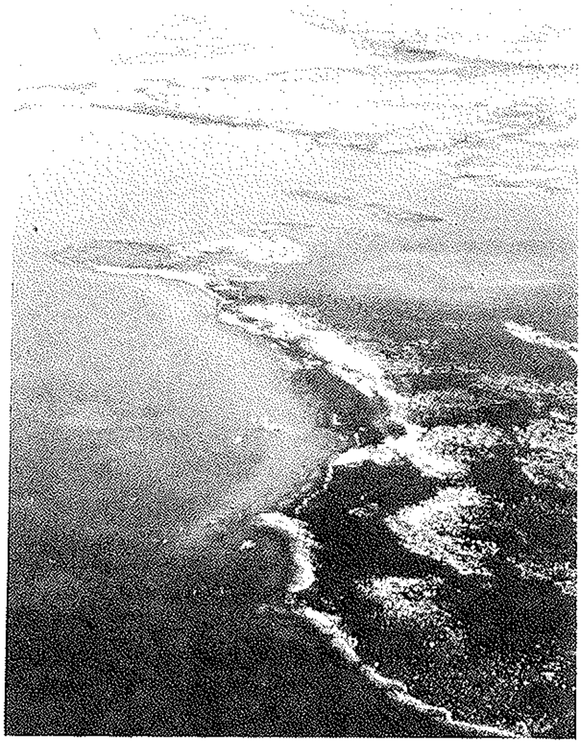


Photo 26. Marsh environment in north Mitchell Bay, Lake St. Clair (photograph by N.A. Rukavina, 27 May 1978).

(Photo 26), bays, channels and small vegetated islands. The section to the south of Mitchell Bay as far as the Thames River has been dyked, but the marsh is connected to the lake by a series of channels and creeks. The lake shore west of the Thames River to Belle River has a short section (3 km) of low marshes backed by dykes, followed by low (1-2 m) cliffs protected by seawalls. Backshore relief is low throughout the subdivision and this coast is subject to flooding during periods of high lake levels or during storm surges.

Sand-size sediments are scarce throughout this subdivision and little material is supplied to the shore zone by the Thames River. The sediment transport pattern is one of convergence towards the Thames River, but the volumes of material involved are small.

Although this coast is open to wind-waves generated by the prevailing westerly winds across the lake, the nearshore zone is very shallow and much of the wave energy is absorbed by bottom friction. Shore-zone erosion, nevertheless, occurs along the cliffed sections of the southeast coast at rates of 0.5 to 2 m/yr (Boulden, 1975).

4. Southwest Lake St. Clair

West of the Belle River, shore-zone sediments are transported towards the Detroit River. The shore-zone character is predominantly low relief with eroding cliffs; narrow, sand-pebble beaches; and numerous artificial protection structures and groynes.

The nearshore zone slope is very shallow, with slopes as low as 1 m in 200 m in places (Boulden, 1975), and this provides protection to the shoreline from wave action. Shore-zone sediment is scarce but groynes have been successful to some degree in trapping nearshore and beach sediments. The beaches are low, less than 1 m above lake level (Photo 27), and backshore areas are frequently subject to flooding.

5. Detroit River

The river is 52-km long and drops 0.8 m between Lake St. Clair and Lake Erie. Relief is low in the central section, and marshes and wetlands form the channel margins on the Canadian

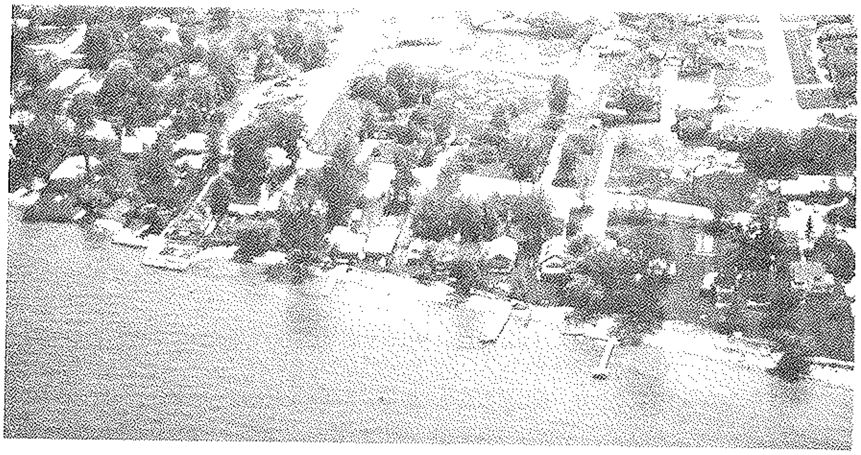


Photo 27. Low coast with narrow beach, near Sarnia on the Lake St. Clair coast (photograph by N.A. Rukavina, 27 May 1978).

shore in areas that are not protected by man-made structures. Relief increases to the north and south, but is still less than 5-7 m; the shore-zone is characterized by low, eroding cliffs cut into unconsolidated clays. These cliffs have either a narrow, coarse-sediment beach at their base or have been artificially protected. As in the St. Clair River, ship wakes are a significant shore-zone process.

In the central section adjacent to Fighting Channel, the river margins are extremely irregular. This sheltered marsh section is in marked contrast to the remaining sections which have generally straight shorelines.

Sediments fed into the river from Lake St. Clair are transported through the system and deposited at the river mouth. No delta has formed due to the relatively small volume of sediment transported by the river, but an extensive system of shoals has developed where the river enters Lake Erie.

4.5 LAKE ERIE REGION

Summary

The north shore of Lake Erie is characterized by eroding cliffs (5 to 20 m in height) and by three large depositional features that have extensive beach-dune and marsh systems.

The cliffs, which are predominantly of unconsolidated sediments, are eroding at an average rate of approximately 0.5 m/yr, with local maxima up to 6.0 m/yr in some restricted sections (Boulden, 1975). Erosion rates increase as shoreline exposure to wave action increases and as the sediment strength decreases. Highest erosion rates occur in sections where sand-size deposits are exposed in the shore zone. The cliff sediments are predominantly clay-silt materials which are more resistant to erosion processes. Cliff erosion rates are higher during periods of high lake levels as waves can then act directly on the cliff base and subsequent basal erosion leads to sliding and slumping. Although erosion provides sediment to the shore zone, beaches are generally low and narrow because much of the sediment is removed in suspension and relatively little sand or coarse-grained material is available for beach development.

Two of the depositional features, Rondeau and Long Point, are migrating to the northeast and east respectively under the influence of waves out of the southwest that are generated along the long axis of the lake. Sediment supply to these two features is ample, although in both cases the southwest-facing beaches are erosional. Both beach systems have extensive, sheltered marsh complexes that have developed in open bays. Point Pelee, the third major depositional section, is migrating slowly to the west and the exposed eastern beach is erosional. The northern half of Point Pelee is dyked and the marshes have been reclaimed for agriculture, whereas, marshes are exposed and unprotected in the south.

At the extreme western and eastern ends of the Lake Erie north shore, relief becomes lower. Wave-energy levels in the west are low due to sheltering, whereas, the more exposed, irregular northeast shore is an alternating sequence of bedrock headlands and embayments with beaches and small river-mouth marshes.

This region has a variety of shoreline types, but is primarily characterized by eroding cliffs of unconsolidated sediments and by three large depositional features that interrupt the relatively straight shoreline.

4.5.1 Coastal Processes and Geology

Winds

The prevailing winds for the region are from the southwest (Windsor: Fig. 3, p. 22; Table 3, p. 24), approximately parallel to the long axis of the lake. There is a distinct, seasonal velocity maximum from November to May due to the passage of cyclonic storms across the region in winter months.

Waves

The maximum fetch is in the order of 300 km along the lake axis and, due to the predominance of winds out of the southwest, there is an increase in wave heights from west to east. Wave data collected off Point Pelee between 1972 and 1975 (Environment Canada, undated) indicate an open-water, mean significant wave height of 0.5 m (Table 14) for the western part of the lake. Richards and Phillips (1970) note that wave heights on the lake exceed 3 m only during brief storm periods in winter months. The strong seasonal variability in the wave heights is evident both from observed data (Table 14) and from estimated values (Fig. 4, p. 26).

TABLE 14. Mean Monthly Significant Wave Height Off Point Pelee: 1972-1975 (Environment Canada, undated)

May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
0.5	0.5	0.4	0.3	0.6	0.6	0.7	0.8	0.5 metres

Ice

Ice formation commences in western sections of the lake and in Long Point Bay in mid-December (Stations 6 and 7, Fig. 6, p. 29). On the average, the ice persists in the shore zone until mid-March, but in some years it can last until mid-April. Lake Erie has shallow depths so that the heat storage capacity of the lake is limited. A 10/10 ice cover is common, even in mild years, with the maximum ice period occurring usually in late February (Rondy, 1976). Ice jams can occur in the Niagara River gorge below the falls, and at the entrance to the river from Lake Erie (Great Lakes Basin Commission, 1975a). Storm winds tend to fracture the lake ice cover and extensive rafting and pressure ridge systems are frequently developed in the shore zone in eastern sections of the lake (Rondy, 1976).

Water Levels

The long-term, mean water level (1860-1970) has fluctuated within a 2.4 m range (Table 4, p. 32); the annual variability is in the order of 0.5 m with a maximum of 1.0 m. Short-term, storm-related surges are of considerable importance. Water-level changes during storms exceeded 3.7 m on four occasions in a 20-year period (Platzman, 1963), and a maximum storm surge of 5.5 m is reported by Saville (1953). Although these extremes are not representative of normal conditions, short-term surges of 1 and 2 m are a relatively common occurrence. An example of the water level changes for Buffalo and Toledo during a single storm is given in Figure 9 (p. 34). In this example, the initial surge on December 10 was followed by a series of water-level oscillations as the lake level returned to normal. This alternating series of high and low water levels is referred to as a seiche (q.v.).

Geology and Coastal Transport Systems

Lake Erie was formed by the scouring action of the ice sheets along a pre-glacial river valley system. This valley developed between two relatively resistant sequences of sedimentary rocks that dip towards the center of the lake from the east and the west (Gregor and Ongley, 1978). In the east, the resistant rocks outcrop as the Niagara Escarpment which separates Lakes Erie and Ontario (Fig, 10, p. 35). Bedrock outcrops in the shore zone in the northeast sections of the lake and in extreme western areas, particularly Pelee Island.

The bedrock is mantled by deposits of clay- and sand-size sediments that form backshore cliffs along the entire north shore of the lake. During the retreat of the ice sheet, several large moraines (q.v.) were deposited in the present lake basin. These ridges of sand and pebble-cobble material have probably been reworked by waves and provided sediment for the construction of three large depositional features (Point Pelee, Rondeau and Long Point).

Except in the vicinity of the moraine deposits, sand or coarser material is relatively scarce as the cliffs are composed predominantly of clays and silts. These fine-grained sediments are readily transported in suspension into nearshore and deeper waters so that cliff erosion provides relatively small amounts of sediment for the development of beaches. In all areas, beach heights rarely exceed 3 m, so that wave heights of 2 m combined with a storm surge of 1 m are sufficient to inundate backshore areas or to allow waves to erode the base of the unconsolidated cliffs.

The shore zone of the region is characterized primarily by cliffs of unconsolidated sediments that reach a maximum height of 42 m. Rates of retreat vary, and in a few locations exceed 2.0 m/yr. These rates are locally variable due to the strength of the sediments and to wave action in combination with lake levels.

Gelinas and Quigley (1973) relate the cliff sediment properties as follows: (1) sands and silts - low resistance to erosion, (2) silty-clays - resistant when wet but lose cohesion when dry, (3) coarse sediment - material forms a protective beach at the base of the cliff, therefore, erosion is slow. Low lake levels result in absorption of wave energy by bottom friction in the nearshore zone and by the beaches. During periods of high lake levels, beaches that have formed at the base of cliffs no longer act to protect the backshore so waves can undercut the cliff face.

Quigley, *et al.*, (1977) note that cliff erosion in this region results not only from wave erosion, but also from sheet erosion of the cliff face, slumping and sliding. These non-marine processes are particularly important during periods of low lake levels when the effects of wave erosion are reduced.

Cliff erosion is the primary source of sediment supply to the shore zone. The sediment transport direction in the shore zone is predominantly from west to east, with local reversals in the lee of the three major depositional features and in the extreme western section of this region. The sediment transport systems can be defined in terms of the source (erosion) areas, the movement of sediment, and zones of accretion. These systems form the basis of the subdivisions that describe the coasts of Lake Erie.

Although the major depositional features of Point Pelee, Rondeau and Long Point originated as the result of reworking of sediments associated with moraine ridges, the present-day features are an integral part of a contemporary sequence of transport systems. Figures 18 and 19 and Table 15 summarize the major features of each of the transport systems discussed in the text.

4.5.2 Coastal Environments of Lake Erie

1. Northwest Coast

This short section of coast between the Detroit River and Colchester is a sheltered environment characterized by low, unconsolidated cliffs and narrow beaches. Shore-zone relief is usually less than 10 m, but rises locally to 25 m. Relief decreases to the west and the westernmost 10 km is a section of low beaches that enclose lagoons and marshes (Photo 28).

Photo 28. Low barrier beach across Big Creek that encloses lagoon and marshes; Holiday Beach Provincial Park (Photograph by N.A. Rukavina, 27 May 1978).

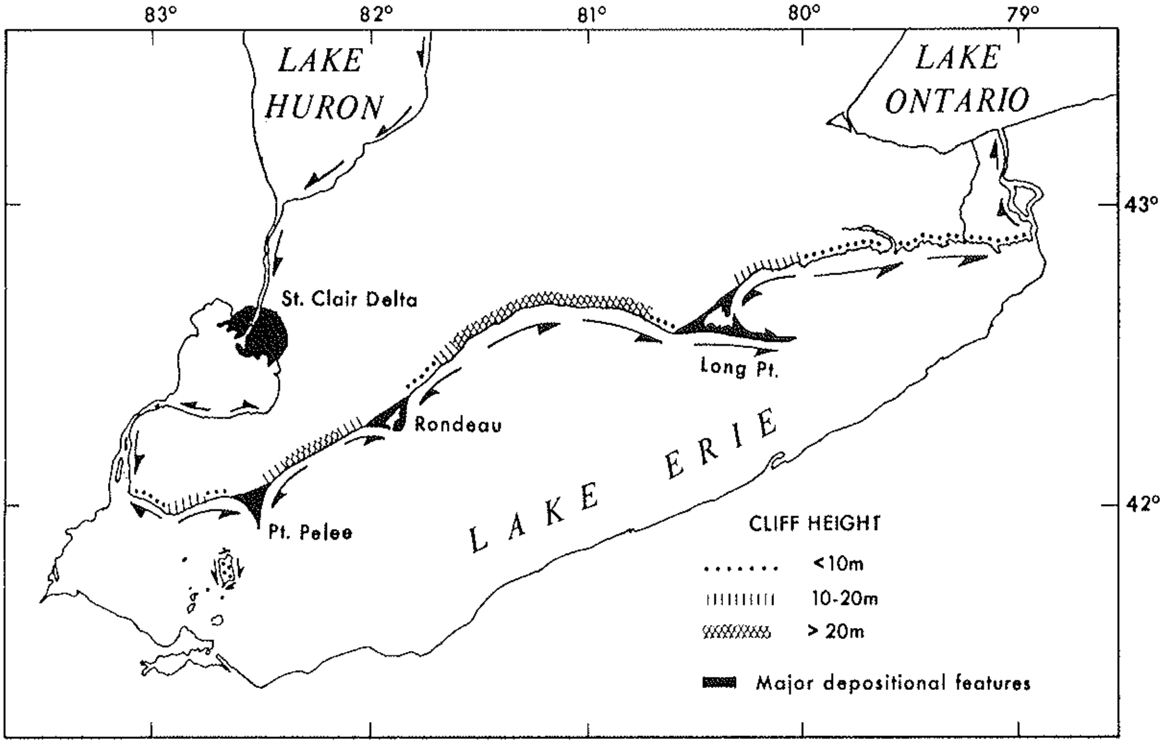


Figure 18. Lake Erie: cliff heights, sediment transport directions and depositional features (in part from Rukavina, 1976).

Cliff erosion rates are very low as this section of coast is open only to waves generated over a short southerly fetch (<50 km). Sediment transport in the shore zone is to the west, with net transport volumes in the order of 10,000 m^3/yr (Skafel, 1978).

At the bases of the cliffs, the beaches are narrow and composed of sand-pebble-cobble sediments. Beaches are well-developed only in western sections in the vicinity of Big Creek (see Photo 26).

2. Pelee Island

Pelee Island is a low bedrock island mantled by predominantly clay-silt sediments. Cliff heights vary between 0.5 and 3.0 m

TABLE 15. COASTAL ENVIRONMENTS OF LAKE ERIE

SUBDIVISION	RELIEF AND GEOLOGY	COASTAL ZONE		FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
		SHORE-ZONE CHARACTER	BEACH CHARACTER		
1. Northwest Coast	Low relief (<10 m): unconsolidated sediments rest on bedrock that outcrops below lake level	Straight coast of eroding cliffs that give way to low beaches in extreme western section	Low, narrow beaches of sand, pebble, cobble sediments	Very sheltered coast, maximum fetch 50 km; shore-zone ice up to 4 months/year	Limited supply; transport to the west
2. Pelee Island	Low relief (<3 m): bedrock (limestone) outcrops mantled by clay-silt sediments and by marshes	Small island with either low bedrock cliffs fronted by beach deposits with sand foreland at southern end of the island, or barrier beaches backed by marsh dykes	Low, narrow beaches of sand, pebble, cobble sediments; west coast protected by artificial structures; some limestone outcrops in the shore zone	West coast is sheltered (max. fetch 50 km); east coast exposed to 300 km fetch but lower energy because winds are from southwest; shore-zone ice up to 4 months/year	Limited supply; transport predominantly towards southern end of the island
3. Point Pelee System	Cliffs 10-20 m, of predominantly clay-silt sediments; foreland developed on moraine ridge	Straight coasts of eroding cliffs with large triangular foreland that is migrating slowly to the west	Beaches adjacent to cliffs are narrow or absent; west coast Pelee - wide, sand beach; east coast - narrow, eroding sand beach	West-facing coasts have short fetch (max. 75 km); east-facing coasts more exposed (max. fetch 300 km) and higher wave energy levels; shore-zone ice up to 4 months/year	Eroded cliff sediments transported towards Pelee from west and east; eastern shore is a zone of bypassing with net accretion on west coast of Pelee
4. Rondeau System	Relief 10-20 m in cliffed sections; sediments in cliffs predominantly clay-silt size; foreland developed on moraine ridge	Straight coasts of eroding cliffs with large triangular foreland that is migrating slowly to the east	Beaches adjacent to cliffs are narrow or absent; west coast Rondeau - narrow, eroding sand beach; east coast - wide, accreting, sand beach	West-facing coasts exposed to waves out of southwest (fetch 100 km); east-facing coasts more sheltered despite longer fetch because winds are westerly; shore-zone ice up to 4 months/year	Eroded cliff sediments transported towards Rondeau from west and east; western shore is a zone of bypassing with net accretion on east coast of Rondeau

5. Long Point System	Relief 10-40 m in cliffed sections; cliff sediments are variable - include silts, clays and sands; spit developed on moraine ridge	Straight coast of eroding cliffs and long (40 km) flying spit that is extending to east and migrating to north	Beaches adjacent to cliffs are narrow or absent; Long Point beaches are generally sandy, narrow and eroding; except in accreting eastern section where beach widens and is backed by dunes	Exposed, high wave energy coast, maximum fetch 250 km; shore-zone ice up to 4 months/year	Eroded cliff sediments transported to east; bypass central section of spit to accumulate in eastern areas
6. Long Point Bay-Turkey Point System	Backshore relief up to 40 m in cliffed section with unconsolidated sand and some clay-silt sediments; spit and large embayment in lee of Long Point spit	Sheltered bay and spit system with eroding cliffs in Inner Bay and to east of Turkey Point; extensive marshes on north Long Point and in Inner Bay	Beaches are generally narrow except on the east coast of Turkey Point	Sheltered coast, maximum fetch to the east (100 km); shore-zone ice up to 4 months/year	Eroded cliff sediments transported to southwest and accumulate at Turkey Point; elsewhere sediments are scarce
7. Northeast Coast	Relief decreases from maximum of 40 m in west to less than 10 m in eastern half; sedimentary rocks outcrop east of Peacock Point	Eroding clay-silt cliffs (10-20 m) give way east to bedrock headlands with beaches in embayments	Beaches narrow or absent except in easterly embayments; here wide, sand beaches developed, often backed by dunes	Exposed, high energy coast with maximum fetch of 300 km to southwest; some local sheltering due to the headlands in eastern section; shore-zone ice up to 4 months/year	West to east transport of eroded sediments; zones of accumulation on west sides of headlands in eastern section; elsewhere sediments are scarce
8. Welland Canal-Niagara River	Low backshore relief; canal has man-made shore, river cuts through bedrock outcrops and crosses resistant dolomite escarpment	River bank or man-made shorelines	Beaches absent or narrow and low with sand-pebble sediments	Low-energy riverine or channel systems; shore-zone ice up to 4 months/year	Sediments are scarce, transported by river currents to north

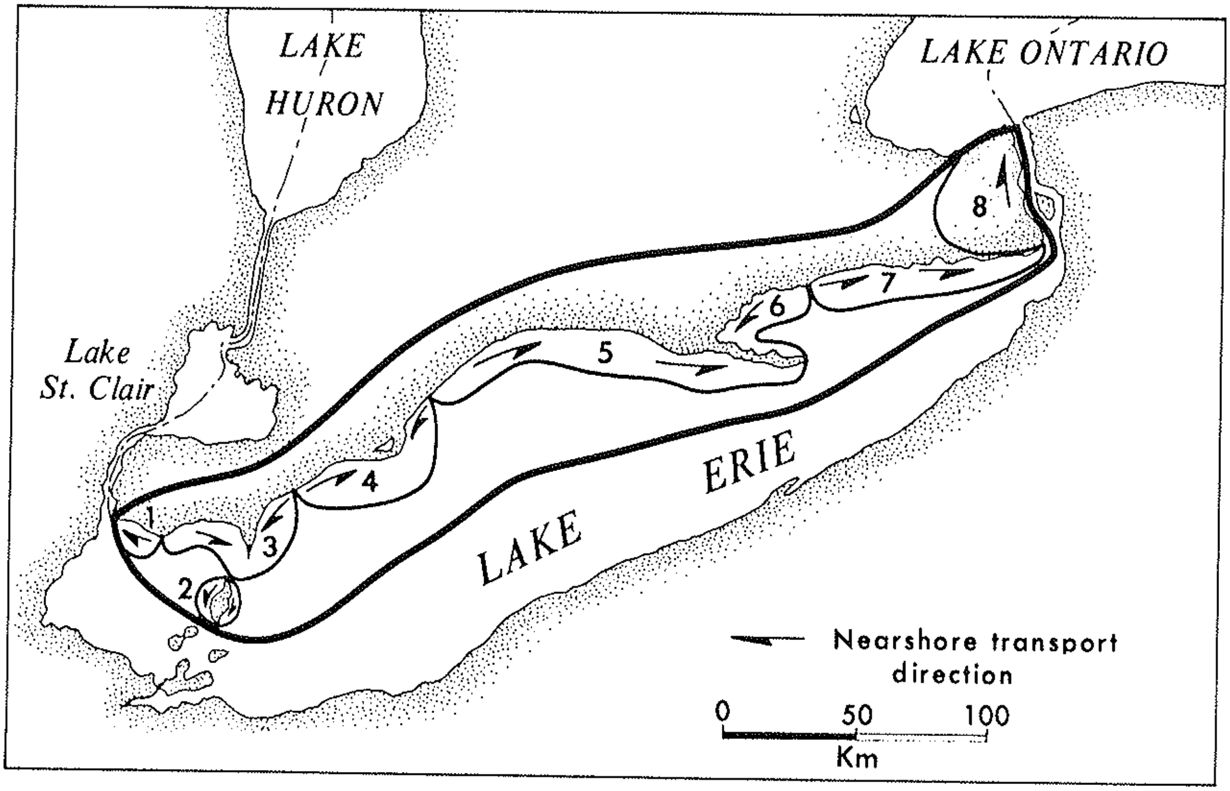


Figure 19. Coastal environments and shore-zone transport directions - Lake Erie region.

and the cliffs are generally fronted by narrow sand-pebble-cobble beaches. A large sand foreland has developed at the southern extremity of the island (Stone, 1949) at the end point of the sediment transport system.

Four limestone outcrops (in the northwest at Sheridan Point, in the northeast at Lizard Point, in the east central section at Middle Point, and in the southern half of the island) were originally separate islands that have been joined by barrier beaches to enclose extensive marshes and to form a single island (McCutcheon, 1967).

The sediment transport pattern in the shore zone is essentially clockwise around the island, except on the west coast (between Sheridan Point and Fish Point) where transport is to the south (Fig. 18). The foreland at Fish Point developed due to the convergence of the shore-zone sediment transport system at the southern tip of the island.

The shore zone is characterized by sand-pebble-cobble beaches with sand accumulations in the areas of Lighthouse Point and Fish Point. Beaches are backed either by low till cliffs or by dyked and reclaimed marshes. Limestones outcrop as rock platforms in the shore zone near Sheridan Point, Middle Point and Mill Point. Despite the short fetch (50 km), the west coast of Pelee Island is the more exposed shore as the prevailing winds are out of the westerly quadrant. The shore zone on this west coast is protected along almost the entire length by groynes and/or rip-rap (McCutcheon, 1967).

3. Point Pelee System

The Point Pelee system is characterized by two zones of cliff erosion which supply sediment to a large depositional foreland that is a zone of sediment transport convergence (Fig. 18).

West of Point Pelee the bedrock outcrops below the present lake level and is mantled by unconsolidated glacial and fluvial deposits. These sediments are predominantly clays and silts that form low cliffs (<3 m) at the shoreline. Two sections of sand-silt deposits between Colchester and Oxley and between Kingsville and Leamington form higher cliffs (10-25 m) (Coakley and Cho, 1972). East of Colchester, cliff erosion rates reach maxima of 1.2 m/yr (Coakley and Cho, 1972), and the sandy and silt cliff sediments are transported to the east by wave action. Erosion rates in the section east of Kingsville are relatively low (about 0.1 to 0.5 m/yr) (Coakley and Cho, 1972). Skafel (1978) notes that the potential sediment transport in this eastern section is in the order of 100,000 m^3/yr, but that the actual net transport to the east is only in the order of 20,000 m^3/yr as the transport potential due to the sheltered location of this coast is greater than the actual sediment supply to the shore zone.

East of Point Pelee, transport of the eroded sediment is towards the west (St. Jacques and Rukavina, 1976). The shore-zone character is relatively uniform on this straight coast and beaches at the base of the eroding cliffs are either narrow or absent. Sediments have accumulated on the east side of Wheatley Harbour due to interruption of the transport system by jetties. Computed, net, longshore sediment transport rates at Wheatley Harbour are in the order of 50,000 m^3/yr (Skafel, 1977). The section east of Wheatley (for 5 km) is characterized by low cliffs (<10 m) which are eroding at rates up to 1.0 m/yr (Boulden, 1975). To the east of this short section, the remaining coast within this subdivision is characterized by cliff heights of 10-20 m and by erosion rates in the order of 0.5 m/yr.

The symmetrical sand foreland of Point Pelee (Photo 29) which extends approximately 15 km into the lake, was formed by the reworking of sediments deposited in the lake basin as a moraine ridge (Coakley, 1976). The foreland has decreased in size since its origin and has migrated slowly to the west

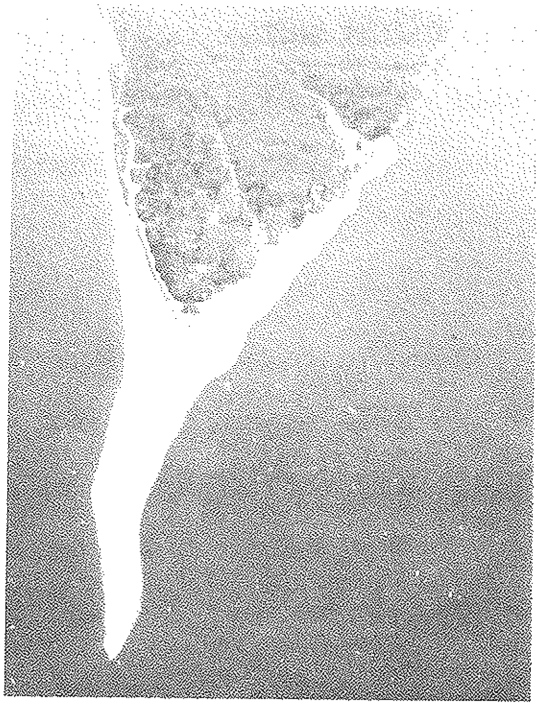


Photo 29. View to north of the southern tip of Point Pelee (photograph by N.A. Rukavina, 27 May 1978).

(Coakley, 1976; Trenhaile and Dumala, 1978). The foreland is exposed to waves from the west and east, with higher energy levels on the east-facing shore due to the longer fetch distance in that direction. There is a marked seasonal variation in wave-energy levels (Table 14, p. 106) due to the greater frequency of storms in late autumn and early winter months. Net shore-zone sediment transport is to the south on the east coast, and to the north on the west coast, with computed net transport rates of 26,000 and 4,400 m^3/yr respectively (Skafel, 1977). The beaches of the northern half of Point Pelee are backed by a drained marsh that is protected by dykes and seawalls. The southern section has been developed as a National Park and is characterized by sand-pebble beaches, backshore dunes up to 8 m in height, and an extensive marsh.

The eastern shore of Point Pelee is a narrow barrier beach that is backed by marshes which are dyked in the northern half of the section. This shore is undergoing erosion at rates in the order of 0.5 to 2.0 m/yr (Coakley, *et al.*, 1973), and the low beach is frequently overtopped by storm waves in unprotected sections (East, 1976). Erosion rates increase to the south. Rapid local erosion in the area of Bush and Lake Ponds (Photo 30) has resulted from sediment starvation due to the recent (1971) construction of groynes on Marentette Beach in the adjacent up-drift section (East, 1976). The southern tip of Point Pelee is protected by rockwalls, pilings and concrete crosses placed in the nearshore zone to absorb wave energy.

The western shore of Point Pelee is a more sheltered wave-

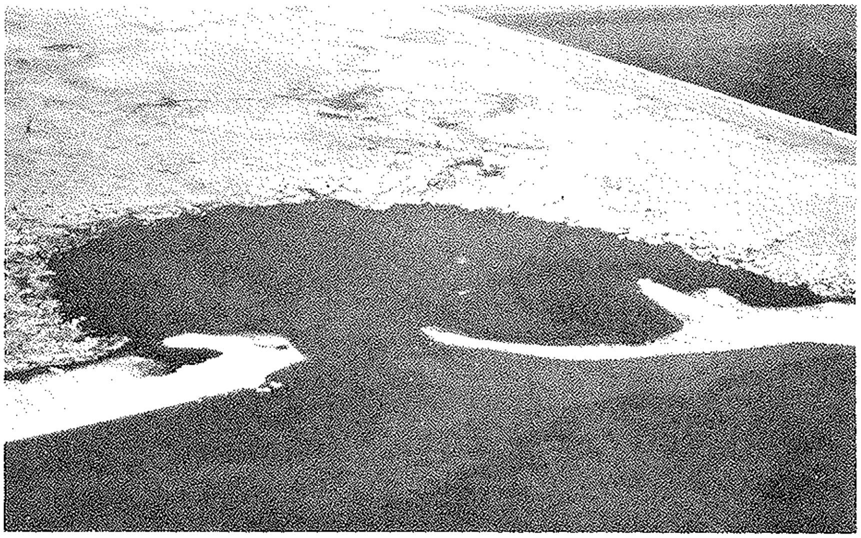


Photo 30. Bush Pond on the east coast of Point Pelee. The shoreline in this section has been eroded and the pond breached since 1971 due to sediment starvation. The dyke and reclaimed marsh areas are visible in the upper right of the photograph (27 May 1978).

energy environment and erosion rates decrease to the north on this beach. The beaches are wider than on the eastern shore and in the National Park the backshore zone has an extensive system of dunes. The section north of the Park is largely protected by seawalls.

On both east and west shores of Point Pelee the nearshore zone is characterized by discontinuous parallel bars (Shaw, 1977) that appear to respond to the seasonal variations in wave-energy levels (Haras, quoted in East, 1976). The beach environments undergo considerable changes due to storm-wave action, and overwash is a major process on the unprotected sections of the eastern shore.

4. The Rondeau System

Although similar to Point Pelee in that the foreland is a zone of sediment transport convergence, Rondeau differs significantly as it is more exposed to waves out of the southwest and it is migrating towards the northeast.

The section west of Rondeau is characterized by high (10-20 m) cliffs (Photo 31) and by sediment transport to the east, as evidenced by the accumulation on the west side of the jetties of Erieau Harbour. The cliffs of this section are composed predominantly of clay-silt sediment so that, despite an estimated annual sediment erosion in the order of 230,000 m^3/yr, less than one quarter is in the sand-pebble size range (St. Jacques and Rukavina, 1976). In most sections a narrow beach of sand-pebble-cobble sediments protects the base of the cliff from normal

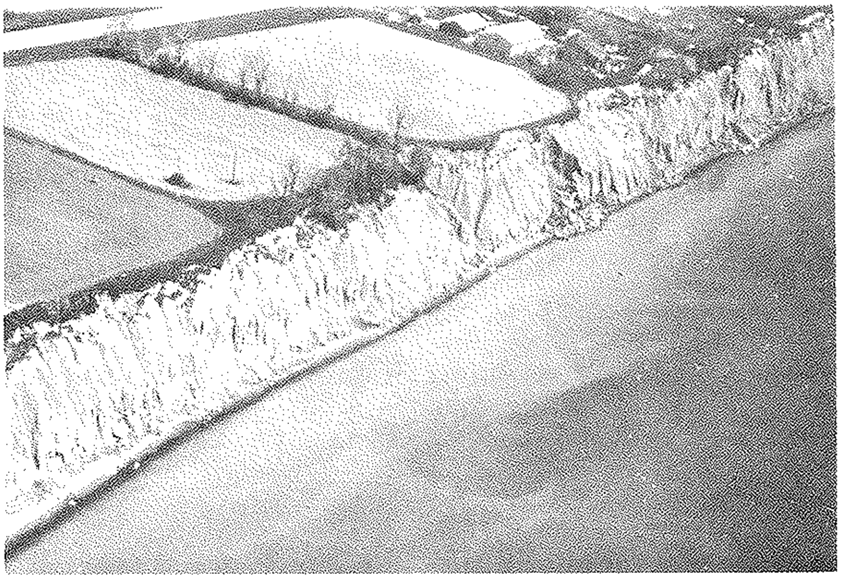


Photo 31. Vertical cliff of silt-clay sediments near Port Alma. The erosion rate in this relatively sheltered western section of the subdivision is in the order of 0.25 m/yr (27 May 1978).

(non-storm) wave erosion (Photo 31) and, for the most part, the cliffs have a vertical face that is subject to basal erosion and undercutting during storms. Where erosion rates are low, the cliff face is at a lower angle and is vegetated.

East of Rondeau the coast is partly sheltered from waves out of the southwest by the foreland. The clay-silt cliffs are eroding at rates of 0.25 to 1.0 m/yr and the sediment is transported westwards towards Rondeau.

The foreland of Rondeau, which extends 11 km into the lake from the mainland shore, developed on a moraine ridge that was deposited in the lake basin during the retreat of the ice. The foreland encloses a large bay with marshes and has migrated towards the east so that little remains of the original west-facing beach system.

In contrast to Point Pelee, which is migrating towards the west, this foreland is more exposed to waves generated out of the southwest, over a fetch of approximately 100 km. The west-facing shore is characterized by a narrow, eroding beach (Photo 32a) that has been breached in the central section. Sediment is supplied to this shore from the west, as evidenced by the accretion on the west side of Erieau Harbour (Latham, 1975), but the supply has been insufficient to offset the removal and longshore transport of beach material by wave action. The southern and eastern sections of the foreland (Photo 32b) have prograded as eroded beach sediments have been transported to the west around Point aux Pins from the eroding beach section, and as sediments from cliff erosion to the east of the foreland have been carried westwards by waves out of the east. East of Point aux Pins the beach is wide (Photo 32b), but the low berm is subject to overwash during periods of storm waves. In this zone of sediment transport convergence, the beach is prograding at rates in the order of 0.5 m/yr (Boulden, 1975).

The enclosed bay of Rondeau Harbour is fringed by extensive, low marshes that have a complex, irregular shoreline created by the presence of numerous creeks and channels. In the northwest corner of the bay, a small section of the marsh has been dyked but elsewhere the marshes are unprotected.

5. The Long Point System

The large spit of Long Point extends 40 km into the lake (Fig. 18), and was formed by reworking of a moraine deposited

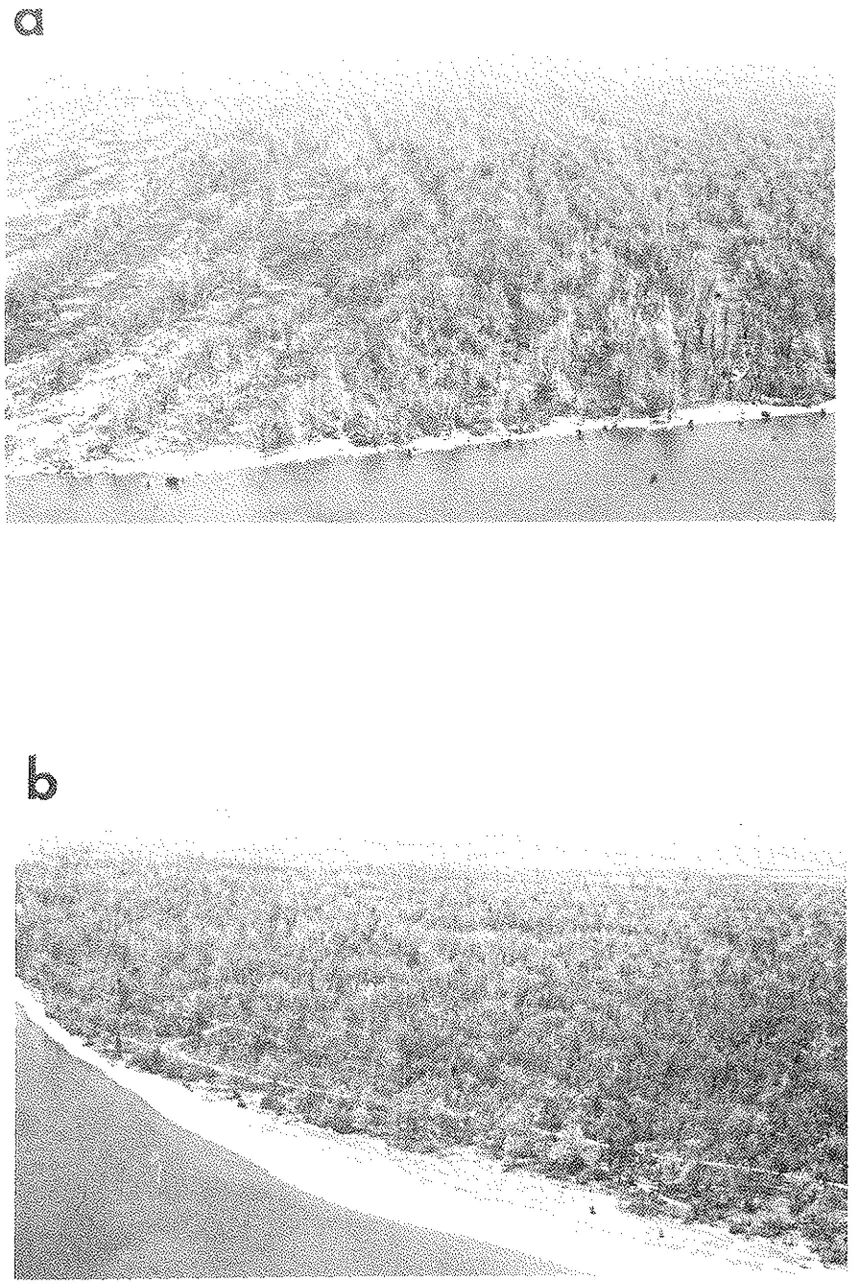


Photo 32. (a) Eroding southwest-facing and (b) accreting southeast-facing beaches adjacent to Point aux Pins (27 May 1978).

by the retreating ice. Sediment is supplied into the present system from the west and the spit continues to grow eastwards at a rate of approximately 7 to 8 m/yr (Wood, 1960). Cliff erosion provides approximately 3,000,000 m^3/yr of material to the shore zone and the supply of sand and gravel-size sediments to the spit system from the west is estimated to be in the order of 420,000 m^3/yr (St. Jacques and Rukavina, 1973 and 1976). The relatively rapid growth rate of Long Point is due to the combination of the availability of sediments and the high wave-energy levels. The latter is a function of the coincidence of the prevailing southwest winds and the long fetch to the southwest (250 km).

To the west of the spit the coast is relatively straight and is characterized by high cliffs (10 to 40 m). The cliffs in this subdivision are comprised of predominantly clay and silt sediments (Photo 33), except to the east of Port Stanley where sections of the unconsolidated cliffs are sands and silts (Photo 34). Where present, these sand-silt deposits are exposed at the base of the cliffs and are less resistant to erosion by waves than the clay-silt deposits. Beaches are narrow or absent except at Port Stanley, Port Bruce and Port Burwell where sediments have been trapped on the west sides of harbour jetty systems.

Immediately to the east of Port Talbot, cliff recession is in the order of 0.5 m/yr as far as Port Stanley, except for one section where rates of 2.0 m/yr have been recorded (Boulden, 1975). Erosion rates increase sharply to the east of Port Stanley as exposure to waves increases. In two sections, one

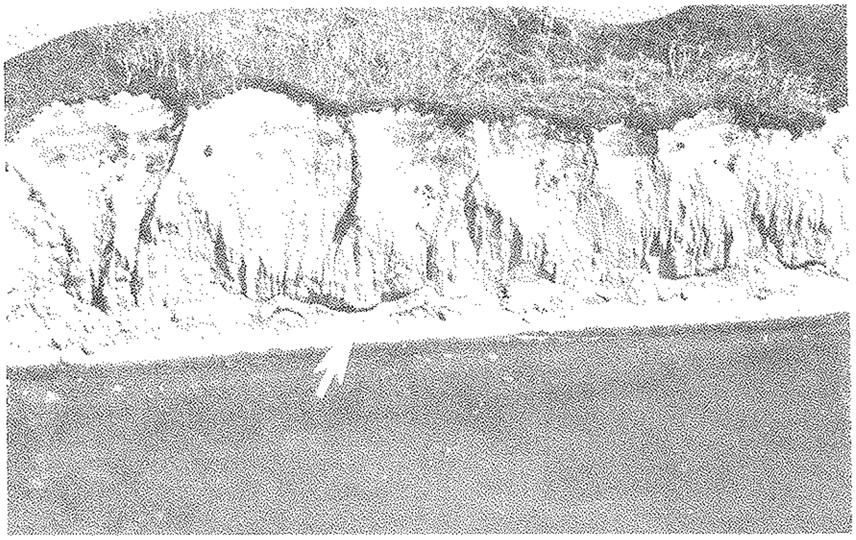


Photo 33. Vertical scallopped cliffs just west of Port Stanley. Note the wave-cut notch at the base of the cliff (indicated by the arrow) that is partially buried by sediments eroded from the cliff face (27 May 1978).

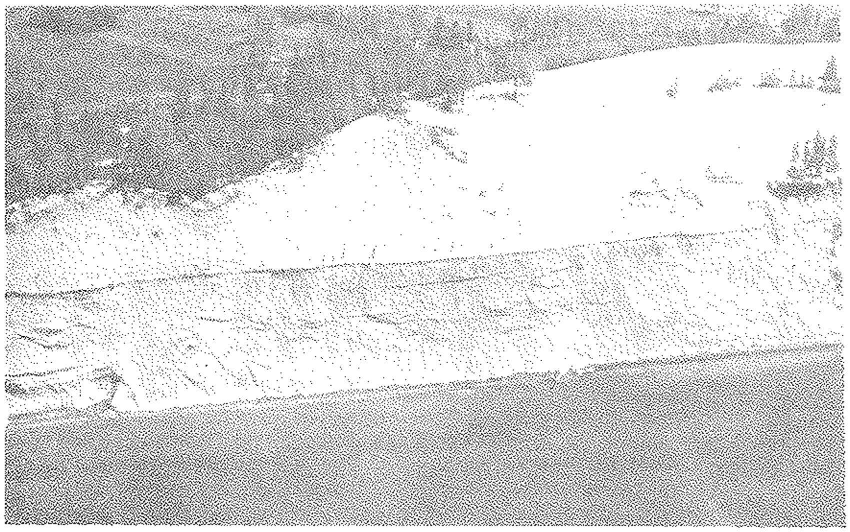


Photo 34. Sand cliff with perched dunes at Sand Hills Park, Jacksonburg (27 May 1978).

immediately east of Port Stanley and the other immediately east of Port Burwell, high erosion rates are due primarily to the presence of the sand and silt deposits (Gelinas and Quigley, 1973). In these sections, the absence of clay sediments reduces the strength of the exposed deposits and frequent small slides result from basal erosion by wave action (Quigley, *et al.*, 1977) (Photo 34).

Between Port Stanley and Clear Creek, most sections are retreating in the order of 3.0 m/yr with local maxima up to 5.0 m/yr in places. In contrast to the western half of this subdivision where cliff erosion is a combination of sheet wash, landslides, and wave erosion, the rapid retreat rates in the eastern half are due primarily to wave erosion. High lake levels over the past 10 years have enabled waves to cut into the base of the cliffs and thereby cause large-scale slumping (Quigley and Gelinas, 1976).

In general, wave-energy levels, cliff height, and retreat rates increase towards the east in this subdivision. The shore zone is characterized by vertical cliffs except where jetties interrupt the longshore sediment transport system. In the west the cliffs are relatively stable and recession results primarily from cliff face erosion. East of Port Stanley wave erosion at the base of cliffs is presently causing large-scale slumping and sliding of the less resistant cliff sediments.

The beach system of Long Point, although growing to the east, is also retreating northwards. The neck of the spit is a 2.5 km-section that has been breached and closed several times.

At present this section of the spit is discontinuous and, where present, the beaches are very low and subject to inundation and overwash even during periods of mild wave activity. The 30-km section east of the neck is a zone of sediment accumulation and is characterized by a wide sand beach system backed by dunes up to 10 m in height (St. Jacques and Rukavina, 1973).

6. Long Point Bay - Turkey Point System

This relatively sheltered subdivision comprises the lee (north) shore of Long Point and the Turkey Point spit, the latter being supplied with sediment transported to the west from the adjacent cliffed coast (Fig. 18).

The north shore of Long Point spit is a sheltered environment characterized by an alternating and complex sequence of narrow, low beaches and marshes. To the north of the neck section of the spit, Inner Bay is an open, shallow embayment. The south, east and northeast shores of Inner Bay are marshes, whereas, the northwest shore is a section of clay cliffs up to 40 m in height (Sly and Lewis, 1972).

Turkey Point is a small spit that is slowly prograding and extending southwards to close off Inner Bay and has developed by the northeast to southwest transport of sediments eroded from the cliffs to the northeast. The beaches on Turkey Point are low but wide, and the southern 2 km of the spit and the Inner Bay shore of the spit is an extensive marsh complex.

The coast east of Turkey Point to Port Dover is a section of eroding cliffs. The shoreline is relatively straight with shore-zone sediment transport to the west towards Turkey Point. The cliff material is predominantly sands (St. Jacques and Rukavina, 1973). Erosion rates are in the order of 0.5 to 0.9 m/yr (Boulden, 1975).

7. Northeast Coast

This subdivision has a west to east transport system (Fig. 18) and can be further divided into two units based on shoreline types. The western unit from Port Dover to Peacock Point is a straight coast characterized by clay cliffs that decrease in elevation from 18 m at Port Dover to 8 m at Peacock Point (St. Jacques and Rukavina, 1973). The eastern unit, from Peacock Point to Fort Erie, is an irregular shoreline with alternating sequences of bays and headlands.

The average cliff erosion rates in the western unit are high (1.5 m/yr) (St. Jacques and Rukavina, 1973). Unconsolidated cliffs also occur to the east of Peacock Point (Photo 35) but are lower in elevation and have lower erosion rates (in the order of 0.5 m/yr).

The headlands that give the shoreline east of Peacock Point an irregular configuration result from bedrock exposure in the shore zone (Photo 36). This eastern unit is one of low relief, generally less than 10 m, with backshore cliffs of clay deposits that rest on the exposed bedrock (St. Jacques and Rukavina, 1973). Sand or sand-pebble beaches have developed in the embayments between headlands and in some sections are backed by high (20 m) dune systems.

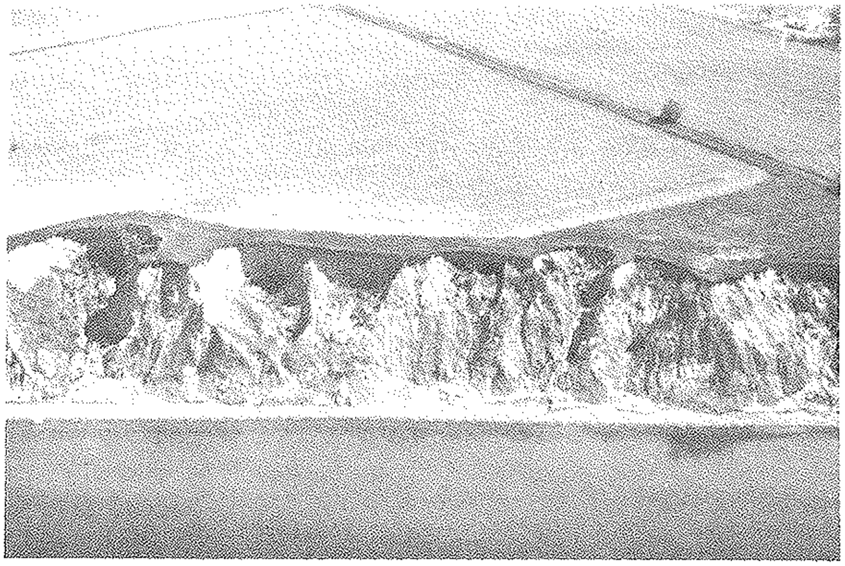


Photo 35. "Scallop" cliffs cut into till on the west coast of Mohawk Point. (27 May 1978).

Photo 36. Exposed bedrock headland with backshore pebble-cobble beach at Point Abino (27 May 1978).

This whole coast is exposed to waves along the axis of the lake and is subject to high lake levels that result from seiche effects. The shore-zone sediment transport direction is to the east. The headlands act as natural groynes so that in many cases, beaches have developed, particularly on the western shores of the headlands, for example, at Grant Point and at Port Maitland. Port Abino (Photo 36) extends 3 km lakeward from the main trend of the shore and has well-developed beach-dune systems on both west (Photo 37) and east shores (Rukavina and St.Jacques, 1971). Bedrock outcrops are more prevalent east of Port Maitland, and in the intervening embayments, rivers and creeks have marsh shores and the river exits are partially closed by spits and barriers.

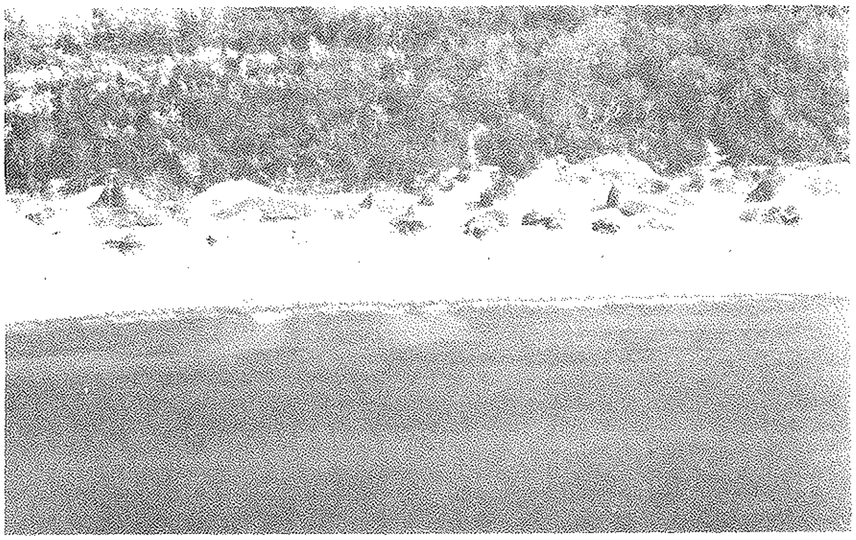


Photo 37. Wide sand beach backed by low dunes on the west coast of Port Abino (27 May 1978).

8. Welland Canal - Niagara River

The present Welland Ship Canal, which was completed in 1932, drops 99.7 m through a system of eight locks over the 44-km distance between Lakes Erie and Ontario. The canal banks are largely man-made materials and in the lower (northern) section, concrete blocks and natural sediments characterize much of the canal shore. The channel is generally 100 m wide and the banks are continuously affected by ship wakes. Even though the ship speeds are slow, the water displacement is sufficient to create waves up to 0.5 m.

The natural outlet for Lake Erie is through the Niagara River, which is 60 km long and drops into Lake Ontario through a series of rapids and falls. The river is characterized by strong currents, and the upper (southern) and lower (northern) rapids drop 15 m and 25 m respectively; the intervening falls are 55 m in height. The water level of the river above the Falls fluctuates up to 1.0 m due to variations in Lake Erie water levels. The flow over the Falls is regulated by a series of five power-plant diversions. Below the Falls, rapid water-level fluctuations up to 0.2 m are common due to water discharges from the pump-storage systems associated with the power plants (Great Lakes Basin Commission, 1975a).

During winter months ice jams at the river entrance. Since 1964 an ice boom has been deployed between December and April or May to prevent the movement of ice down the river. The boom is designed to consolidate the early ice cover so that it does not break up and move down river (Great Lakes Basin Commission, 1975a). A second, natural ice bridge forms at the gorge below the Falls and, at times, has reached 24 m above the river level.

The river banks are a mixture of man-made structures, bedrock outcrops and beaches of poorly-sorted sediments.

4.6 LAKE ONTARIO REGION

Summary

The coasts of Lake Ontario are similar to those of Lake Erie in the sense that bedrock outcrops in the eastern and western sections, and the north shore is characterized by cliffs of unconsolidated sediments. However, the coast is more variable in character and the unconsolidated cliffed sections are generally lower in height and are eroding at slower rates than those in Lake Erie. Erosion rates are low on the northwest and south coasts as these are relatively sheltered environments. In the Scarborough Bluffs section, erosion rates are artificially high at present due to sediment removal that has reduced the natural protection at the base of the cliffs. To the east of the Scarborough Bluffs, many sections of the cliffs along the north shore are vegetated and relatively stable.

Although much of the sediment supplied to the shore zone is fine-grained and removed in suspension, sufficient sand- or pebble-size sediments are available to nourish a series of large depositional features. Sediment transport directions are predominantly to the west in western sections and to the east along the north shore. The large depositional features have developed at the end points of sediment transport systems in the southwest and in the northeast. To the east of the Prince Edward Peninsula, the coast changes to a complex system of islands and channels with predominantly bedrock outcrops in the shore zone.

Burlington Bar and the barrier systems on the west coast of Prince Edward Peninsula developed as a result of sediment trapping. Burlington Bar is relatively stable, although it has been undergoing some erosion in recent years. The Prince Edward Peninsula beach-dune systems are a series of bayhead barriers that are backed by extensive marsh areas. The Toronto Harbour spit developed by the accumulation of sediments eroded from the Scarborough Bluffs. This system is now characterized by a series of extensive protection structures that were made necessary in part by sediment starvation due to man's activities in modifying natural shore zone processes.

The northeast coast of the lake is a series of predominantly low-energy channels and islands characterized by bedrock outcrops and extensive marshes. The Prince Edward Peninsula is a section of resistant limestone outcrops that gives way to Shield rocks east of Kingston. The entrance of the St. Lawrence River is characterized by an archipelago of islands and channels.

Although the shoreline types of this region are varied, the character of the coastal zone is predominantly eroding cliffs of

unconsolidated sediments or bedrock outcrops. Large depositional features are restricted to three localities. Elsewhere, beaches are generally low and poorly-developed due to limited supplies of sand and coarse-grained sediments.

4.6.1 Coastal Processes and Geology

Winds

The prevailing wind direction is out of the southwest and parallels the lake axis (Windsor: Toronto, Fig. 3, p. 22; Table 3, p. 24). The seasonal variation in the wind regime is characterized by maximum velocities from November to April (Table 3).

Waves

In addition to the seasonal variation in wave heights (Fig. 4, p. 26), there is a spatial variation that results from the prevalence of southwesterly winds. Measured values (Table 16) indicate that wave heights in the eastern parts of the lake are approximately twice as great as those in the western sections. Main Duck Island is exposed to a maximum fetch of 250 km; and the fetch direction (southwest) coincides with the prevailing and dominant wind direction. The southwest part of the lake is relatively sheltered as winds are out of the northeast and east (*i.e.*, onshore) only 25% of the time at Burlington; wave data collected on this section are similar to that recorded at Toronto.

Ice

Lake Ontario rarely has an ice cover greater than 6/10, although a 100% cover has been reported twice in the last century (1892-93 and 1933-34, Anderson, *et al.*, 1961). The average ice

TABLE 16. Measured Mean Monthly Significant Wave Height (m) (Environment Canada, undated)

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Toronto (1972-1973)	0.9	0.7	0.7	0.6	0.2	0.2	0.2	0.3	0.4	0.5	0.8	0.9	0.4
Cobourg (1972-1973)	-	-	-	0.5	0.3	0.3	0.3	0.4	0.5	0.6	1.0	0.8	0.5
Main Duck Island (1973-1975/76)	-	-	-	0.8	0.7	0.6	0.5	0.7	0.9	1.3	1.1	-	0.8

cover is 1/10 to 2/10, with the maximum occurring in early March (Rondy, 1976). The ice is concentrated primarily in the eastern sections (Fig. 6, p. 29), due to the strong southwesterly winds. Shore-zone ice protects all the lake coasts (Photo 1, p. 30), forming in mid-late December and persisting in western parts until mid-March, and in sheltered eastern areas until early April (Fig. 7, p. 31).

Water Levels

The maximum, long-term, lake-level variation is 2.0 m, and the average annual variations are in the order of 0.5 m (Table 4, p. 32). The lake is subject to storm surges similar to, but not as large as, those that occur in Lake Erie (p. 107). Water levels recorded during a single storm in January 1972 were: Burlington, -0.27; Toronto, -0.06; Point Petre, +1.0; and Kingston, +0.46 m (Bolduc, 1974).

Geology and Coastal Transport Systems

The lake basin is oriented southwest-northeast and follows the trend of a pre-glacial river system that was scoured by the ice sheets. The sedimentary rocks dip towards the south, and the relatively resistant rocks of the Niagara Escarpment form the southern and western margins of the lake basin (Fig. 10, p. 35). Bedrock outcrops in the shore zone in extreme eastern and western sections of the lake. To the east of Kingston, very resistant metamorphic Shield rocks form the eastern margin of the lake. These resistant rocks are cut by the St. Lawrence River which is the outlet for the Great Lakes system to the Gulf of St. Lawrence and the Atlantic.

In sections where bedrock is exposed, shore erosion rates are low and little sediment is supplied to the shore zone. The primary areas of erosion are sections of cliffs cut into unconsolidated sediments on the south coast west of the Niagara River, and on the north coast between Scarborough and Colborne. Both sections are characterized by predominantly silt-clay sediments; low relief (5-20 m) except in the Scarborough area; erosion rates that range between 0.5 and 1.0 m/yr; and narrow beaches.

On the south coast west of Jordan River, the sediment is transported to the west towards the Burlington Bar system, a barrier that has developed across the entrance to Hamilton Harbour. To the northeast, a large flying spit encloses Toronto Harbour. This depositional feature originated by the westward transport of sediment eroded from the Scarborough Bluffs. Further to the east (beyond Whitby), eroded sediments are transported eastward and have been trapped in a series of large bays that result from the protrusion of the Prince Edward Peninsula into the lake basin. This peninsula is a low-lying outcrop of relatively resistant limestones and is separated from the mainland by the narrow channel system of the Bay of Quinte. The large bay-mouth bars on the exposed west coast of the peninsula are in marked contrast to the low-energy rocky shores of the sheltered north and east coasts of the peninsula. The resistant limestones give way eastwards to Shield rocks as the lake narrows into the St. Lawrence River.

The transport of eroded sediments in the shore zone of Lake Ontario follows a relatively simple pattern (Fig. 20). In the western part of the lake transport is to the west and in the central and eastern sections sediment is transported towards the east. The three areas of large-scale sediment accumulation (Burlington Bar, Toronto Harbour spit, and west Prince Edward Peninsula) have resulted directly from the erosion, transport and

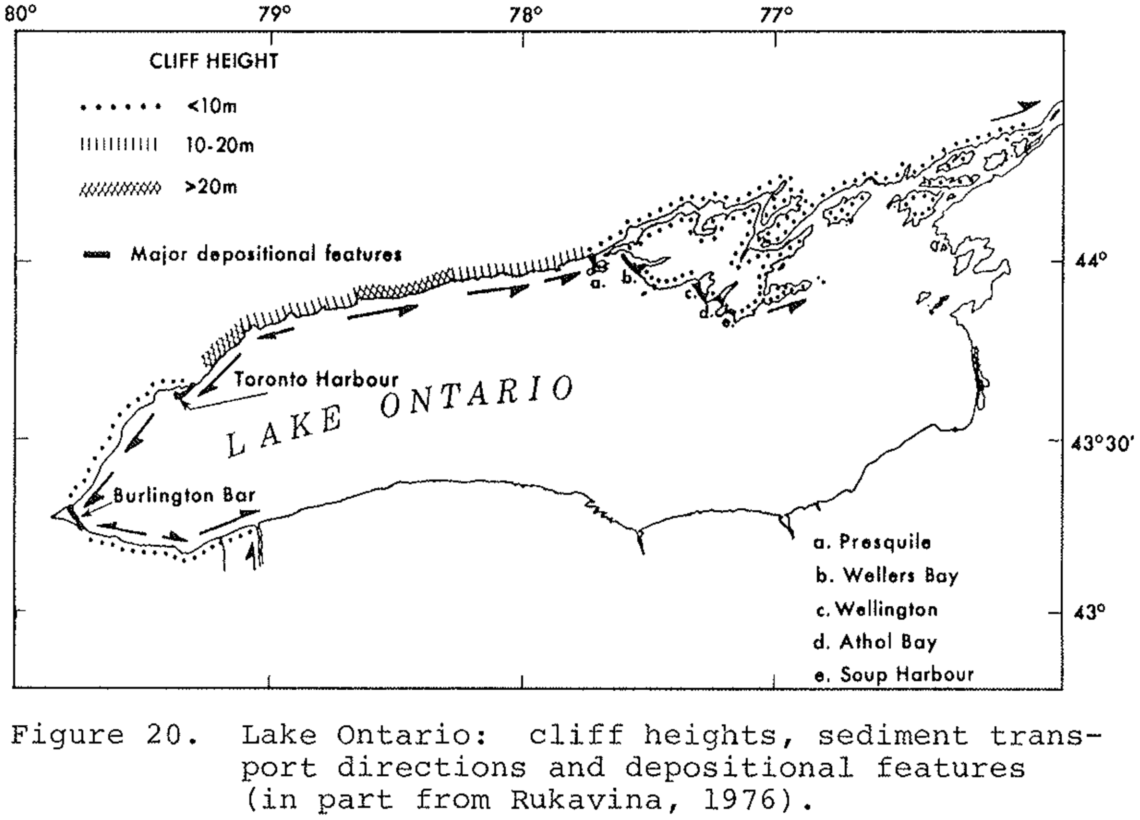


Figure 20. Lake Ontario: cliff heights, sediment transport directions and depositional features (in part from Rukavina, 1976).

accretion of sediments eroded from adjacent sections of unconsolidated cliffs. The northeast section of the lake (Bay of Quinte-St. Lawrence River) has a complex shoreline with very localized transport systems, except for the St. Lawrence River where sediments are carried east towards the Gulf of St. Lawrence.

The text description of the shore zone is based on the subdivision of the coast into the primary sediment transport systems which are outlined in Figure 21 and summarized in Table 17.

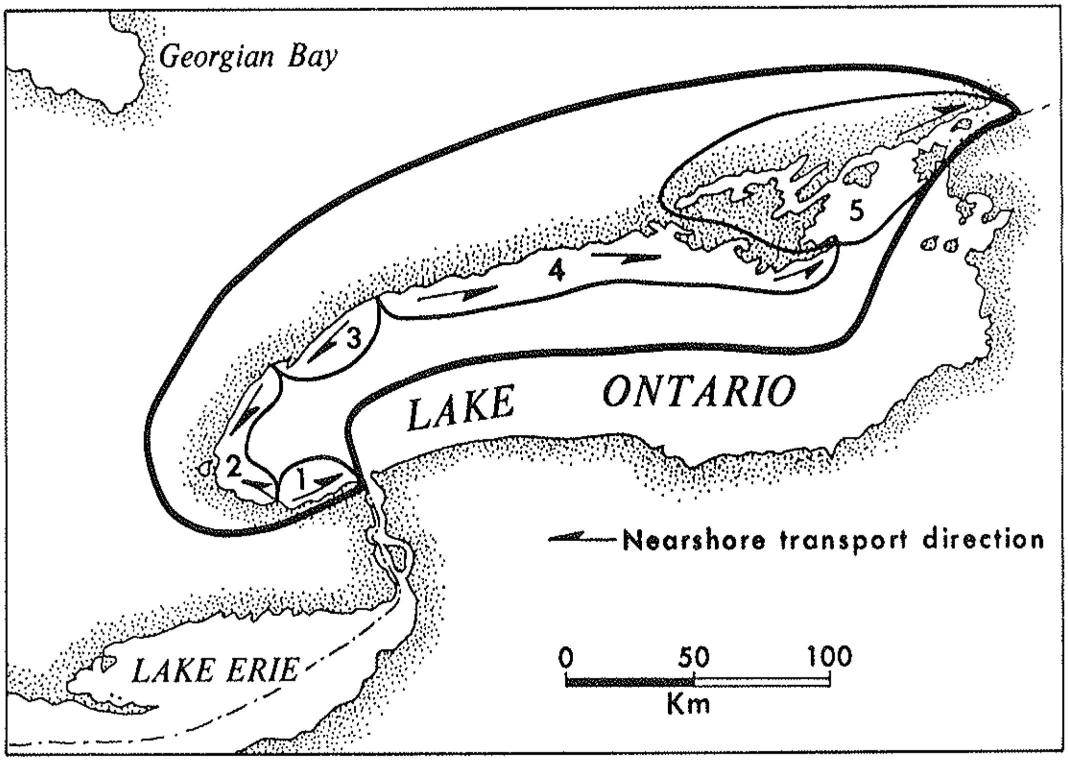


Figure 21. Coastal environments and shore-zone transport directions - Lake Ontario region.

TABLE 17. COASTAL ENVIRONMENTS OF LAKE ONTARIO

		COASTAL ZONE			SEDIMENT
SUBDIVISION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	BEACH CHARACTER	FETCH, WAVE EXPOSURE AND ICE	AVAILABILITY AND TRANSPORT
1. Southeast Coast	Low relief (<10 m): unconsolidated cliffs of predominantly clay-silt sediments	Straight coast of low cliffs with beaches across mouths of small rivers: many sections of artificial protection	Low, narrow beaches of sand, with pebble-cobble sediments adjacent to cliffed sections	Exposed to northeast (fetch 250 km), but sheltered coast because of predominantly offshore (westerly) winds: shore-zone ice up to 4 months/year	Limited sediment supply with transport to the east
2. Burlington Bar System	Sedimentary rocks outcrop in many sections, relief <10 m: some sections of unconsolidated materials	Straight, low coasts with large bay-barrier across Hamilton Harbour: many sections of artificial protection	Beaches absent or low and narrow except at Burlington Bar: this barrier has a high (2 m), wide sand beach	Exposed to east (fetch 250 km): sheltered coast because of predominantly offshore (westerly) winds: shore-zone ice up to 4 months/year	Sediments transported to the west, Burlington Bar is a convergence zone: sediments generally scarce along north coast of this system
3. Toronto Harbour System	Cliff heights decrease to east from a maximum of 100 m in Scarborough Bluffs: cliffs are unconsolidated silts, sands and gravel	Straight, high, cliffed coast gives way in west to large flying spit system that has been protected and stabilized by numerous artifical structures	Beaches absent or narrow in cliffed sections: Toronto spit beaches are low and narrow due to recent scarcity of sediments	Exposed to east and southeast (fetch 50-200 km), relatively sheltered because predominant west winds have maximum fetch of only 50 km; shore-zone ice up to 4 months/year	Sediments transported to the west, present-day supply of sediments is relatively scarce
4. North Coast-Southwest Prince Edward Peninsula	Unconsolidated cliffs (<15 m) give way in east to low, bedrock (limestone) shore zone	North coast-straight, cliffed section with few beaches; the west coast of peninsula is an alternating sequence of rock headlands and bay-mouth barriers with many backshore marshes	Bay-mouth barriers generally have wide sand beaches with dunes; elsewhere sand-pebble beaches are absent or narrow	Exposed, high-energy coast: fetch 250 km; shore-zone ice up to 4 months/year	Sediment transport to east, material trapped in west-facing bays
5. Northeast Coast	Low relief: limestone outcrops give way east of Kingston to resistant Shield rocks	Complex coastline of channels, islands, headlands and bays: predominantly bedrock outcrops with few sections of unconsolidated cliffs; marshes in sheltered bays	Beaches absent or narrow: few sections of well-developed beaches: sediments are sand-pebble-cobble	Sheltered, low-energy coasts, fetches are generally <50 km; riverine processes east of Kingston; shore-zone ice up to 5 months/year	Sediments scarce: numerous local, small transport system

4.6.2 Coastal Environments of Lake Ontario

1. Southeast Coast

This low-lying coast (Fig. 21) is a region of predominantly offshore winds so that, although the fetch extends up to 250 km to the northeast, wave-energy levels are generally low. During periods of storm winds out of the northeast quadrant, however, shoreline energy levels can be high. The shore zone of this subdivision is characterized by eroding clay-silt cliffs, generally less than 10 m in height. Beaches are well-developed only adjacent to rivers and creeks and are either very narrow or absent in cliffed sections of this coast. Where beaches are developed, the sediments are in the sand and pebble size range. The beach berms are low, less than 1.5 m above lake level, and are easily overwashed during storms. Much of the eroding sections of the coast are protected by rock, rubble or seawalls (c.f. Photo 38), but the protection is generally haphazard rather than a planned effort to control the shore-zone erosion. Marsh areas are associated with the beaches that have formed in embayments or at river exits. Although not extensive, the marshes are an important local feature of the shore zone.

The net sediment transport direction is from west to east (Fig. 20). The annual sediment input from shore erosion is in the order of 460,000 m^3, of which approximately 70% is in the silt-clay size range (Rukavina, 1976).

2. Burlington Bar System

The accumulation of sediments to form the barrier of

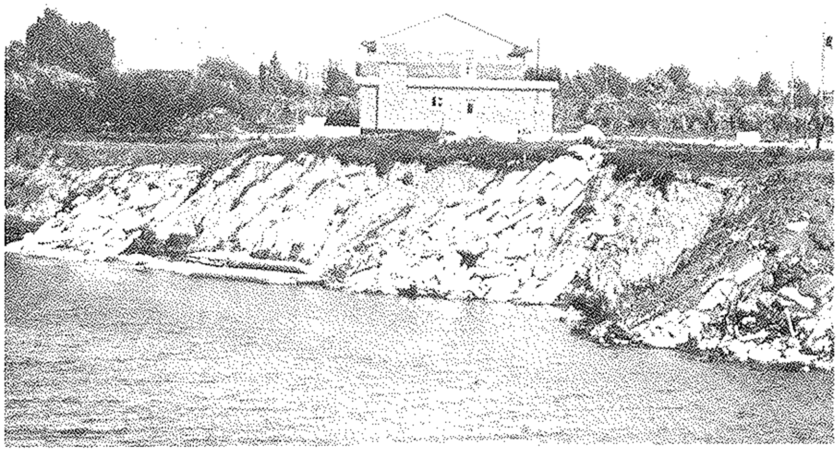


Photo 38. Silt-clay till cliff just west of Grimsby. Note the use of surplus and discarded building supplies to protect against erosion. Shoreline retreat in this section is greater than 1.0 m/yr (29 May 1978).

Burlington Bar across Hamilton Harbour has resulted primarily from sediment transported into this section from the east along the south shore of the lake, as only minor volumes of material are derived from erosion of the coast to the northwest (Rukavina, 1976).

Along the south shore of the lake, the cliffs are predominantly unconsolidated fine-grained sediments (Photo 38) and bedrock outcrops only near Grimsby and Vineland. The rock outcrops are shale and are virtually horizontally bedded. Beaches are well-developed only in western sections or adjacent to rivers or creeks and are either very narrow or absent in cliffed sections of this coast. Although this is a relatively sheltered section of the Lake Ontario shoreline, erosion rates are high (in the order of 1.0 m/yr) (Boulden, 1975), and several locations are retreating at long-term rates of 2.0 m/yr or greater. The coast west of Grimsby is more stable than the other sections as bedrock outcrops in the shore zone and forms a more resistant coast than the clay cliffs. Boulden (1975) notes that the beach sections of this subdivision are also eroding. Rukavina (1976) estimates that approximately 450,000 m^3/yr of sediment is eroded from this coast (this includes river-borne sediments), but that less than 30% of the material is sand or coarser sediment. From Jordan Harbour to Hamilton Harbour, sediment transport in the shore zone is dominantly to the west (Fig. 20). The most westerly section of the coast is low-lying and is characterized by beaches of sand and pebble sediments that have been trapped in groynes.

Along the north coast the low, relatively straight shoreline between Burlington Bar and Humber Bay in Toronto is a section of bedrock or protected shorelines. Shore-zone sediments are generally scarce and have only accumulated at a few restricted river mouths (*e.g.*, Bronte Creek), or where groynes have trapped sediment. Bedrock outcrops in many sections west of Port Credit; these rocks are part of the same formation that outcrops near Grimsby on the south shore. In the eastern half of this section, unconsolidated clays and sands rest on the bedrock and, in places, form eroding cliff sections. Backshore relief is low, less than 10 m everywhere, and erosion rates are low, approximately 0.1 m/yr. Rukavina (1976) estimates an annual sediment supply volume of only 7,000 m^3 for this section of coast. Although the shore zone is predominantly bedrock or man-modified, the coast is interrupted at several points by small river valleys which have low barrier beaches and marshes where sediment is available.

The beaches of Burlington Bar are predominantly sand in the south (Photo 39), increasing in size to sand and pebbles in the most northerly sections. Photo 40 shows a section of the northern beach in May, a time when the sediments were exclusively pebble-cobble. On a subsequent visit to the site in October of the same year, this beach section was entirely sand. North of the harbour entrance, beach width and berm height decrease. The barrier beach is subject to erosion-accretion cycles that are related to storm conditions; periods of erosion are particularly important in early spring following melt of the ice foot (J. Coakley, pers. comm).

Wave measurements on this coast during September and October, prior to the autumn-winter increase in wind velocities, indicate that significant wave heights greater than 30 cm occurred only during 19% of the study period (Coakley and Cho, 1973) (c.f. data for Toronto, Table 16, p. 133). Also, a maximum significant wave height of 1.4 m was recorded during this study, compared to a value of 2.2 m recorded in mid-November during a severe storm.

Within Hamilton Harbour the south shore is predominantly man-made structures; the western extremes are marshes; and the north shore is characterized by narrow, poorly-sorted beaches and low vegetated backshore cliffs. The marshes are largely confined to Cootes Paradise in the inner part of the harbour, which is connected to the main water body by a narrow channel that has been excavated through a relict barrier beach.

Photo 39. Wide sand beach, south of the harbour entrance, Burlington Bar. The beach berm is more than 2 m above lake level (29 May 1978).

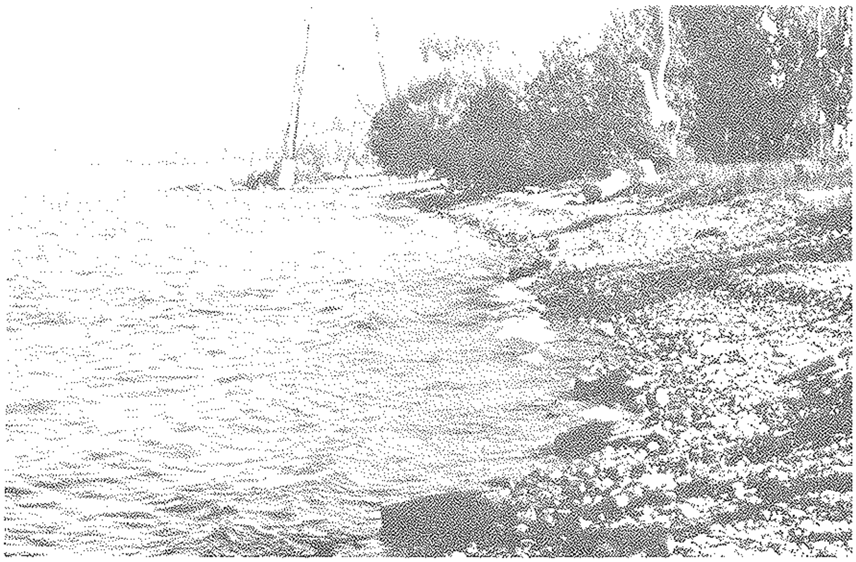


Photo 40. Narrow pebble-cobble beach in the extreme northern section of Burlington Bar (see text) (29 May 1978).

3. Toronto Harbour

This short subdivision is identified as a unit on the basis of the growth of the flying spit at Toronto that resulted from erosion and transportation of unconsolidated sediments from the adjacent coast to the northeast. The updrift section is characterized by high, vertical cliffs (Photo 41) of unconsolidated silts, sands, and gravels that supply approximately 200,000 m^3/yr of sediment to the shore zone (Rukavina, 1976). Approximately 50% of the eroded sediment is in the sand-gravel fraction; this material is transported to the southwest by waves out of the easterly quadrant (Rukavina, 1976). The spit that now encloses Toronto Harbour has been considerably modified by man's activities and many sections are now artificially protected. Since

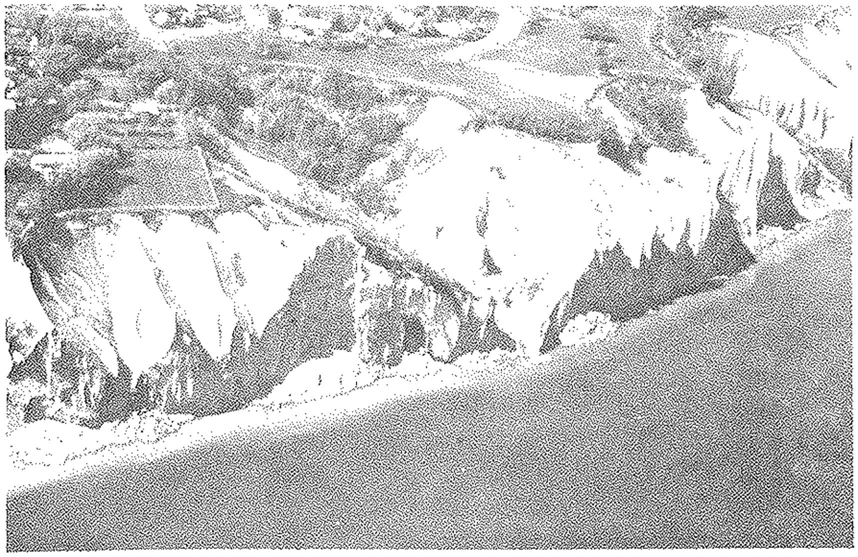


Photo 41. Vertical cliffs in the western section of Scarborough Bluffs. Note the absence of a beach, the slumped sediments from the cliff face and the pronounced gullying (28 May 1978).

1965, a 5-km long artificial headland has been constructed to form the new Outer Harbour which protects the proximal section of the spit.

The Scarborough Bluffs are up to 107 m in height and were stable until the early 1800's (Parkins and Acres, 1970). Removal of material, especially boulders, from the base of the cliffs and from the adjacent nearshore zone has led to erosion which at present is in the order of 0.5 m/yr, and locally reaches more than 2.0 m/yr. Attempts to control erosion on this section of coast have resulted in a reduction of sediment supply to the southwest that has affected the stability of the spit system (Fricbergs, 1970). Similarly, dredging of a shipping channel in the proximal section of the spit has resulted in sediment starvation downdrift and the sand-pebble beaches in the western sections of the spit are now artificially protected (Photo 42). To the west of Toronto Harbour, the sand-pebble beaches of Humber Bay are entirely protected by offshore seawalls. Within the harbour itself, land reclamation of the south shore and harbour facilities on the north and east shores have considerably modified the natural shoreline.

The Scarborough Bluffs form one of the most spectacular sections of the Lake Ontario shoreline. The stability of these vertical cliffs and of the associated downdrift spit system has been of considerable concern due to the high value of the backshore properties and to the importance of maintaining Toronto Harbour as a major shipping facility. The natural system in

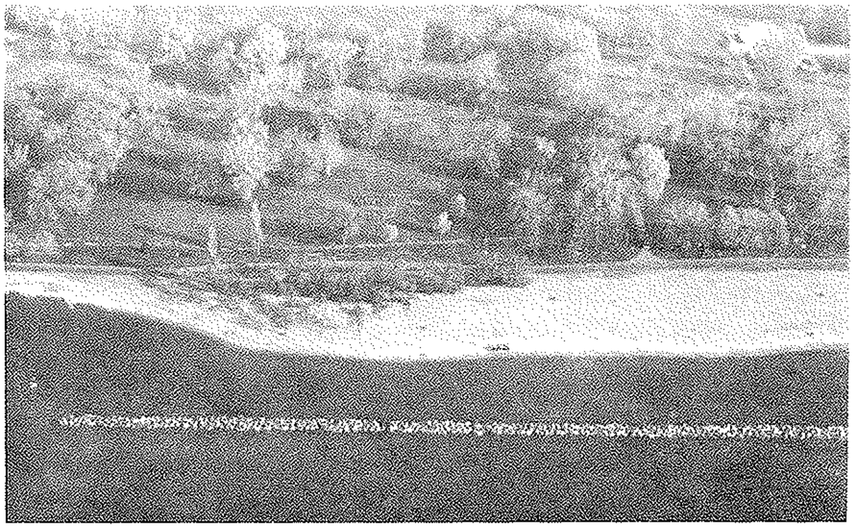


Photo 42. Sand beach protected by nearshore breakwater, south shore Toronto Harbour spit. Note that the protected section of beach is wide compared to the unprotected beach at left (27 May 1978).

this subdivision has been modified and much of the shore zone is protected by artificial structures.

4. North Coast and Southwest Prince Edward Peninsula

To the east of Whitby, the direction of sediment transport on the north shore is eastward. The main section of this subdivision is a straight, cliffed coast. Sediment eroded from this section is transported east to a zone of accumulation on the west coast of the Prince Edward Peninsula.

The section that extends east to Colborne is a relatively straight coast of unconsolidated cliffs (Photo 43) and beach-marsh systems in low-lying valleys. Relief is generally less than 15 m, but, in the central section between Bowmanville and Port Hope, cliff heights rise to 50 m locally. Along this coast, eroded sediments are transported to the east under the

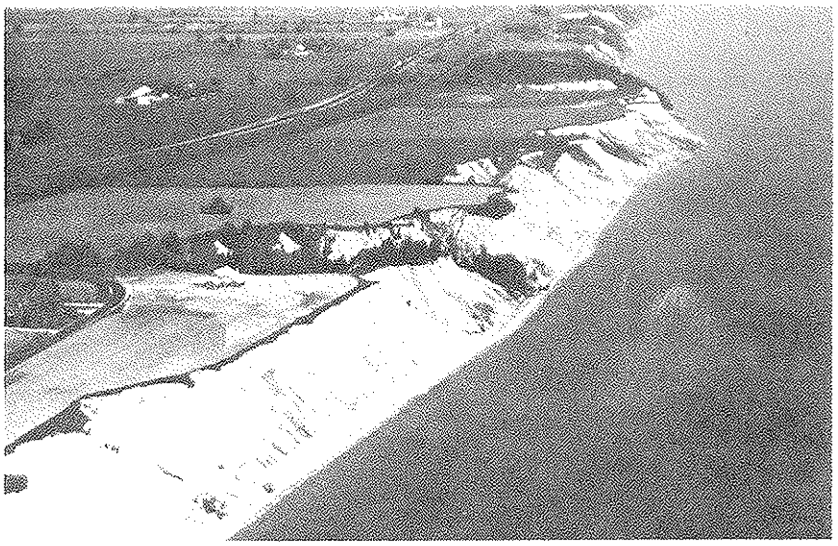


Photo 43. Erosion rates are 0.5 m/yr on this cliffed section just east of Bond Head near Newcastle (27 May 1978).

influence of wind-generated waves out of the southwest (Rukavina, 1970) (Fig. 20). Sediments have accumulated on the west sides of the jetties at Oshawa, Port Hope and Cobourg. Beaches are present throughout most of the subdivision; they are low and narrow in cliffed sections but wider in low-lying areas where they protect backshore marshes.

The retreat rates of the unconsolidated cliffs are highest between Oshawa and Port Hope (0.5 to maxima of 1.5 m/yr), decreasing to 0.1 to 0.2 m/yr in the west, and to 0.1 to 0.5 m/yr in the east. Many cliff sections are wholly or partially vegetated indicating stable conditions. The nearshore zone is generally shallow and, in parts, is characterized by boulders. Rukavina (1976) indicates that the annual sediment input along this section is about 600,000 m^3, 60% of which is in the sand-gravel size range.

East of Colborne bedrock is exposed in the beach and nearshore zones and the relatively resistant limestone rocks of the Prince Edward Peninsula extend southward into the lake basin. The local relief exceeds 70 m above lake level inland but the shore zone is generally low-lying. The structural trend of the outcrops in the peninsula is southwest-northeast, and a series of large barrier beaches have developed across low embayments that parallel the structural trend. The barriers developed as the sediment transported into this section from the west accumulated in the embayments. The west shore is characterized by alternating barrier beaches and low rock headlands. The south shore of the peninsula is a low coast with a thin beach of pebbles and cobbles resting on the rock surface that outcrops at lake level.

This coast is exposed to high wave-energy levels (see Main Duck Island: Table 16, p. 133) and the beach sediments of the barrier systems are predominantly well-sorted sands. The barrier beaches enclose extensive marshes that have developed in the sheltered bay areas. The major barrier systems are: (a) Presqu' ile, (b) Wellers Bay (which also includes small barriers across North Bay, Pleasant Bay (Photo 44), and Huyck Bay), (c) Wellington Bay, (d) Athol Bay, and (e) Soup Harbour (Fig. 20, p. 135). Dune systems occur on all of the barriers and are particularly well-developed on the Wellington barrier that encloses West Lake; in this system dune heights reach 30 m in backshore areas (St. Jacques and Rukavina, 1972). The headlands on the west

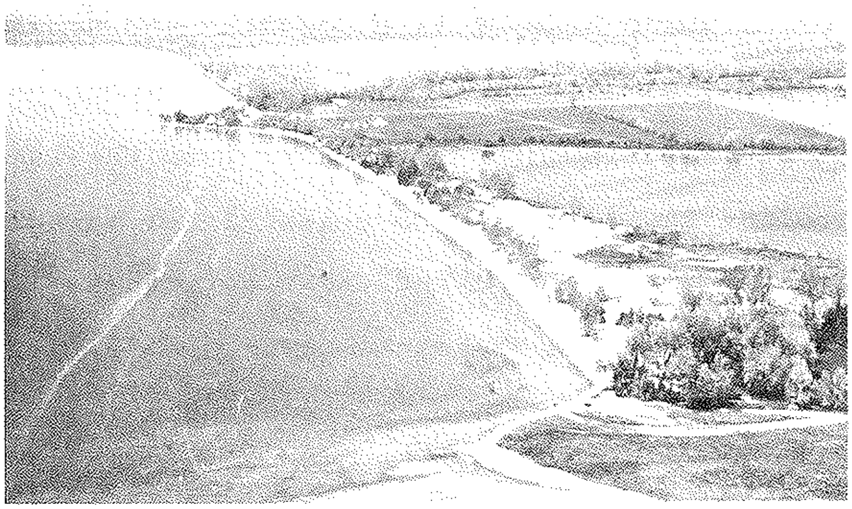


Photo 44. Barrier beaches that enclose North (top) and Pleasant (lower) Bays. Bedrock outcrops at Island Point at the bottom of the photograph and at the headland at Pierson Point that separates the two beaches (28 May 1978).

coast are characterized either by low bedrock cliffs (up to 5 m) or by wide rock platforms (Photo 45).

The south coast of the Peninsula is a low rock platform that has a thin beach deposit of pebble-cobble sediments. In many eastern sections, where relief is very low, the beaches are backed by marshes. Energy levels at the shore are generally low on this section as wave energy is absorbed by the very shallow, nearshore rock platforms.

5. Northeast Coast

This subdivision is a complex coast of islands, channels, and low-energy shorelines. In the Prince Edward Peninsula area the shoreline complexity results from erosion along the northeast-southwest structural trends that has produced a series of interconnected headlands and narrow bays. In particular, the Bay of

Photo 45. Exposed rock platform near Wellington Bay, May 1968.

Quinte, Adolphus Reach and North Channel system is aligned northeast-southwest and is characterized by straight and narrow (1 to 2 km) channels. Long Reach cuts across the general trend to connect the Bay of Quinte with Adolphus Reach and is a fault-controlled erosional feature (Sly and Lewis, 1972).

The more exposed shores of Prince Edward Bay and southern Amherst Island have sections of bedrock cliffs and low barrier beaches with marshes. These shores are in contrast to the sheltered low-energy coasts of the more northerly sections. Within the Bay of Quinte, relief is low and the shore zone is characterized by low cliffs at headlands and poorly-sorted, coarse sediment beaches or unprotected marshes in embayments (Photo 46). The west shore of Long Reach and Picton Bay, and the south shore of Adolphus Reach have steep bedrock cliffs. Elsewhere coastal slopes are very low. Marshes are extensive throughout the sheltered bays and channels.

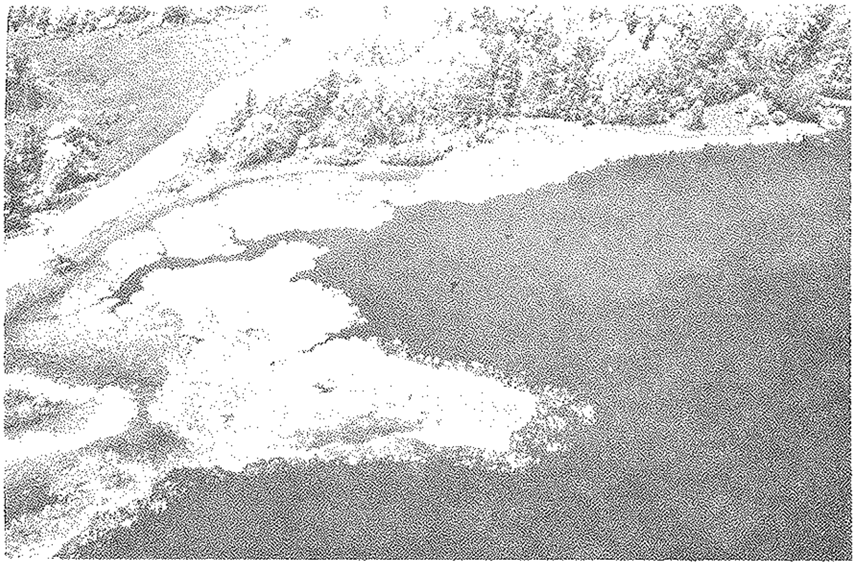


Photo 46. Small marsh on an open coast, north shore of Bateau Channel opposite Howe Island (28 May 1978).

Between bedrock headlands on the west coasts of Wolfe and Amherst Islands, a series of low barriers and marshes have developed in the bays. This section is similar to the west coast of the Prince Edward Peninsula except that it has developed in a lower energy environment and the beaches are low without dune systems.

East of Kingston, Lake Ontario drains through the Thousand Islands into the St. Lawrence River. The constriction results from the outcrop of metamorphic Shield rocks. Relief is low and the complex system of islands and channels is a sheltered environment dominated by river currents rather than by wave-generated processes (Photo 47). Waves generated by passing boats can be up to 0.5 m in height and are an important factor on shores adjacent to shipping lanes.

The shore zone of this section of the subdivision is dominated by low rocky outcrops with a few sections of low cliffs.

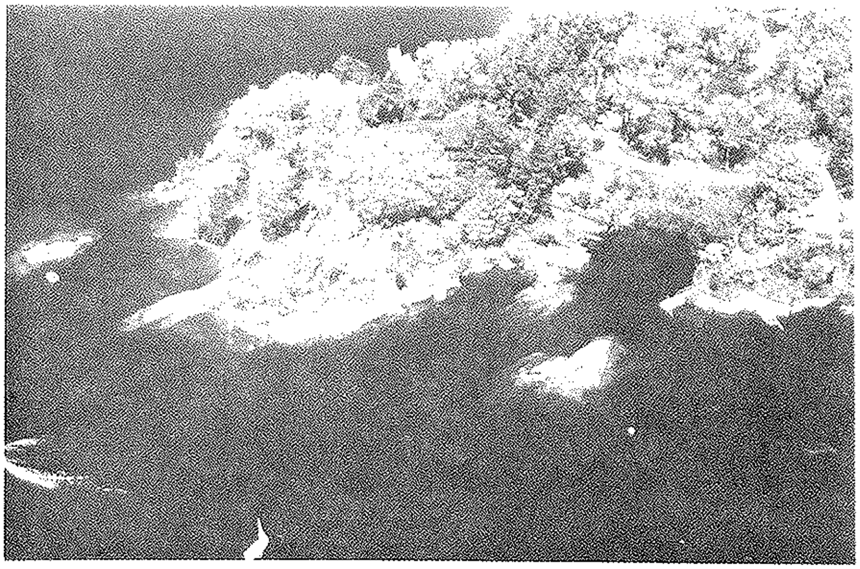


Photo 47. Low rocky coast on Treasure Island, east of Kingston (28 May 1978).

Marshes are common in sheltered bays where fine-grained sediments have accumulated, but beach deposits are rare. The complex archipelago of the Thousand Islands gives way east of Mallorytown Landing to a single, narrow channel (approximately 2 to 4 km wide) as the river cuts through the Shield rocks in a section of slightly higher relief.

4.7 COASTAL REGIONS OF THE CANADIAN GREAT LAKES

The primary characteristics of the coastal processes and shore-zone morphology are summarized for each region at the start of each section and as a series of tables in the text. There exists considerable variability within each of the six regions but the broad scale character of each region is outlined in Table 18 which is presented as a brief synthesis of the material discussed in this part of the report.

TABLE 18. COASTAL REGIONS OF THE CANADIAN GREAT LAKES

REGION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
1. Lake Superior	Resistant Shield rocks with high backshore relief in many areas (up to 300 m)	Predominantly rocky coasts, but few cliffs in shore zone: beaches restricted to short sections where sediments trapped in bays: sediments usually coarse: complex shoreline configuration in northwest and southeast, elsewhere coasts are relatively straight	Maximum fetches up to 500 km: wave-energy levels increase to the east: shore-zone ice up to 5 months/year	Sediments very scarce in all areas: sediment sources usually related to local rivers: three major transport systems on north and east coasts but transport paths interrupted by numerous indentations: local transport systems within embayments
2. North Channel-Georgian Bay	Resistant Shield rocks outcrop on north and east coasts, resistant sedimentary rocks on south and west coasts: backshore relief generally low except on east coast of Bruce Peninsula where Niagara Escarpment gives high relief	Predominantly rocky coasts except in southeast Nottawasaga Bay: Shield coasts have complex shoreline with many islands and bays - predominantly low rocky coasts: remaining coasts are indented with low, rock outcrops, boulder-strewn nearshore bedrock platforms and narrow beaches: only extensive beach system is in Nottawasaga Bay	Maximum fetches up to 200 km but most coasts very sheltered, due to complex shoreline configuration: shore-zone ice up to 4 or 5 months/year	Sediments very scarce except in southeast Nottawasaga Bay, which has a local source area; local transport systems in all areas due to irregular shoreline
3. Central Lake Huron	Resistant sedimentary rocks that dip gently lakeward in northern sections are mantled by unconsolidated clays and sands south of Point Clark: shore-zone relief is very low on the rocky northern coasts and increases to 20 m in the southern half of the region	Northern sections have an irregular coast of bays and headlands that is characterized by wide, rock platforms and few beaches: where present, sediments are usually coarse and often in the boulder size range: the southern section has a straight coast of eroding, unconsolidated cliffs that gives way south to several extensive beach systems backed by high dunes	All coasts are exposed with maximum fetch distances up to 300 km: the irregular coast in northern areas produces considerable local sheltering and low-energy bay environments: shore-zone ice up to 4 months/year	Sediments are very scarce in the northern sections but cliff erosion in the south provides material for beach development: sediments are transported predominantly to the south along all sections, except for a local reversal to the north of Point Clark: the cliffed sections are zones of sediment bypassing

REGION	RELIEF AND GEOLOGY	SHORE-ZONE CHARACTER	FETCH, WAVE EXPOSURE AND ICE	SEDIMENT AVAILABILITY AND TRANSPORT
4. Lake St. Clair	Low relief area with no rock outcrops: unconsolidated sediments in the shore zone in some sections	A large delta has formed at the mouth of the St. Clair River which drains Lake Huron: the delta has a "bird-foot" shape and is a marsh environment: the shores of Lake St. Clair are low marsh in the north and east, and low, protected cliffs with some beaches in the south: the Detroit River, like the St. Clair River, has low shores of cliffs, narrow beaches and seawalls or groynes	Lake St. Clair is a very low energy environment with a maximum fetch of 40 km: the river sections have narrow channels and strong currents but very low shoreline energy levels: ice persists for up to 4 months/year and can form large jams in the river section	Sediments fed into the St. Clair River have bypassed the channel and accumulated at the river mouth: on the southeast coast of the lake transport is to the east; and is west towards the Detroit River on the southwest coast: sediments in the Detroit River are transported to the south and have formed large shoals at the river mouth adjacent to Lake Erie
5. Lake Erie	Bedrock outcrops only in the west on Pelee Island and in the extreme northeast: unconsolidated clay-silt-sand deposits occur in all other areas: relief is generally low (<20 m) with maxima of 40 m in a few sections: three large depositional features have formed on moraine ridges and extend into the lake away from the general trend of the coast	Predominantly a straight coast of eroding, unresistant cliffs, beaches are generally of coarse sediment and narrow where present: the three depositional areas have sand beaches, dunes and extensive marshes in sheltered areas: Point Pelee is migrating slowly to the west, whereas, Rondeau and Long Point are moving towards the east	Maximum fetches up to 300 km along the axis of the lake and wave-energy levels increase to the east due to prevailing westerly winds that parallel the lake axis: shore-zone ice up to 4 months/year	Sediments are generally abundant but the cliffs have narrow beaches as material is transported away from these sections: sediment transport is predominantly to the east with reversals in the extreme west and in the lee of the three depositional features which are transport convergence zones
6. Lake Ontario	Bedrock outcrops in western and eastern sections of the region and resistant, Shield rocks outcrop at the entrance to the St. Lawrence River: elsewhere the bedrock is mantled by consolidated clay-silt-sand deposits: relief is	The straight coasts of the western and central sections have eroding, unresistant cliffs, with a few bedrock outcrops in the extreme west and two large depositional features: the resistant bedrock outcrop of the Prince Edward Peninsula extends into the lake and gives way east to complex, rocky coast of islands and channels: bay-head beaches	Maximum fetches up to 250 km along the axis of the lake and wave-energy levels increase to the east due to prevailing westerly winds that parallel the lake axis: the northeast section is a low-energy environment due to the complex shoreline character: shore-zone ice	Sediments are generally abundant along the central section and material is transported west to Toronto Spit and east to be trapped by the Prince Edward Peninsula: Burlington Bar is a zone of transport convergence: the sheltered northeast section has a scarcity of sediments and has numerous local transport systems

PART 5 - OIL

SYNOPSIS

The impact of a spill depends in part on the volume and on the physical and chemical properties of the oil. Oil rarely covers the entire shore zone, except in the event of a large spill. The properties of crude and refined oils vary considerably and these properties change constantly following a spill. "Light" oils spread rapidly and have volatile components that evaporate on exposure to the atmosphere; "heavy" oils have a high viscosity and degrade more slowly.

Rates of degradation (*i.e.*, persistence) depend primarily on: (a) the physical and chemical composition of the oil, and (b) the available mechanical and thermal energy. The principal energy inputs to oil stranded in the shore zone are a function of waves and temperature. Rates of degradation, particularly due to evaporation, are usually high immediately following a spill. Degradation is slow if oil is stranded in sheltered environments or above the limit of wave action and if the oil is buried.

5.1 INTRODUCTION

The effects of stranded oil on the natural environment vary considerably depending on: (a) the chemical and physical properties of the oil, (b) the volume of spilled oil, (c) the character of the shoreline substrate, and (d) the coastal processes in the spill area. This section focusses on those aspects of oil which determine the impact, the degradation, and the persistence of stranded oil. Shore processes and the physical aspects of the shore zone are discussed in the next section (Part 6, p. 169) followed by an evaluation of the expected impact of a spill on the major shore zone types (Part 7, p. 193).

5.2 VOLUME OF OIL

The impact of a spill is partly determined by the volume of oil. If shoreline contamination involves small amounts of oil, the oil is usually washed ashore in patches and is deposited at the upper limit of wave swash. Only in the case of large spills does oil completely cover the shore zone.

If the oil is on the water, an estimate of the expected volume that will be stranded is of great value in assessing the probable impact and in preparing a suitable response. On the other hand, if the oil has already become stranded, an estimate of the volume will provide information for the selection of the most suitable cleanup method.

When gathering the baseline spill information, note should be made of: (a) the source of the spill, (b) the volume spilled (if known), and (c) the duration of the spill. In the latter case (c), this involves a knowledge of whether or not the spill has terminated. A continuous leakage of oil from the source will pose different protection and cleanup problems than a single spill in which no further oil would be released.

The amount of stranded oil on a shoreline must be considered both in terms of surface distribution and the depth of penetration into the sediments. An estimate of the surface area covered with oil can be expressed as a percentage, and this estimate should indicate not only the total coverage but also the actual distribution on the beach (*e.g.*, the lower beach may have a 10-20% cover, whereas, the upper beach near the limit of wave swash at the time of the spill may have a 60-70% cover). The depth of oil penetration beneath the surface can be determined by digging pits in the beach with a shovel or by obtaining cores.

5.3 TYPES OF OIL

Crude and refined oils have a wide range of chemical and physical properties. These properties are a function of the compounds in the oil, which range from light gases to heavy solids (see Appendix, p. 249). The most important of these properties in terms of the impact of spilled oil are: (1) the boiling point, (2) the flash point, (3) the pour point, (4) the surface tension, and (5) the viscosity.

(1) The boiling point of the fractions within an oil determines the temperature at which those fractions will evaporate. In light, volatile oils evaporation is a major degradation process.

(2) The flash point is the lowest temperature at which fractions of the oil will ignite. Knowledge of the flash point of the oil is an important safety factor for personnel in the area of a spill.

(3) The pour point is the temperature below which the oil will not flow. For the many different oil types these temperatures range between -57°C and +32°C, but the majority of oils have a pour point below 0°C. An oil with a pour point above ambient air or water temperatures acts as a semi-solid material. Air temperatures at one site can vary considerably from day to night as weather conditions and seasons change, so that the ability of stranded oil to flow can vary accordingly.

(4) The surface tension of oil controls the spreading of thin layers of oils which have a low viscosity. The surface tension of these oils can be lowered by the application of dispersants to increase solubility and mixing. Conversely, surface tension can be increased by the application of collectants to prevent or reduce spreading.

(5) The viscosity is a measure of the resistance of the oil to flow, in terms of the internal cohesiveness of the material. This property, therefore, controls the rate of spreading of the oil and the degree to which oil can penetrate into beach sediments. Temperature is a major factor in determining viscosity and as temperatures increase then viscosity decreases and the oil spreads more readily. As oil spreads more surface area is exposed and, therefore, weathering rates increase. Viscosity, therefore, plays an important role in determining weathering rates by controlling the total exposed surface area of the oil.

To simplify the discussion throughout this report, oils have been grouped into three broad categories:

(1) *Liquid or free-flowing oils* (such as unweathered light crudes, aviation gasoline, diesel fuels, kerosenes, and most other refined oils). These have high rates of evaporation and are generally very volatile so that they should be approached with care. The oils of this group have a low viscosity and float on water, but rarely form stable emulsions.

(2) *Very viscous oils* (such as heavy crudes, weathered light crudes, and Bunker fuels). These are less volatile due to the lower amounts of light fractions, a result of either refining processes or of natural evaporation. The oils of this group float on water and readily form emulsions (for example, "chocolate mousse" - a water-in-oil emulsion).

(3) *Semi-solid or tarry oils* (such as asphalt, weathered crudes or weathered Bunker fuels). These are non-volatile and are very viscous at normal (<38°C) termperatures. They may float on water or sink, and generally they do not emulsify.

The light, free-flowing oils spread rapidly and usually form only a thin layer and/or penetrate deeply into shoreline sediments. In general, the more viscous oils contaminate smaller sections of shoreline but result in thicker deposits of oil. These viscous oils penetrate shoreline sediments on pebble or cobble beaches, which have large spaces between particles. Some penetration by viscous oils into the upper few centimeters of sand-sized sediments can occur when air temperatures are high enough to decrease the viscosity.

In assessing the potential impact of a spill it is necessary to identify the basic nature of the oil on the water. This knowledge can then be applied to estimate the expected penetration of oil into sediments and the effect of oil on shore zone plants and animals.

Spilled oil is dynamic in the sense that the physical and chemical properties change through time. Rates of change are relatively slow in cold environments, but increase rapidly as temperatures increase. In particular, the volatile oils undergo rapid change due to evaporation when exposed to air (Mackay and Matsugu, 1973). Also, wave action can alter an oil into an emulsion, which results in changes in the viscosity. It is important, therefore, to anticipate these changes when assessing the expected impact of spilled oil on the shoreline.

5.4 DEGRADATION OF SPILLED OIL

The degradation of oil by natural processes involves changes in the physical properties and/or chemical composition. The processes by which degradation takes place are bio-degradation (particularly microbial oxydation), emulsification, evaporation, dissolution and photo-oxydation. The primary factors that control the process of degradation are the composition and physical nature of the oil. Refined oils, such as gasoline or kerosene, degrade very rapidly (*i.e.*, they have a low persistence) because the light (volatile) fractions of spilled oil tend to evaporate rapidly when exposed to the atmosphere. Residual fuel oils or Bunker oils are less readily degraded as the light fractions are removed during the refining process, thus causing these oils to be more persistent than the lighter grades.

As oil weathers and changes chemically its physical properties also change. For example, the process of emulsification leads to a lower viscosity so that oil flows more readily. As weathering progresses the loss of the lighter fractions produces a more asphaltene residue which has a higher viscosity and is less mobile. In the case of light-grade oils this process results in the evaporation of the oil and rarely produces a residue.

A factor in the degradation process is that oil solubility increases as salinity decreases. In fresh-water environments such as the Great Lakes spilled oil is therefore more readily diluted and thinned than in ocean environments.

5.5 THE PERSISTENCE OF STRANDED OIL

The rates of natural degradation and physical dispersion of stranded oil are important factors in protection and cleanup decisions. If natural cleaning of a shore zone is rapid, no cleanup response may be necessary.

A major factor in the rate of oil degradation is the amount of energy available for the degradation processes. This energy can be either thermal or mechanical, or can result from biochemical processes. Thermal energy is related to air and water temperatures and as these increase so do rates of most degradation processes. Mechanical energy is a function of waves and winds which result in the dispersion and physical breakdown of the oil. The relationship between the weathering and persistence of stranded oil to the inputs of energy and to the properties of oil is illustrated in Figure 22.

Two important factors which affect the broad relationship between degradation processes and persistence are: (a) depth of oil penetration in the shore sediments or burial of the oil, and (b) air and water temperatures. In the first case, oil that is buried by sediments, or that has penetrated into a beach, is protected from wave action unless the beach is eroded. The second factor, related to temperatures, involves the viscosity and pour point of the oil. As temperatures rise oil may begin to flow and can then penetrate into sediments, but this may be offset by the fact that higher temperatures may cause an increase in physical and biochemical degradation.

The rate of dispersion of stranded oil is initially a function of removal by wave action. In the period immediately following a spill inputs of thermal or biochemical energy are considered less significant than the contribution from inputs of mechanical energy (Owens, 1978). In general, as levels of mechanical (wave) energy increase, rates of natural dispersion and degradation

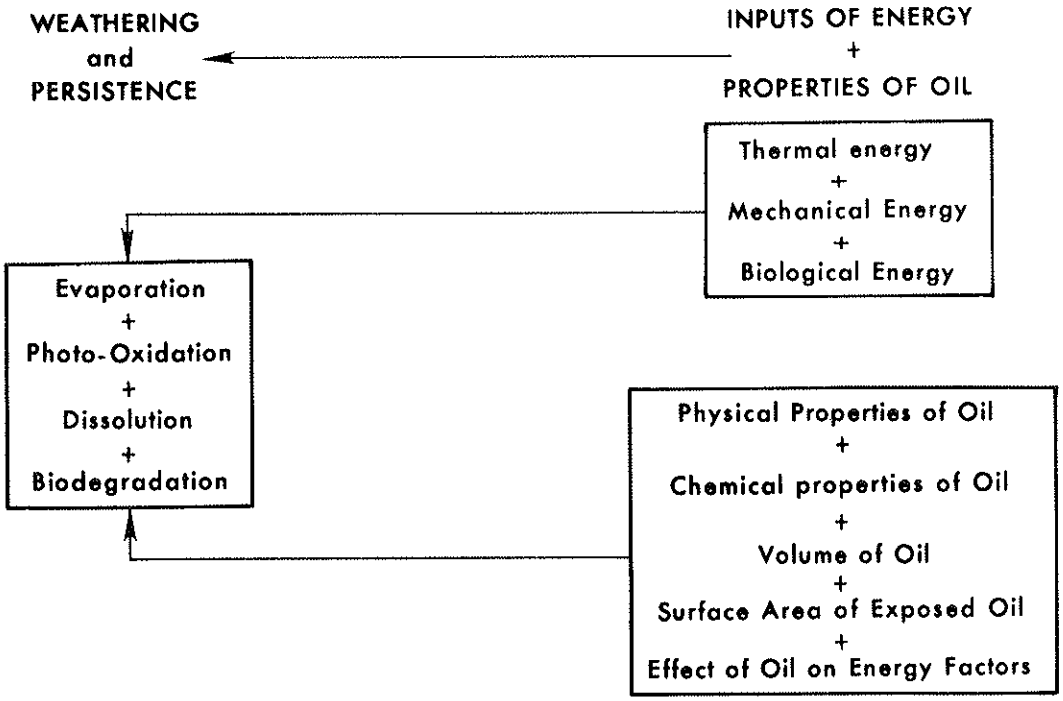


Figure 22. Factors that affect the degradation (weathering and persistence) of spilled oil (from Owens, 1977).

increase. The wave-energy level at any location is a function of a series of process and shoreline factors that are outlined in Figure 23 and discussed further in Part 6.

Following the *"Arrow"* spill in Chedabucto Bay, Thomas (1977) has shown that rates of oil removal vary according to changes in local wave-energy levels. In Figure 24, Station 3 is a moderately exposed site, Station 5 is a sheltered location, and Stations 6 and 7 are very sheltered shorelines. The results indicate that natural oil removal is in proportion to exposure to wave action; other surveys agree with this conclusion. On very exposed beaches in Chedabucto Bay virtually all stranded oil was removed within the first year.

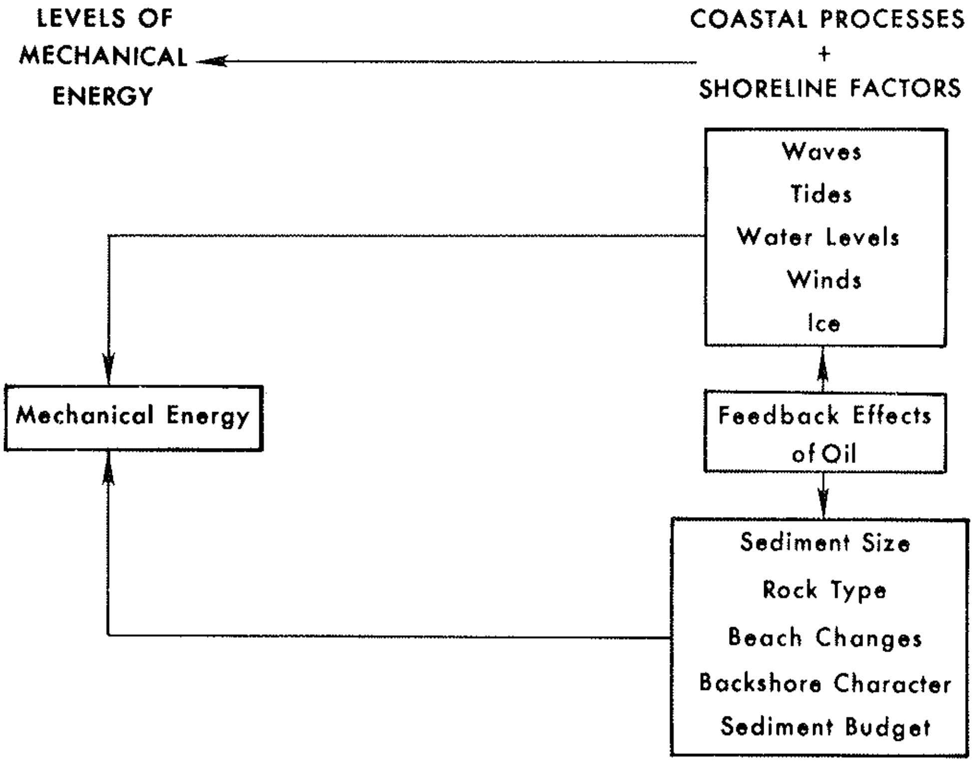


Figure 23. Factors that affect levels of mechanical energy at the shoreline (from Owens, 1977). Note that tides are not a factor in the Great Lakes system.

Where oil is stranded in sheltered sites or above the limit of wave activity, natural removal is a function of thermal energy levels and biochemical processes, and usually proceeds at relatively slow rates. A study by McLean and Betancourt (1973) in Chedabucto Bay demonstrates that oil stranded in a sheltered location, which was not exposed to wave action, lost 20% by weight within the first year, but thereafter degradation virtually ceased (Fig. 25). Once oil reaches a quasi-equilibrium with local environmental conditions, the rates of weathering decrease rapidly, until such time as these environmental conditions change. The latter can occur as temperatures increase during spring and summer months or as inputs of mechanical energy

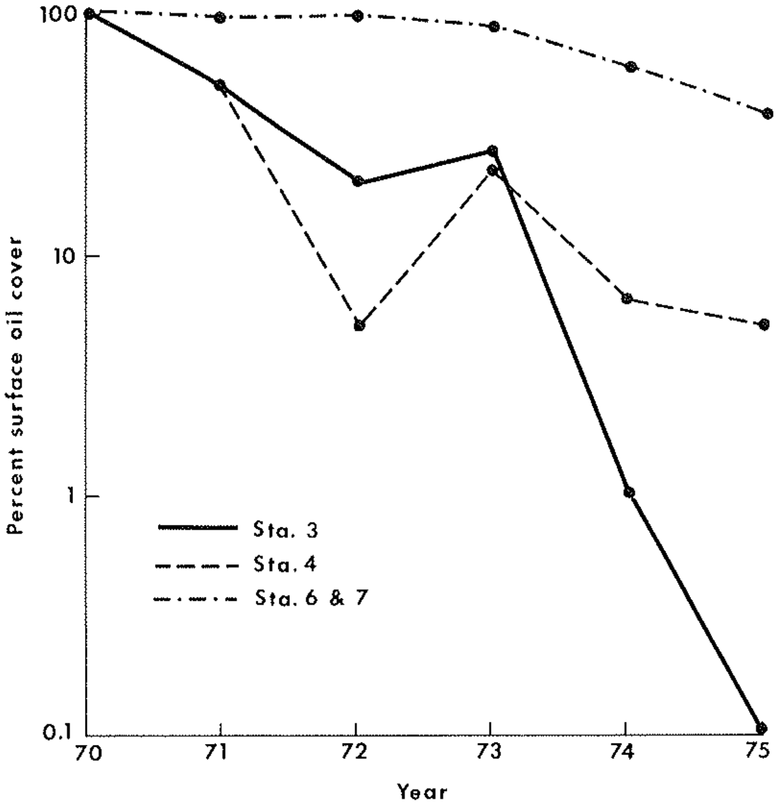


Figure 24. Surface oil cover at the high-water mark from stations in northern Chedabucto Bay 1970-1975 (from Thomas, 1977).

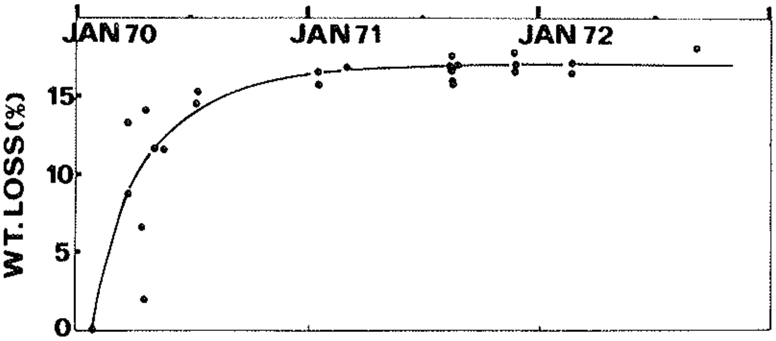


Figure 25. Variation in weight loss of weathered Bunker C oil with time (from McLean and Betancourt, 1973).

expose new surface areas of oil. In those cases where oil in Chedabucto Bay has been stranded above the beach or is not exposed to wave activity, Vandermeulen (1977) estimates a residence (or persistence) time of longer than 150 years.

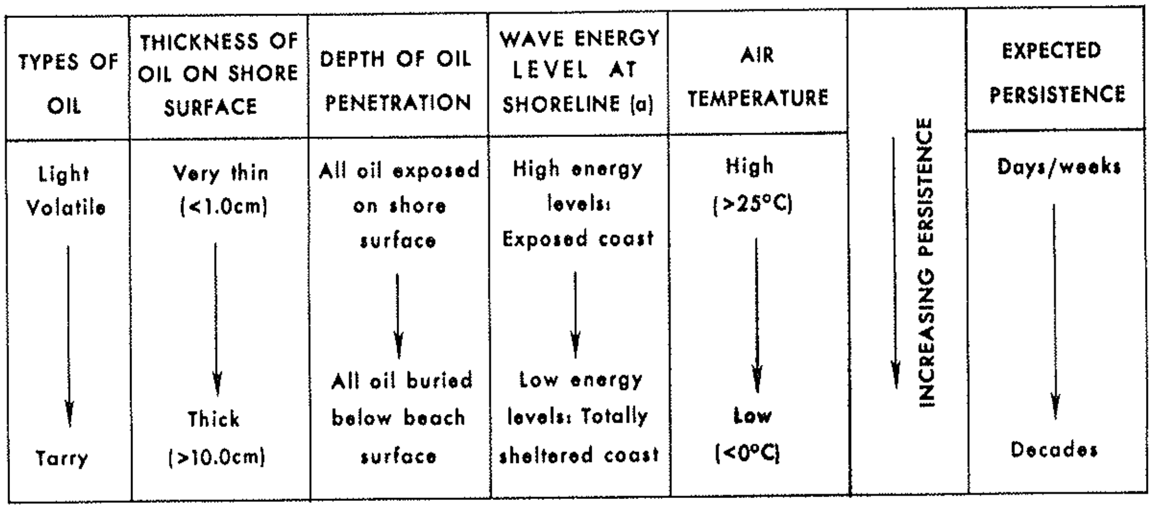
Following the *"Arrow"* spill Vandermeulen (1977) notes that the general pattern of natural oil removal was:

(a) short-term removal by wave action: about 50% of the oil that was stranded within the zone of wave action was removed within 1 year; 75% within 3 years; and 95% within 7 years. The rate of oil removal at each site was a direct function of the level of wave energy (see Part 6.4, p. 180).

(b) long-term removal by biochemical processes: oil deposited above the limits of wave action or in sites sheltered from wave action showed very slow rates of degradation, particularly if the oil was buried in the sediment.

Although information from previous spills provides useful examples of persistence times of oils, to date no methods have been developed to predict degradation rates. Such a method would involve a large number of variable factors for each type of oil spilled in different coastal environments.

For oil stranded on beaches subject to wave action, an assessment of persistence time can be estimated from: (a) the volume and type of the oil, (b) the depth of oil penetration, and (c) the levels of wave energy at the shoreline. Such an assessment may be of great importance in deciding whether or not natural cleaning of the shore would occur within an acceptable period of time. As energy levels at the shoreline increase, then rates of natural dispersion and degradation of stranded oil increase and requirements for a cleanup response may decrease. Figure 26 combines the major factors and provides the framework for assessing the potential persistence of stranded oil.



TYPES OF OIL	THICKNESS OF OIL ON SHORE SURFACE	DEPTH OF OIL PENETRATION	WAVE ENERGY LEVEL AT SHORELINE (a)	AIR TEMPERATURE		EXPECTED PERSISTENCE
Light Volatile	Very thin (<1.0cm)	All oil exposed on shore surface	High energy levels: Exposed coast	High (>25°C)	INCREASING PERSISTENCE	Days/weeks
Tarry	Thick (>10.0cm)	All oil buried below beach surface	Low energy levels: Totally sheltered coast	Low (<0°C)		Decades

Figure 26. Persistence factors for stranded oil, for (a) refer to Table 20, p. 182.

5.6 SPILL INFORMATION

Prior to implementing spill response operations, it is necessary to obtain basic information on the nature of the spill, the type of oil, and the extent and character of oil on the water and/or on the shore. Table 19 provides a checklist of information that can be used as a basis for the first phase of spill response decisions. In some cases the information may involve estimates rather than accurate numbers, but where possible the checklist should be updated as further information is received. The assessment of the volume and character of oil on the shore should be recorded for each section of beach and for each shoreline type. Several measurement units for oil volumes are in current use; the conversion factors are given in the Appendix (p. 252).

TABLE 19. SPILL INFORMATION CHECKLIST

1. OIL ON WATER

Source of Spill: ____

Is oil still being spilled?

YES - Spill Discharge Rate: ____________________________

- Estimated Duration of Spill: ______________________

- Estimated Final Spill Volume: _____________________

NO - Volume of Spill: __________________________________

Type of Oil: ____

Is oil flammable or otherwise hazardous to personnel? YES/NO

Will the oil be stranded? YES/NOT KNOWN/NO

*Where will the oil be stranded? __________________________

*Requires spill movement prediction information not contained in this report.

2. OIL ON SHORE

Has the spill ceased? YES/NO

Is there a danger of more oil being washed ashore? YES/NO

Oil Viscosity: Low (fluid) ___ Moderate ___ High (semi-solid) ___

Oil Flammability: Very Dangerous ___ Potentially Flammable ______
Low Risk ___ Inert ___

DO THIS FOR EACH SECTION

Section Name or Identification: ____________________________

Surface Area Covered by Oil: ________%

Thickness of Surface Oil: __________cm

Distribution Across Shore Zone: ____________________________

Depth of Oil Penetration: __________cm

Volume of Stranded Oil on Beach: ___________________________

Shoreline Exposure: (see Part 6.4, p. 180) __________________

Wave Energy at Shoreline: (see Part 6.4, p. 180) _____________

PART 6 - SHORELINES

SYNOPSIS

The most important process in the shore zone is the action of waves. This process largely controls the erosion of rocks, the transport of shore-zone sediments, and the dispersal of stranded oil. Ice plays a critical role in preventing wave generation, dampening existing waves, and protecting the shore zone from the effects of waves during winter months.

Levels of wave energy at the shoreline depend on fetch and exposure. Onshore winds combined with a long fetch and a straight exposed coast result in high wave-energy levels. On the other hand, wave-energy levels are very low in sheltered locations such as bays, channels, or coasts protected by headlands and/or islands. There is a seasonal variation in wave-energy with maxima during the period from October to April; this is offset by the presence of ice in the shore zone for three to four months during this period. The dispersion rate of stranded oil decreases as levels of wave energy at the shoreline decrease. Stranded oil that is buried by beach sediment is dispersed and degraded very slowly.

Beach changes occur in response to changes in the level of wave energy. Erosion caused by strong wave activity during storms is balanced by accretion and beach recovery during periods of lower wave-energy levels.

Shoreline types can be divided simply into: (i) coasts without sediment, and (ii) coasts with sediment. Further subdivision of coasts with sediment is based on: (a) the size of the sediments, and (b) the presence of vegetation in the shore zone. A major factor in characterizing the shoreline for spill response operations is accessibility to the shore zone by equipment and personnel.

6.1 INTRODUCTION

In this section a classification of shoreline types for the Canadian Great Lakes is developed that is relevant to oil spill impact and cleanup programmes. The definition of shoreline in this context includes the margins of the interconnecting rivers and channels that form an integral part of the Great Lakes system.

6.2 SHORELINE PROCESSES

Shore processes include waves, water-level changes, winds and the effects of ice. These processes act to form or change the shore zone and play an important role in affecting stranded oil. The action of wind-generated waves is the most important form of energy at the shoreline.

Waves

Waves result from the interaction of the water surface with winds and gravity. Waves transmit energy through the water and this energy is largely dissipated in shallow water or on the beach. The level of wave energy is controlled by the velocity and duration of winds over the water surface and by the fetch (q.v.). The mechanical energy that waves transmit to the beach causes the erosion of rocks, the transport of beach sediment, and the physical dispersion and breakdown of oil.

Oil on the water surface can be mixed with water by the action of waves breaking near the shore to form emulsions, such as "chocolate mousse". Oil on the shoreline can be broken down into smaller particles by wave action or may be abraded by sediments that are moved by wave action.

Where the water depths at the shore are deep, as in the case of breakwaters or steep rocky coasts, waves are frequently reflected back into the lake. This reflection can prevent oil from being stranded on that section of the shore zone and the turbulence created by the meeting of incoming and reflected waves can lead to mixing and dispersion of the oil into the water (Owens, 1977a).

Variations in levels of wave energy through time or between different sections of coast result in differential rates of sediment transport and of oil dispersion. Stranded oil is abraded or buried as beach sediments are eroded or transported in the shore zone by wave action. The processes by which this can occur are discussed in Part 6.3 (p. 174).

In channels or rivers, wind-generated wave action is generally limited, however, if there is significant boat traffic, particularly large boats or ships, wakes can be an important factor in increasing shoreline energy levels. In this case, the wave-energy levels are controlled by the volume of the traffic and the distance of the shipping lane from the shore or river bank.

Water Levels

The variations in water levels on the Great Lakes have been described in more detail elsewhere (Part 3.2.4, p. 31). The water level at the time oil is washed ashore largely determines the location of oil deposition. Oil that is spilled during a storm when the lake level is elevated above normal may be deposited on the higher parts of the shore. This oil is then stranded above the normal limit of wave activity and will not be affected by waves until the next period of high water levels unless there is an increase in wave height that allows waves to affect that part of the shoreline (Fig. 27).

On the other hand, oil that is stranded at a period of temporary low water levels would be underwater and subject to constant mechanical wave energy as the water returns to its normal level.

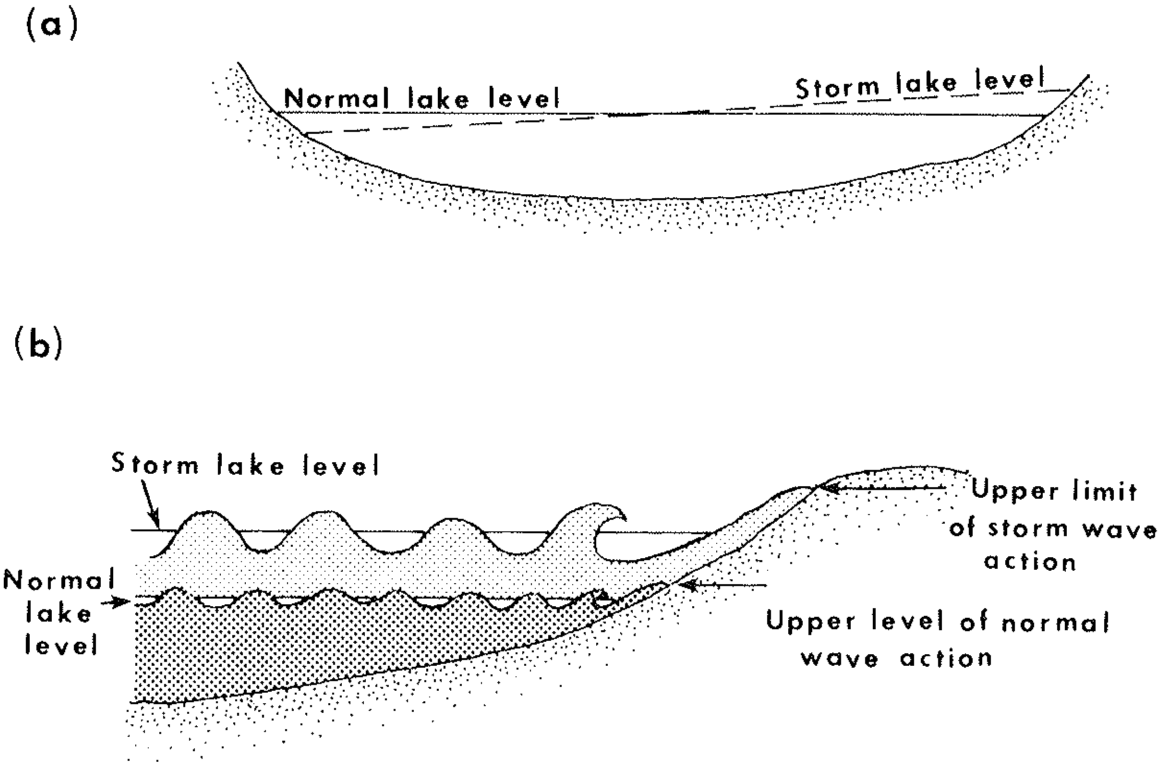


Figure 27. (a) Changes in lake level due to the effects of storm winds, (b) higher lake levels combined with high waves result in an increase in the upper limit of wave action during storms.

Winds

In addition to playing an important role in generating waves, winds can transport fine-grained sediments on a beach and can cause relatively large water-level changes (p. 31). The transport of sand by wind can result in partial or complete burial of oil that has been stranded on a beach (O'Sullivan, 1978). The effect of this burial is to reduce rates of weathering and aging.

Wind can have a direct effect on the physical and chemical properties of spilled oil as the process of evaporation of the light fractions is dependent in part on wind velocity (McMinn and Golden, 1973). Light grade oils can be completely dispersed by evaporation, whereas, heavier oils are reduced in volume by the loss of light fractions, viscosity is increased and an asphaltene residue is produced.

Ice

The formation of ice on the water surface reduces wave generation during winter months. In the Great Lakes the presence of lake ice for periods up to 4 months each year coincides with the period of maximum wind velocities, and thereby prevents wave generation at a time when mechanical energy levels at the shoreline would otherwise be high.

Ice that forms on the shoreline is usually referred to as an ice foot (q.v.). The ice foot forms before and persists longer than lake ice. This shorefast ice protects the shore zone from wave action, particularly if the lake surface is ice-free. Waves can be reflected from an ice foot to cause mixing and the physical breakdown of oil on the water surface as well as preventing the oil from reaching the ice foot.

Although an ice foot prevents oil from becoming stranded on the shore (Ruby, *et al.*, 1977), the development of an ice foot after oil is stranded can result in the burial of oil if cleanup has not been implemented. In such cases the oil would remain buried beneath or enclosed within the ice until the ice foot thaws.

Ice pressure can result in the movement of beach sediments as ice is pushed into the shore zone. This movement can affect stranded oil by mixing it with beach sediments or by burial beneath the sediments. The effect caused by ice pushing sediments and oil up the beach would be the deposition of oil above the limit of wave activity.

6.3 BEACH CHANGES

On coasts with sediments the most important effect of wave energy is the transportation and redistribution of the beach sediments. On rocky coasts devoid of sediments the wave energy is reflected back from the rocks or is absorbed in eroding the rock surface.

The beach changes that are associated primarily with wave action result from either the onshore-offshore movement or the alongshore movement of sediments. The actual amount of sediment transported and the magnitude of beach change are related to the size of the material and to the available wave energy. As sediment size increases, so the level of energy necessary to initiate and maintain transportation increases. Sands are readily moved by all but the smallest waves, but cobbles require a much higher force for transportation. An increase in wave energy on a beach results in higher rates of sediment transport and, therefore, an increase in the amount of beach change that can occur.

During periods of high-energy wave activity (*i.e.*, storms) beaches are usually eroded. On sand beaches this results in movement of sediment into the nearshore zone adjacent to the beach. As energy levels decrease after the storm, the sediment is returned to the beach by constructive wave action. The mechanism of sediment return is often associated with the onshore migration of a ridge which welds onto the beach, provided that the sequence is not interrupted by further storm-wave activity (Fig. 28).

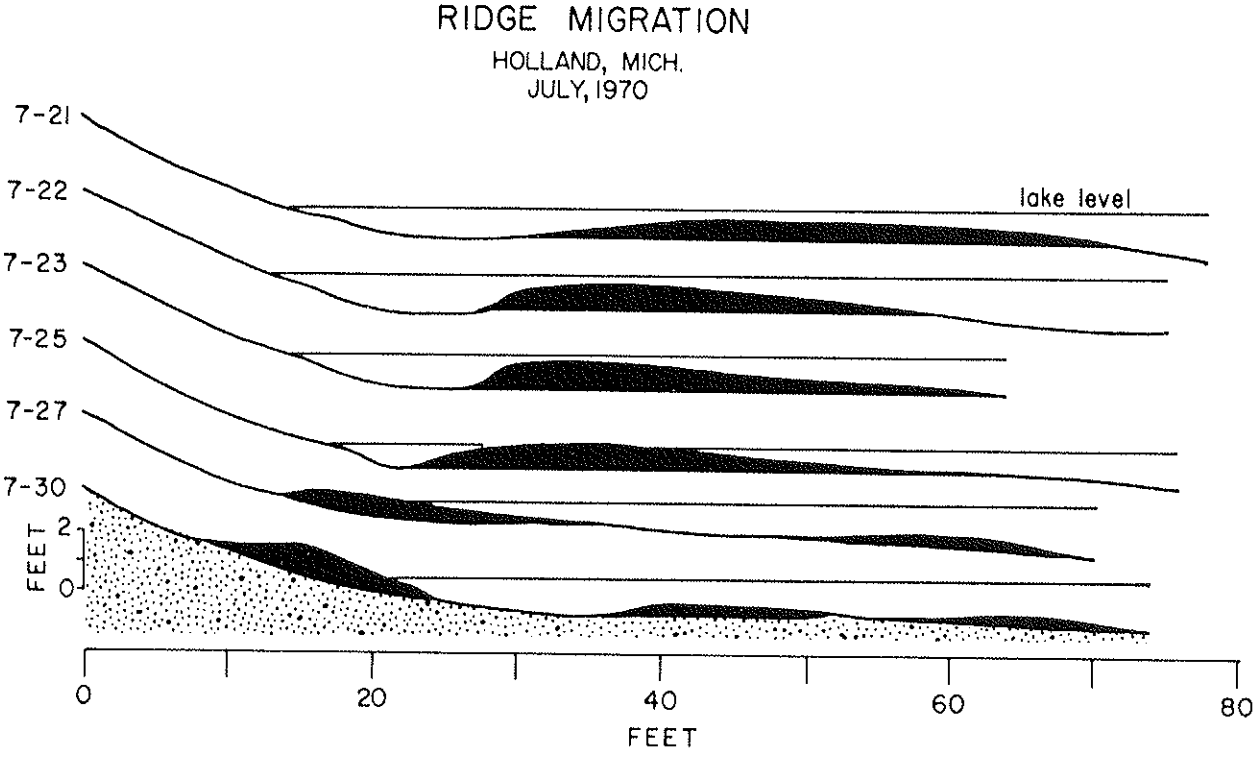


Figure 28. Sequence of onshore ridge migration over a 10-day period (July 21 to July 30, 1970), Lake Michigan (from Davis and Fox, 1971).

Oil stranded on a beach prior to a storm could be eroded by wave action and dispersed. However, if oil is deposited immediately following erosion, but before recovery has commenced, the oil would become buried as the ridge migrates onshore (Fig. 29). The buried oil would be degraded very slowly and would then be exposed and dispersed only by further beach erosion. In some cases this <u>storm/post-storm</u> cycle is replaced by a seasonal

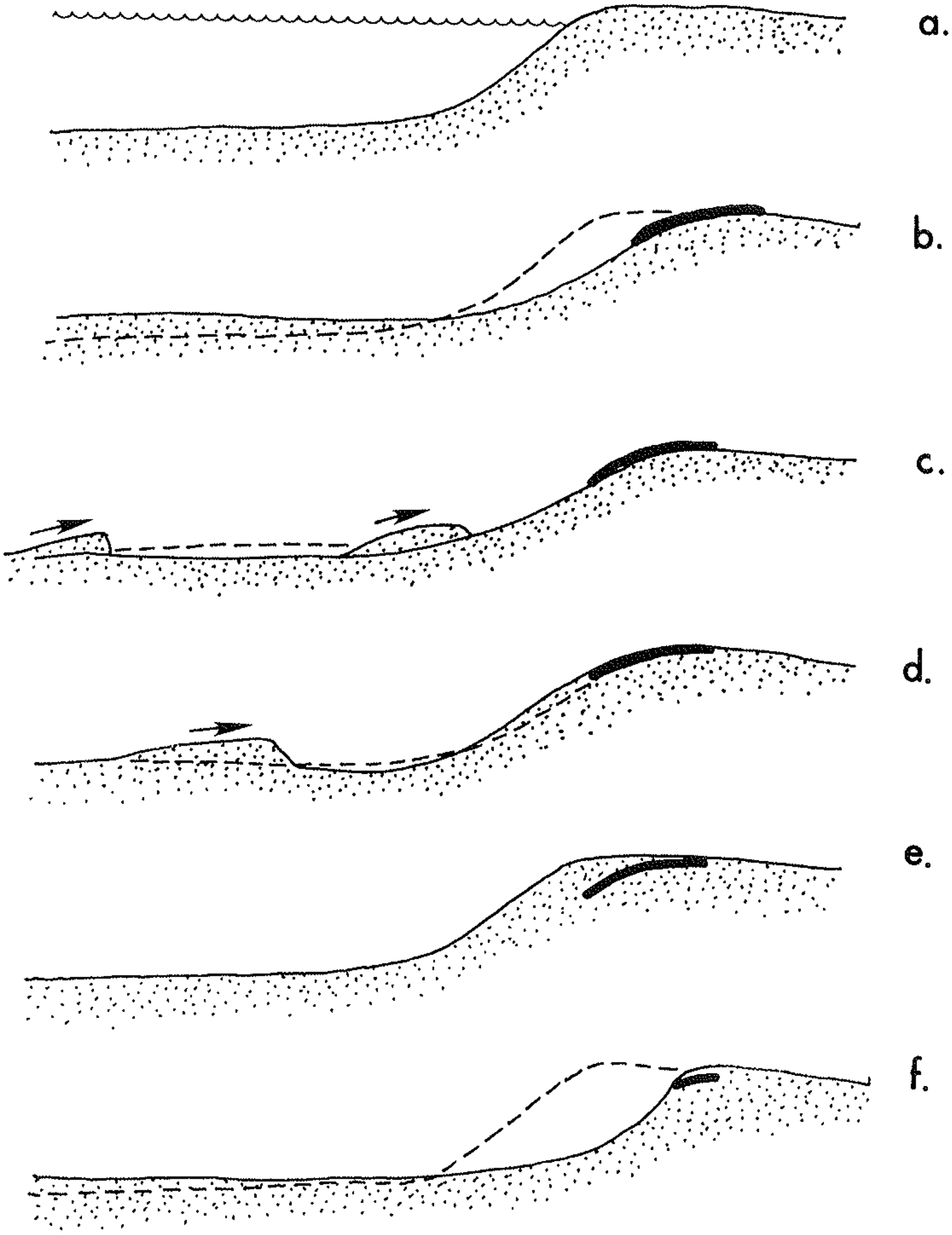


Figure 29. Sequence of storm erosion and oil deposition (b); burial (d) (e); and exposure following a second storm (f) on a sand beach (from Owens, 1977b).

summer/winter cycle associated with summer accretion and winter erosion. Although the two cycles occur over different time scales, the effects of both cycles on stranded oil are similar.

The effects of storm waves on pebble or cobble beaches are somewhat different. In this case the sediments tend to be moved up the beach by storm-wave action to form a storm ridge. Oil stranded during higher water levels on the storm ridge of a pebble or cobble beach would then be buried by this upward migration of sediment during a period of storm-wave activity (Fig. 30).

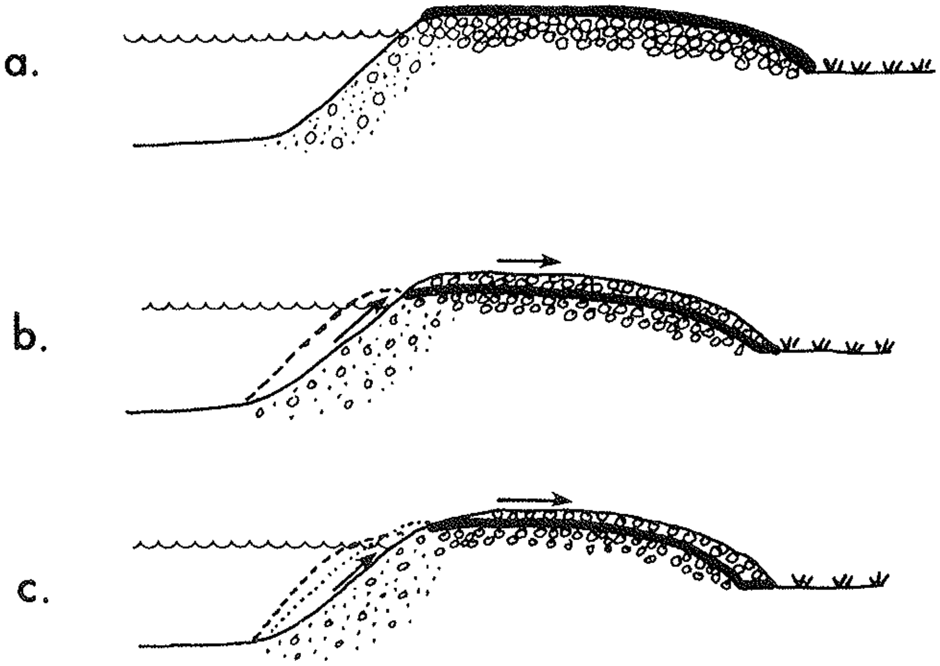


Figure 30. Effects of storm-wave activity on oil stranded on a cobble beach: (a) oil is deposited above the normal limit of wave action during storm conditions; (b) a second storm erodes the beach and waves push material onto the upper beach to cover the oil; (c) a subsequent storm continues the process, gradually exposing more of the buried oil layer (from Owens, 1977b).

Beach changes can have a strong alongshore component as sediments are transported by waves that approach the shore at an angle. A common feature on sand beaches is a type of rhythmic topography called beach cusps. These features can be of various sizes and can migrate along the beach, causing alternating periods of erosion and deposition on a given section of the shore. The movement of such features on a beach with stranded oil would result in a continuous sequence of burial and erosion of the oil (Fig. 31).

Beach changes also result as the level of the lakes varies through time. At times of low lake levels more of the shore zone is exposed and beach width and berm height relative to lake level are increased. With above average lake levels, the converse is true. As the lake levels vary seasonally there are, therefore, regular changes in the dimensions of a beach.

The shore zone is a dynamic environment. The beach changes discussed above are an integral part of the dynamic framework in which sediments are continuously transported and redistributed. Oil can play an important role in reducing rates of change if the oil cover is sufficiently thick to prevent sediment movement or if the oil binds the sediments together and prevents the movement of individual particles. The latter is particularly common with heavy or weathered oils that frequently form an "asphalt pavement" (Photo 48). Once the sediments are immobilized and the voids filled with oil, dispersion occurs only slowly. This is a common feature of stranded oil in sheltered wave environments. In addition to the reduced role of mechanical degradation due to burial

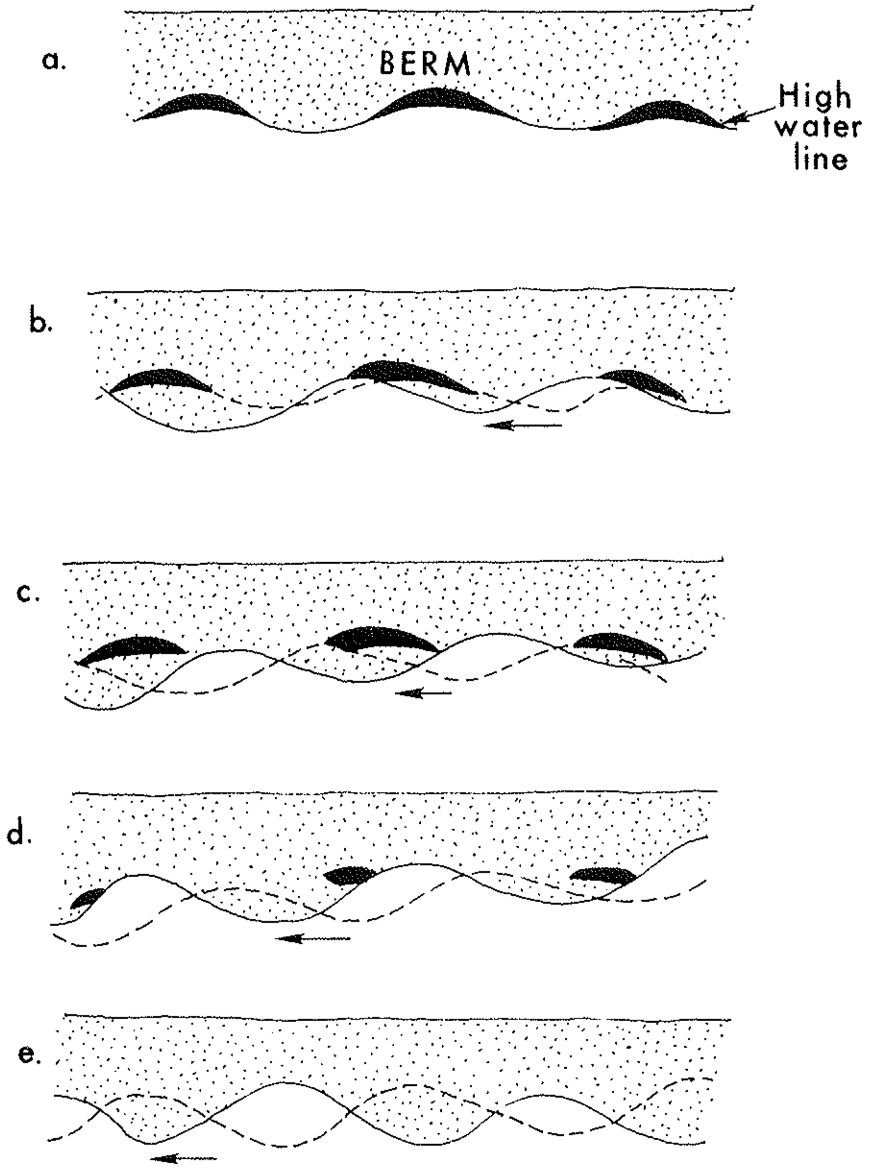


Figure 31. Plan view of the effects of oil deposited at the high-water level by migrating rhythmic topography (from Owens, 1977b).

or to the formation of asphalt pavements, Colwell, *et al.*, (1978) note that in these instances weathering and microbial degradation are also ineffective.

Photo 48. Part of an "asphalt pavement" in the upper beach on Crichton Island, N.S., 3 1/2 years after the spill (photo by J.R. Belanger, Bedford Institute).

6.4 SHORELINE EXPOSURE AND WAVE-ENERGY LEVELS

The levels of wave energy on a beach depend on the degree of exposure or sheltering as well as on the generation of waves over the adjacent lake. Exposed shorelines are defined as having no protection and these receive the full force of incoming waves. Sheltered shorelines are common on irregular coasts where headlands or islands act to protect the shore zone from wave action. For example, the effect of sheltering is clearly evident when comparing the high wave-energy levels on the exposed shores of eastern Prince Edward County in Lake Ontario with the low-energy environments on the sheltered adjacent coasts of the Bay of Quinte.

The actual levels of incoming wave energy are primarily a function of winds and fetch. On coasts with predominantly offshore winds, such as the Lake Ontario shoreline of the Niagara

Peninsula or the east coast of the Bruce Peninsula, wave-energy levels at the shore are relatively low when compared to coasts with predominantly onshore winds. The fetch lengths control maximum wave-energy levels by limiting the surface area over which wave generation is possible.

There is considerable geographical variation of energy levels within the Great Lakes system due to the available fetch distances, the degree of exposure or sheltering, and the direction of prevailing and dominant winds with respect to the coast. Superimposed on these factors are temporal variations in wave-energy levels that result from changes in wind velocities due to weather patterns. The highest levels of wave energy on exposed coasts occur during periods of storm winds, which are most common in ice-free winter months. But even an exposed coast with large available fetch distances may have very low levels of wave energy at the shore during summer months.

Although it is not possible to accurately determine shoreline wave-energy levels without long-term measurements, an approximate and relative approach can be used for estimation purposes. The index of relative shoreline wave-energy levels for the Great Lakes (Table 20) is developed using only the primary process factors (wind direction, fetch, and degree of exposure). Wind velocity is not considered as this is assumed to be a relatively constant factor in the Great Lakes region. The impact of ice on the shore is effectively to reduce energy levels to zero as the mobility of the system, in terms of sediment transport and shore zone dynamics, is temporarily suspended.

TABLE 20. Relative Shoreline Wave Energy Levels for the Great Lakes

PREVAILING ONSHORE WINDS	Open straight coast: fetch >200km	10
	Indented coast: fetch >200km	9
	Open straight coast: fetch 50-200km	8
	Indented coast: fetch 50-200km	7
PREVAILING OFFSHORE WINDS	Open straight coast: fetch >200km	6
	Indented coast: fetch >200m	5
	Open straight coast: fetch 50-100km	4
	Indented coast: fetch 50-200km	3
	Sheltered coast: fetch <50km	2
	Narrow channel, enclosed bay or backshore lagoon	1
	Ice on beach	0

The basic relationships between the primary factors are illustrated in Figure 32. The height of the beach, that is the height of the berm or ridge above lake level, and sediment sorting are response features related directly to energy levels, and can be useful field evidence for establishing an estimate of relative energy levels. The height to which sediment is pushed up a beach to build a berm (on sand beaches) or a ridge (on pebble/cobble beaches) is a direct function of wave height; as wave height and wave energy increase then the higher the berm or ridge. Lake level variations must also be considered when comparing beach heights between lakes, but can be regarded as a constant factor for comparison of beaches within a smaller area.

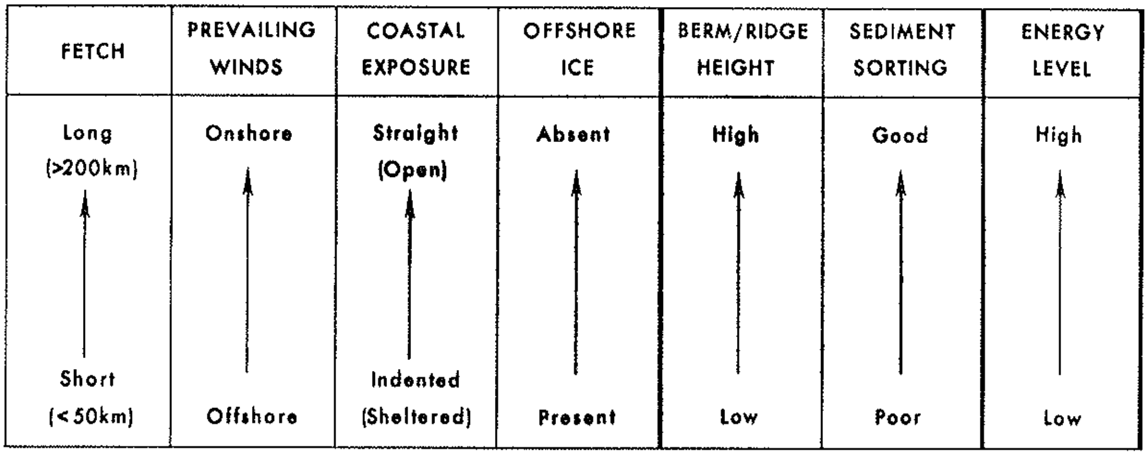


Figure 32. Shoreline energy levels.

The degree of sorting of beach sediments can be a useful indicator of shoreline energy levels. High wave-energy level beaches are usually characterized by well-sorted sediments (*i.e.*, only one size of sediments). In sheltered, low-energy locations the beach is usually composed of a mixture of sediment sizes.

6.5 SHORELINE GEOMORPHOLOGY

The character of the shoreline is a function of the interaction between the shoreline processes, energy levels, and the availability and size of the sediments in the shore zone. A primary distinction can be made between those coasts which have sediments in the shore zone and those which do not. In the latter case, this distinction refers to rock coasts or man-made structures that are without sediments exposed above the water level. On coasts which have sediments in the shore zone, the predominant distinguishing feature between shore types is the sediment size (Table 21). A subdivision of shorelines with sediments is vegetated coasts in which plant colonization is the primary feature of the shore zone. This preliminary definition of shore zone types is very simplified as many shore zones are composed of one or more basic types, for example, coasts which have a rock shore zone with a sand or pebble beach in the upper sections.

TABLE 21. Shoreline Types Based on Substrate

COASTS WITHOUT SEDIMENT	COASTS WITH SEDIMENT
Rock	Mud
Man-made structures	Sand
- concrete	Pebble
- metal	Cobble
- wood	Boulder
	Mixed sediments
	Vegetated - marshes - backshore dunes

On exposed beaches wave action tends to segregate the size fractions of sediments. As wave-energy levels increase the sorting of beach materials also increases. In high-energy environments, the beaches are usually composed of only one size of sediment or the sediments have a distinct zonation across the beach. In low-energy environments, sediments in the shore zone are usually a poorly-sorted mixture of several sediment types (*e.g.*, sands, pebbles and cobbles) (Table 22).

TABLE 22. Sediment Size Grades

TYPE OF SEDIMENT	PARTICLE DIAMETER
Mud	< 0.06 mm
Sand	0.06 - 4 mm
Pebble	4 - 64 mm
Cobble	64 - 256 mm
Boulder	> 256 mm

On those coasts in the Great Lakes which have sediments, the beaches are generally narrow and have low berms (q.v.). The beach width and height are a direct function of local wave heights and water levels. On exposed beaches with large fetches, wave heights >1 m are relatively common, particularly in winter months. In these locations waves can build berms up to 1.5 m to 2 m above the lake level (Photo 49). As exposure and energy levels decrease, the beaches become lower and narrower so that in very sheltered environments a beach of poorly-sorted sediments may be only 1 m or 2 m wide and extend less than 0.5 m above lake level.

For the most part the nature of the backshore is not of great importance in terms of the impact of the oil. However, backshore geomorphology is a significant factor in terms of sediment supply and accessibility. Many sections of the shore zone in the lower Great Lakes are backed by easily erodible cliffs of unconsolidated sediments. In some cases the beach is very narrow or absent and waves act directly on the cliffs. The absence of

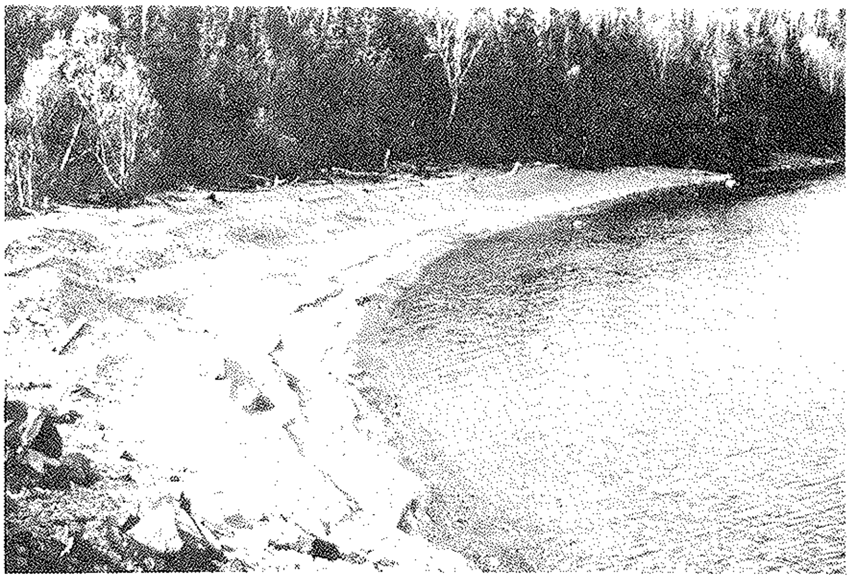


Photo 49. Exposed pebble-cobble beach (fetch >200 km) in Hibbard Bay near Mamainse on the southeast coast of Lake Superior. Note that the storm ridge is more than 2.0 m above the lake level and that logs have been stranded on top of the ridge (15 October 1978).

a beach may be due to a deep nearshore zone or to burial by slumping or sliding of the cliff face.

On coasts backed by unconsolidated cliffs, the beach acts as a buffer to wave energy and protects the base of the cliffs from erosion. The reduction of beach width, by high lake levels or by sediment removal by man, reduces the amount of protection and can result in cliff undercutting. The result of this undercutting is usually that the cliff face becomes unstable and slope failure or collapse follows.

6.6 SHORELINE ACCESSIBILITY

The character of the shoreline and backshore morphology determines the accessibility of a given section of coast or beach by land, sea or air. Accessibility is of considerable importance in planning a spill response. The major access categories are outlined in Table 23. It should be remembered that access conditions can change through time depending on beach width, wave conditions, lake levels and weather.

TABLE 23. Shoreline Accessibility

LAND ACCESS

1. Roads or tracks that can support heavy equipment or trucks, with direct access to the shore zone or beach.
2. Tracks or trails that provide access to the shore zone for light vehicles.
3. Tracks or trails that provide only pedestrian access.
4. Inaccessible by land.

WATER ACCESS

1. Unobstructed beach or shoreline access for boats and barges.
2. Shallow-water access for small boats only.
3. Inaccessible by water.

AIR ACCESS

1. Flat ground available for helicopter access.
2. Inaccessible by air.

6.7 SHORELINE CLASSIFICATION

The characterization of a section of coast for spill response situations requires information or data on shore processes, wave-energy levels, sediment availability, sediment type, and accessibility. Due to the large number of factors involved and the great range within each factor, it would be an over simplification to classify the shoreline by using only one or two of the major factors. The approach that has been developed provides a checklist of information (Table 24). This information then can be used to characterize the shoreline section. In preparation

TABLE 24. SHORE ZONE CHARACTER CHECKLIST

1. BEACH SEDIMENTS AND MORPHOLOGY

	Substrate	Sediment Size(s)
Lower Beach	____________	____________
Upper Beach	____________	____________
Backshore	____________	____________

Sediment Sorting: Good ____ Poor ____

Angularity of Sediments: Rounded ___ Angular ___ Sharp Edges ___

Debris: Cover on lower beach ____% On upper beach ____%

Beach Width: ____m

Maximum Berm or Ridge Height (above lake level): ____m

2. SHORELINE EXPOSURE AND ENERGY LEVELS (for the Great Lakes)

Maximum Fetch (km) >200 ____ 50-200 ____ <50 ____

Predominant Winds: Onshore ____ Offshore ____

Coastline Straightness: Straight ___ Irregular ___ Indented ___

Degree of Exposure: Open ___ Partly Sheltered ___
Completely Sheltered ____

Presence of Ice Foot: Absent ____ Present ____

Relative Exposure/Energy Level: (from Table 20, p. 182) __________

Seasonal Energy Level: (see text, p. 191) High _____
Intermediate ____ Low _______

3. SHORELINE ACCESS (see Table 23, p. 187)

Heavy Vehicles: Land Access: Existing ____ Required ____
Seaborne Access: YES/NO

Light Vehicles: Land Access: Existing ____ Required ____
Seaborne Access: YES/NO

Pedestrians: Land Access: YES/NO
Seaborne Access: YES/NO
Aerial Access: YES/NO

for spills this aspect of information gathering is an important part of contingency planning and is best carried out prior to a spill so that the information is already on hand.

The substrate (q.v.) is probably the single most important factor for determining impact and response. The absence of sediment or the predominant sediment size controls the depth of oil penetration and, to a large extent, the persistence of oil. The sediment size and oil penetration depth are also primary controls on the effectiveness and applicability of available cleanup methods.

The degree and angularity of the sediments can be a useful indicator of shoreline energy levels. In locations sheltered from waves, energy levels at the shoreline are low and beaches are usually composed of a mixture of sediment sizes and pebbles or cobbles that are often angular or have sharp edges (Photo 50). Angularity is only a useful indicator where the sediment is derived from local erosion of rocks. If the pebbles or cobbles have been eroded from deposits of glacial or river sediments they may be already rounded before reaching the shore zone.

The substrate type can be determined by visual observations. On beaches with more than one size of sediment the types should be listed in descending order of abundance (*e.g.*, cobbles and sand) or by location if there is an across-beach zonation (*e.g.*, sand - lower beach; cobbles and sand - upper beach; marsh - backshore). These location definitions are explained in the Appendix (Fig. 36, p. 248). The basic shoreline types and sediment size grades are given in Tables 21 and 22.

The presence of debris lines or logs can hamper cleanup but

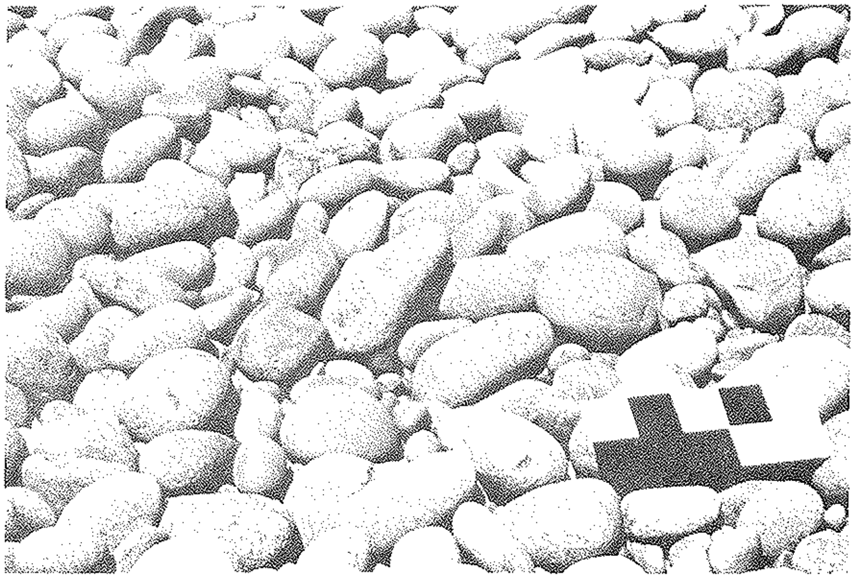


Photo 50 a. Well-sorted and well-rounded sediments on a high-energy cobble beach (scale is 25 cm long).

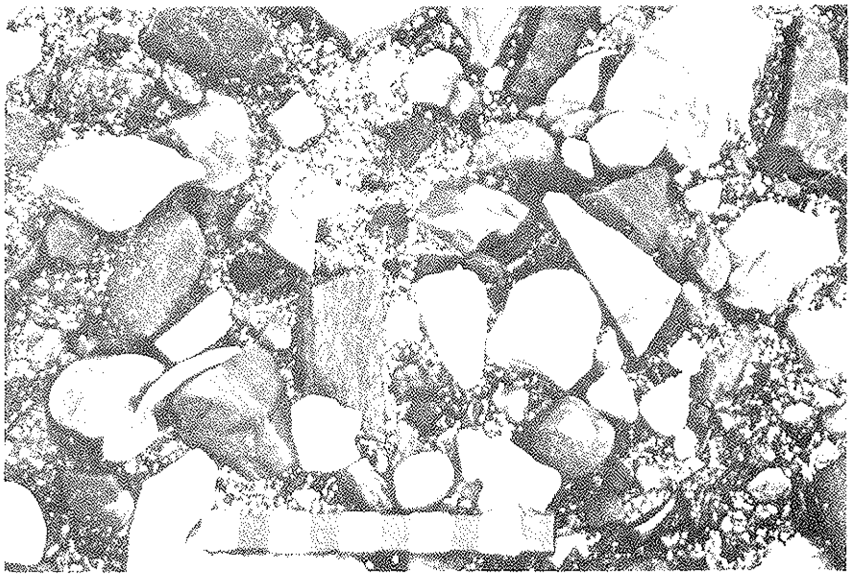


Photo b. Poorly-sorted sediments (sand to cobble sizes) with angular pebbles and cobbles on a sheltered, low energy beach (scale is 10 cm long).

can also be an indicator of the maximum upper limit of wave action. If debris lines are above the normal limit of wave action this indicates that the shore is subject to periods of high waves, and, therefore, high wave-energy levels (see Photo 4, p. 56).

An estimation of relative wave-energy levels at the shoreline can be obtained by defining fetch, exposure and the prevailing wind direction. This estimate must take into account the large seasonal variation in wind velocities and, therefore, wave heights. On a general basis this seasonal variation can be accounted for by regarding the period from November to April as "high-energy"; from June to August as "low-energy"; and May, September, and October as "intermediate-energy" (Fig. 4, p. 26).

The accessibility to the shore zone is an important characteristic for spill response operations and this information (based on Table 23) is included in the shoreline checklist.

PART 7 - THE IMPACT OF OIL AND SHORELINE SENSITIVITY

SYNOPSIS

The impact or effect of oil on the shoreline varies according to: (a) the type of oil, and (b) the shoreline type. Superimposed on these two primary factors are: (c) the actual volume of stranded oil, and (d) meteorological conditions (air/sea temperatures). The persistence of stranded oil depends on the above four factors and on: (e) the shore zone wave-energy levels, and (f) the degree of penetration and/or burial of the oil. Knowledge of these six factors provides the basic information for estimating the expected impact of a spill and for predicting the residence time (persistence) of stranded oil.

The sensitivity of a section of shoreline to a spill is frequently related to the shoreline type and to the shore zone sediments. When this index of shoreline sensitivity is applied, low wave-energy and vegetated shorelines are the most sensitive to spills, and coasts without sediment are the least sensitive. In practical terms, an assessment of shoreline sensitivity must also involve an estimation of the degree to which stranded oil affects and alters: (1) normal shore zone processes (both ecological and geological), (2) man's normal use of the shore zone (recreational, cultural and commercial), and (3) possible damage that could be caused by shoreline cleanup operations. The most critical factors in determining the sensitivity or vulnerability of a shoreline section to spilled oil are related to shore zone ecology and to man's use of the shore zone.

7.1 INTRODUCTION

The implementation of shoreline protection and cleanup operations is governed by two groups of factors: (a) those which define the geological, ecological, and cultural-economic impact of a spill (the shoreline sensitivity), and (b) those which relate to the applicability and effectiveness of available protection and cleanup techniques. In this section the impact of oil on the various shoreline types (Part 7.2), and shoreline sensitivity (Part 7.3) are briefly reviewed prior to the discussion of protection and cleanup operations (Part 8, p. 203).

7.2 THE IMPACT AND PERSISTENCE OF STRANDED OIL ON SHORELINE TYPES

The definition of major shoreline types in Table 21 (p. 184) is based on the absence of, or on the size of, shore zone sediments. The impact of oil on each of the shoreline types varies with the type of oil (*e.g.*, Bunker C, diesel, etc.) that becomes stranded. The persistence of the stranded oil is a function of the oil type, the degree of burial or penetration, and mechanical wave-energy levels at the shoreline. These two relationships can be simply stated:

- the impact of a particular type of oil is similar for each shoreline type (varying only with the volume of oil and air temperature changes)
- the persistence of a particular type and volume of oil on a particular shoreline type varies depending only on the wave-energy level and the degree of oil burial

As these relationships are relatively simple, it is possible to review the impact of oil on the shoreline types without a detailed account of the shoreline processes in each case (Table 25).

7.3 SHORELINE SENSITIVITY

The sensitivity of a section of shoreline can be defined by the impact of stranded oil on:

(a) the normal shoreline processes (geological and biological),

(b) man's normal use of the shore zone (cultural, recreational and commercial), and

(c) unique shore zone features (cultural and biological).

Shoreline type, wave-energy level, and the volume of oil are critical in determining the persistence of stranded oil, but are not sufficient parameters for defining shoreline sensitivity. Normal

TABLE 25. The impact and Persistence of Stranded Oil

SHORELINE TYPE	IMPACT OF OIL	PERSISTENCE
Coasts Without Sediment		
ROCK MAN-MADE	- oil may be reflected - coats exposed dry surfaces - wave splash can throw oil above normal limits of wave action - oil does not easily adhere to wet surfaces - thickness of oil cover decreases as steepness increases - oil collects in rock pools	- oil readily abraded if it is stranded below normal limit of wave activity, except in sheltered sites
Coasts With Sediment		
MUD	- mud has very small spaces between particles and these are usually filled with water, therefore, only very light grades of oil penetrate	- muds are easily transported by waves, therefore, oil can be buried - buried oil degrades very slowly in muds - surface oil may be easily removed by waves because water usually separates the oil from the mud
SAND	- only light oils can penetrate sand - heavy oils rarely penetrate more than 2 to 3 cm - penetration depths are greater during periods of high temperatures - oil is usually deposited at upper limit of wave action	- oil can be easily abraded if it is not buried and if it is within the zone of wave action - possibility of burial is high if beach is subject to wave action during storms - oil/sediment may form an "asphalt pavement", thereby increasing persistence
PEBBLE COBBLE BOULDER	- as the size of the sediments increases, the depth of penetration of all oils increases - penetration of medium and heavy oils can be as much as 1.0 m - light grades of oil may be washed through the beach into the lake by waves	- buried oil and "asphalt pavements" are very persistent - surface oil is easily abraded by waves and moving sediments
MIXED SEDIMENTS	- spaces between larger particles are filled with smaller-sized sediments, therefore, oils rarely penetrate (except light grades)	- usually low energy environments, therefore, even surface oil persists - "asphalt pavements" are common
MARSHES	- oil is usually restricted to the marsh edges - light oils are more toxic to the vegetation and can penetrate the marsh sediments - impact is less severe in autumn and winter months	- mechanical energy levels are low, but biochemical degradation is rapid if oil is not buried - marshes usually recover naturally unless the oil is very toxic or very large volumes of oil carpet the vegetation

shoreline processes and man's use of the shore zone are of critical importance. In certain instances the impact of stranded oil may be severe and the damage may be irreparable. On the other hand, high-use recreational sand beaches contaminated in winter months may be cleaned rapidly by natural processes or by cleanup operations with little or no impact and damage to the ecology or to man's normal activities. Between these two extremes are a great range of sensitivity levels.

As an initial framework, the major shoreline types of the Great Lakes have been ranked in terms of sensitivity in Table 26 (see also Gundlach and Hayes, 1978). The shoreline types have been slightly modified from Table 21 to include an assessment of shoreline energy levels. This modification is important because oil tends to collect and to be more persistent in sheltered locations and because sheltered environments are usually more ecologically sensitive. Dunes are also included in this table as these are ecologically and geologically sensitive to human and vehicular traffic associated with cleanup operations (Part 8.5, p. 227).

This ranking in Table 26 is intended only as a general guide to the impact of oil; within each shoreline type it is necessary also to consider the effects of the oil and of the cleanup programme in terms of:

1. the type of oil spilled,
2. the persistence of stranded oil, and
3. cleanup effectiveness.

The type of oil spilled can determine the severity of impact. Light, volatile oils are more toxic than heavy or tarry oils and would invariably have a greater initial ecological impact. On

TABLE 26. Sensitivity of Shoreline Types

↑ INCREASING SENSITIVITY

I.	Marshes Lagoons
II.	Sheltered Rocky Coasts Sheltered Beaches
III.	Dunes Mud Flats
IV.	Pebble/Cobble/Boulder Beaches Sand Beaches
V.	Exposed Rock or Man-Made Structures

sandy or rocky shores where ecological sensitivity is generally not high, the impact of light oils may not be severe. Similarly, the impact of light oils on a marsh is much less severe in autumn or winter months than in spring or summer.

Oil persistence increases as the volume of stranded oil and the penetration or the degree of burial increases, and as the level of wave energy at the shoreline decreases. If small amounts of light oil are stranded on an exposed coast, natural dispersion may be sufficiently rapid that the economic and cultural impact is low. Such would be the case on low-amenity shores in unpopulated regions. However, even small volumes of oil that would normally disperse rapidly may greatly affect man's normal use of a recreational sand beach in a park or recreational area during summer months.

The shoreline sensitivity can also be considered in terms of the effectiveness of natural cleaning or cleanup operations. If the shore zone can be cleaned easily and effectively by nature or by man, then the impact of the oil is greatly reduced.

Superimposed on the shoreline type, the oil and the cleanup parameters are the effects of the spill. It is then necessary to consider:

4. ecological sensitivity,
5. geological sensitivity, and
6. cultural-economic sensitivity.

Ecological sensitivity is a function of the degree to which normal biological processes are damaged or altered. Important factors in determining ecological sensitivity are:

(a) natural recovery potential,
(b) presence of rare or endangered species,
(c) timing of the spill relative to breeding or growth seasons,
(d) possible adverse effects of cleanup operations, and
(e) economic value (commercial and recreational) of impacted species.

Definition of ecological sensitivity should be undertaken by qualified personnel, preferably with a local knowledge of the area affected, or potentially affected, by the oil.

The most important aspect of geological sensitivity relates to the removal of contaminated sediment from the shore zone. Erosion and beach retreat will result if beach stability is affected because of sediment removal. If the backshore area has been developed for either housing or recreation, those properties could then be exposed to wave action. Similarly, because a beach acts as a buffer to wave action at the base of cliffs, removal of sediment can permit waves to act directly on the cliff and cause cliff retreat.

Damage to dunes or marshes can be caused during a cleanup programme by the use of vehicles in the backshore area. In these cases the destruction of vegetation by machinery incurs both geological and ecological damage. This damage can be more severe than the impact of oil alone.

Normal shoreline processes, sediment transport and beach changes can be altered by oil if an "asphalt pavement" is formed. Although this impact is important in terms of local sediment transport and oil persistence, it is rarely a significant problem. However, in certain circumstances the presence of this impermeable ramp, rather than a permeable beach, can cause higher wave run-up than is normal on a beach. This could allow waves to overtop a beach and to erode backshore areas that would normally be above the limit of wave action.

The degree to which <u>cultural or economic</u> activities are sensitive to an oil spill varies considerably. The impact of oil stranded in a major recreational area during summer months may severely affect normal activities. In this context, a recreational sand beach may be a very sensitive shoreline type during summer months, whereas the same section of shoreline may have a much lower sensitivity in the remaining seasons. The cultural-economic factors to be considered include:

(a) special or unique cultural features,
(b) marinas or harbours,
(c) parks or recreational areas,
(d) commercial or recreational activities (*e.g.*, fishing),
(e) commercial or domestic water supplies, and
(f) seasonal changes in man's activities.

From the foregoing discussion, it is evident that an assessment of shoreline sensitivity involves a series of interrelated factors (Fig. 33). Definition of shoreline sensitivity in terms of a scale or ranking system is both complex and difficult, and is not attempted in this report. The basic shoreline sensitivity given in Table 26 is presented only as a very general guideline to the problem of the impact of oil. Despite the problems of assigning relative sensitivity levels, some assessment of potential or actual damage to the shore zone is necessary in defining protection and cleanup priorities. The information checklist presented in Table 27 provides a framework within which shoreline sensitivity can be assessed.

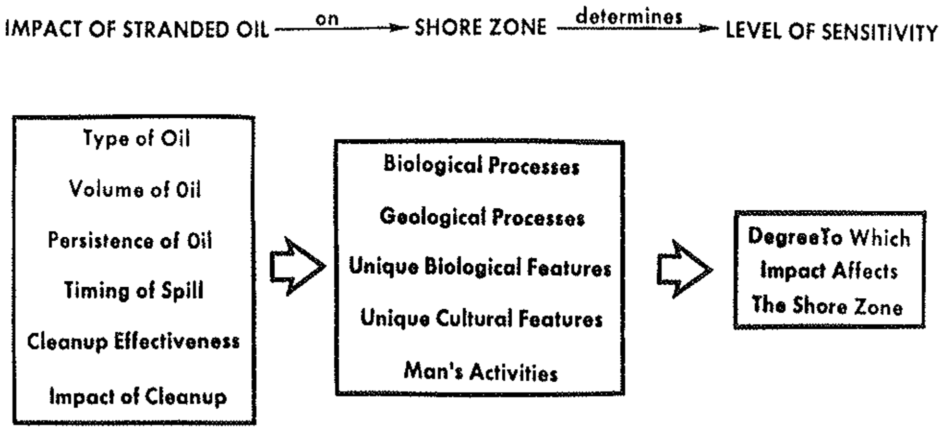


Figure 33. Factors that affect the level of shoreline sensitivity.

TABLE 27. SHORE-ZONE SENSITIVITY CHECKLIST

IMPACT FACTORS

Type of Oil: ____________________

Is oil on shore?

YES - Volume Stranded (from Table 19, p.167): ____________________

NO - Volume of Spill: ____________________

Expected Persistence of Oil: Days ___ Months ___ Years ___ Decades ___

Month of Year: ____________________

Can cleanup be effective? (from Table 31, p. 215) YES/NO

Would cleanup have an impact? (from Table 31, p. 215) YES/NO

If YES, describe: ____________________

____

SHORE ZONE CHARACTER

Shoreline Type (from Table 21, p. 184): ____________________

Rare or Endangered Biological Species: Absent ___ Present ___

Natural Biological Recovery Potential: <1 Yr. ___ Years ___ Decades ___

Natural Geological Recovery Potential: <1 Yr. ___ Years ___ Decades ___

Recreational Use of Shore Zone:
None ___ Low ___ Moderate ___ High ___ Very High ___

Commercial Use of Shore Zone:
None ___ Low ___ Moderate ___ High ___ Very High ___

Biological Impact of Oil:
None ___ Low ___ Moderate ___ Severe ___ Critical ___

Impact of Oil on Rare or Endangered Species:
None ___ Low ___ Moderate ___ Severe ___ Critical ___

Biological Impact of Cleanup:
None ___ Low ___ Moderate ___ Severe ___ Critical ___

Geological Impact of Cleanup:
None ___ Low ___ Moderate ___ Severe ___ Critical ___

PART 8 - SHORELINE PROTECTION AND CLEANUP

SYNOPSIS

Shoreline protection is most effective when oil can be collected and removed before becoming stranded. Protection operations are feasible if: (a) the location and movement of a slick are known, (b) sufficient time is available to implement the operations, and (c) sufficient equipment and personnel are available. The decision to implement a protection operation involves an assessment of the probable impact of the oil and of the shoreline sensitivity and the feasibility of the operation. Protection priorities can be based on shoreline sensitivity with the most vulnerable shoreline sections designated as the highest priority sites. The available offshore protection methods include: (1) booms in combination with oil removal, and (2) dispersants. Onshore protection can involve the use of sorbents, surface treatment agents, or the construction of dykes and ditches on the shoreline.

Cleanup of oiled shorelines is not required when the level of contamination is acceptable or when oil would be removed naturally in an acceptable time period. As more damage may be caused by the cleanup operations than results from the spilled oil, consideration must be given to the impact of the methods to be employed. Damage to vegetation can be critical in marsh and dune systems, and sediment removal can cause beach retreat and backshore erosion in locations where natural sediment replacement is inadequate.

The selection of cleanup methods is based primarily on the volume of oil, the shoreline type and accessibility. The available cleanup methods involve either dispersion, removal or *in situ* cleaning techniques. Lake or shore ice present critical operational problems and the normal cleanup methods may not be practical.

8.1 SHORELINE PROTECTION PRIORITIES AND PLANNING

Prevention of oil reaching sensitive shoreline sections or environments is possible provided that:

(a) accurate predictions of the movement or of locations where the oil will be stranded are available,

(b) sufficient time is available to implement protection operations,

(c) environmental conditions are favourable, and

(d) equipment, materials and manpower are available.

In almost all cases, protection of the shoreline by removal of oil from the water surface is more efficient and easier than shoreline cleanup. In the case of small spills, offshore oil removal can be very effective, but the problems of containment and removal of the oil increase as the size of the spill increases.

The decisions related to protection operations involve consideration of: (i) whether or not it is necessary or beneficial to prevent oil from reaching the shore zone (shoreline sensitivity), (ii) the deployment of available resources to protect those sections identified as sensitive (protection priorities), and (iii) the practicality and logistics of protecting those shore sections (operational feasibility). In cases where shoreline protection is required or is desirable, and it is evident that all of the spilled oil cannot be contained offshore, a system of defining protection priorities must be prepared. These decisions related to priorities involve assessment of the impact of stranded oil on different shoreline sections and consideration of the logistic requirements for each site to be protected.

The priorities could be defined either: (a) in relation to the spill movement, so that the sections nearest the oil would be afforded protection first, or (b) according to the level of shoreline sensitivity. In the first case (a), the assignment of priorities is relatively simple and is largely a problem of logistics. The assignment of priorities in the second case (b), is more difficult as it requires the consideration of a variety of factors. Table 26 (p. 197) indicates the relative sensitivity of shoreline types to oil spills. This can provide an initial ranking of priorities. Superimposed on this ranking are local factors for each shoreline section (Fig. 33, p. 200), in particular, the presence of unique biological features (ecological preservation areas, wildlife sanctuaries or breeding areas, productive commercial areas, etc.) and the cultural/recreational use of the shoreline (marinas, parks, archeological sites, bathing beaches, shore-front cottages or hotels, etc.). *Consideration of these ecological, cultural and economic factors is of greater importance than the actual vulnerability of the shoreline type to oil spills*. For example, protection of sand beaches adjacent to urban communities or within parks would receive a higher priority than sheltered beaches or mudflats in unpopulated, inaccessible areas which have no unique features.

It is not possible to develop a practical ranking system for protection priorities that can be applied universally. Ideally, each shoreline section should be investigated and relevant information should be collected prior to a spill (see p. 5). The impact of oil within an area can then be assessed in terms of biological, geological, recreational, commercial, and cultural criteria. The information checklist for shoreline sensitivity (Table 27, p. 201) can be used as a framework for assessing the probable impact of oil on a section of shoreline.

The information checklist given in Table 28 provides guidelines for decisions to implement a protection operation. The initial decision whether or not to protect can be answered in the first three questions. Question #3 can be answered only following consideration of the sensitivity of the shoreline section

TABLE 28. SHORELINE PROTECTION CHECKLIST

	YES	NO
1. Will the oil become stranded?		
2. Would the shoreline be cleaned naturally in an acceptable period of time?		
3. Would the section of shore zone be seriously affected by the impact of oil?		
IMPACT OF STRANDED OIL 4. Would the oil seriously endanger flora or fauna?		
5. Would the impact on flora and fauna be long-term?		
6. If shoreline cleanup is necessary, would this affect beach stability (*e.g.,* by sediment removal)?		
7. Would the presence of the oil affect man's use of the shore section?		
8. Would protection be more effective than cleanup?		
PROTECTION FEASIBILITY 9. Is sufficient time available to implement the protection operation?		
10. Would the method(s) be effective?		
11. Are sufficient equipment, materials and manpower available?		

METHODS

12. What is (1) the most applicable method? ______________

(2) the most applicable alternative? ______________

(Fig. 33, p. 200) which is based on the answers to questions #4 to #8. Shoreline protection would probably be required if the answer to any of questions #4 to #8 is "YES". Question #8 is included as it is important to determine whether or not cleanup would be effective and whether or not protection is more efficient and more effective than cleanup operations. The feasibility of protection can be assessed in questions #9 to #11. If all the answers are NOT in the first column, then a protection operation should be reconsidered.

8.2 SHORELINE PROTECTION METHODS

The most effective shoreline protection methods for lake spills are containment and removal of the oil from the water surface. These offshore methods basically involve the use of booms to contain or to divert oil on the surface for removal by mechanical or manual methods. In the event of large spills, the use of booms is limited by the practicality of deploying long sections and by water currents or wave action.

Onshore protection methods can be effective if sufficient time is available to implement an operation. In this case, the protection methods are based upon: (1) prevention of oil adhering to the substrate, and (2) containment of the oil to facilitate removal from the beach.

Protection methods are reviewed briefly and the information is summarized in Table 29. The applicability of the onshore protection methods is related to the major shoreline types in Table 30.

TABLE 29. Shoreline Protection Methods

OFFSHORE	METHOD	APPLICABILITY
BOOMS & REMOVAL	- deployed in front of or around the slick to contain or divert oil movement	- currents <0.5 m/s - wave height <25 cm - used to protect bays, harbours, estuaries, or channels
DISPERSION AGENTS	- reduce surface tension of oil by application of chemicals - oil is then dispersed more rapidly into the water	- requires permission of regulatory agencies - increases oil mobility, therefore, stranded oil has greater potential to penetrate beach sediments
COLLECTION AGENTS	- increase surface tension of oil by application of chemicals - oil is prevented from spreading	- decreases oil mobility, therefore, stranded oil has a reduced capacity to penetrate beach sediments
ONSHORE	METHOD	APPLICABILITY
SORBENTS	- applied manually or mechanically to the beach before oil is stranded - oil/sorbent is then removed manually or mechanically	- prevents penetration of oil into substrate - sorbent pads preferable to loose-fibre materials for ease of collection - synthetic products have higher sorbtion capacity than natural materials - usually a labour-intensive method
SURFACE TREATMENT AGENTS	- applied to shore zone before oil is stranded - prevents oil from adhering to the substrate	- applicability and effectiveness not yet fully assessed - may be difficult to apply on long sections of shore - oil must be flushed from the shore and agent removed if it does not degrade naturally
HERDERS	- applied along water line before oil is stranded - reduces natural dispersion of oil	- reduces area of shoreline contamination
DYKES AND/OR DITCHES	- ditch up to 1 m deep dug parallel to shore at upper limit of wave action - sediment removed used to build dyke on landward side of the ditch - on pebble-cobble beaches can fill ditch with sorbents to collect oil and prevent oil penetration	- prevents oil being washed onto the backshore - can be constructed mechanically along long beach sections - ditch acts as a collector of oil which can be removed with buckets, hand pumps, or vacuum pumps

8.2.1 Offshore Protection

Booms used to contain or divert oil on the water surface are very effective in protecting the shoreline if deployment is possible (Vanderkooy, *et al.*, 1976; Tsang and Vanderkooy, 1978). As the size of the spill increases, the practicality of containing or diverting all the oil is reduced. Most booms are effective only when current velocities are low (generally <0.5 m/s) and wave heights are small (<25 cm), but new equipment is being

TABLE 30. Onshore Protection Methods and Shoreline Types

SHORELINE TYPE	ONSHORE PROTECTION METHOD(S)
ROCK MAN-MADE	- sorbents may be useful on low angle slopes
MUD	- sorbents could be effective if collection can be achieved without mixing oil/sorbent into uncontaminated muds
SAND PEBBLE	- ditch/dyke system could be used to protect backshore - sorbents could prevent or reduce penetration and facilitate the removal of oil
COBBLE BOULDER	- no available effective onshore protection - retrieval of sorbents is difficult - ditch/dyke system is too permeable but could stop oil from washing over into the backshore or could be used in conjunction with sorbents
MIXED SEDIMENTS	- can be treated in the same manner as sand/pebble beaches
MARSHES	- ditch/dyke system could protect the marsh edge if the marsh is flanked by sand deposits - dykes across the marsh channels could prevent oil from penetrating into the backshore marsh areas

developed that will probably be able to contain oil under more severe conditions (Cranfield, 1978). Booms can be particularly useful at harbour or marina entrances, across lagoon or river mouths, and across channels and small bays. In some cases it may be practical to divert oil towards one section of shoreline for removal in order to protect a more sensitive or vulnerable section. Thus, although contamination at one site may be high, protection would be provided to other sections where the sensitivity may be greater or where removal may be more difficult.

Shallow channels or creeks can be protected by construction of an earth dam. If damming the flow through the channel is undesirable, water can be transferred through the dam by a pump or by placing pipes in the dam during construction. Flow can then be controlled by opening or closing valves in the pipe.

The use of dispersants could be considered if other protection methods are inapplicable and if sensitive shoreline environments are threatened. In evaluating the use of dispersants, regulatory agency requirements must be satisfied and an assessment of potential biological impact should be undertaken. Dispersants can be effective provided that the dispersed oil does not reach the shoreline. If the dispersion process is not completed before the oil is stranded, then contamination problems are increased as the dispersed oil will be more mobile and will penetrate the sediments to greater depths than undispersed oil.

Collecting agents (or "herders") can be spread on oil before it becomes stranded to reduce the spreading of the slick (Berry, 1972). This protection method reduces the area of shore contaminated and reduces the capacity of the oil to penetrate into beach sediments.

8.2.2 Onshore Protection

Sorbents spread on a shore before contamination collect oil as it is washed ashore and prevent or reduce penetration of the oil into beach sediments.

Synthetic sorbents are more effective than natural organic material (Schatzberg and Nagy, 1971) but are also more expensive. Loose-fibre materials may be useful for collection of oil from pools or hollows but in most situations sorbent rolls or pads are more conveniently deployed and retrieved. Some limitations on sorbents are that they are less effective in cold temperatures (McMinn and Golden, 1973), and that the method is usually labour-intensive for large spills as it requires spreading, mixing, collection and disposal of the material.

Mechanical spreading of loose sorbents can be achieved with snowblowers (Logan, *et al.*, 1976). A useful retrieval method for loose sorbents is to flush them from the beach onto the water where the oil/sorbent mixture can be collected by a variety of mechanical systems (Miller, *et al.*, 1973; Shaw and Dorrler, 1977; Brunner, *et al.*, 1977).

Surface treatment agents are still in the developmental and assessment stage, but could prove to be effective and practical in the near future. The method involves coating the substrate with an agent that prevents oil from adhering to sediment or rock surfaces (Dailey, *et al.*, 1975; Stewart, 1975; Foget, *et al.*, 1977). The oil must be flushed from the shoreline for collection and then removed from the water surface. The agent itself must also be removed if it does not degrade naturally. One agent which may be practical is water. When sprayed over the shore zone the water greatly reduces the amount of oil that is stranded. If ambient temperatures are below the freezing point of the water, spraying of the shoreline would produce a layer of ice that would protect the shore zone. No large-scale field testing of these techniques using water has been undertaken and the applicability and effectiveness is yet to be assessed.

The construction of ditches (or trenches) and dykes on a beach can prevent oil from contaminating the upper shore and backshore areas. A ditch can be dug parallel to the shoreline in the upper swash zone (q.v.). The material excavated can then be used to construct a dyke on the landward edge of the ditch. Oil and water washed up the beach would be collected in the ditch which acts as a natural sump, so that oil can then be removed with buckets, pumps or vacuum systems. The method is particularly applicable to sand and mixed sediment beaches. As the sediment size increases, oil penetration depths increase and the effectiveness of the system is greatly reduced. However, even on coarse-sediment beaches, a ditch filled with sorbents can contain oil as it becomes stranded or a dyke can protect sensitive backshore areas.

Construction of the ditch-dyke system can be achieved by using trench-cutting machines, motor graders, front-end loaders or bulldozers. In particular, trenching machines can excavate a ditch and cast the sediment to build the dyke simultaneously. If there is insufficient time to construct a ditch-dyke system, graders or bulldozers can be used to quickly build a dyke on the beach by using an angled blade to form a windrow in the upper swash zone.

8.3 SHORELINE CLEANUP PRIORITIES AND PLANNING

The cleanup of oil-contaminated shorelines requires: (i) a knowledge of the impact of the oil (shoreline sensitivity), (ii) a review of the relative merits of natural recovery versus cleanup (sensitivity to cleanup methods), and (iii) an assessment of cleanup practicality and logistics (operational feasibility).

The development of a response plan initially involves an assessment of the impact of the oil on particular shoreline sections. In this context, information should be obtained on the shoreline sensitivity to stranded oil (Table 27, p. 201). The damage caused by oil contamination of the shoreline is usually on impact, so that in most cases once the oil is stranded there is usually no necessity for an immediate and rapid response. The exceptions to this would be situations where (a) the continued presence of oil constitutes a severe impact, such as marsh environments actively used by migrating wildfowl or recreational shore sections during the vacation season, or (b) the oil could become buried within the beach sediments due to natural penetration or to the movement of sediments by winds or waves.

The initial decision to clean up, based on shoreline sensitivity, involves answers to two fundamental questions: (1) is the level of oil contamination acceptable, and (2) would cleanup operations cause more damage than allowing the oil to disperse naturally? The first question involves the desirability of removing stranded oil in terms of biological, recreational and commercial factors. If the presence of oil does not interfere with normal shore-zone processes or man's use of the shore zone, the contamination may be acceptable. This first question also involves an assessment of oil persistence, as natural cleaning may be effective within an acceptable time period. In cases where it is decided that cleanup operations are required or preferable to natural recovery, then an assessment must be made of the effectiveness and the feasibility of cleanup operations. If available techniques to remove the oil cannot meet the objectives of the operation (*e.g.*, not all the oil can be removed), the cleanup decision should be reconsidered. Similarly, if a cleanup method is proposed but the operations would involve ecological or geological damage to the shore zone, then it would be necessary to consider the relative merits of (a) other less effective and/or efficient methods or (b) natural recovery.

The selection of cleanup methods is controlled primarily by the volume of oil and by the shoreline type. In particular, the shoreline sediments and geomorphology determine depths of oil penetration, equipment accessibility and equipment trafficability. The available methods are described in Part 8.4 (p. 214) and the applicability and/or limitations of each method to the basic shoreline types are discussed.

The information checklist for cleanup planning (Table 31) provides a framework for operational decisions. The initial information on the nature of the oil, the degree of contamination and the shore zone character are obtained from Tables 19 (p. 167) and 24 (p. 188). Similarly, several of the answers to the questions in Part B can be obtained by reference to Table 27 (p. 201). If the answers to any of the questions in Part B are "YES", then a cleanup operation for that section of shoreline should be considered provided that the answers to all of the questions in Parts C and D are also "YES". If the assessment of the selected cleanup method yields a "NO" to questions in Parts C and D, then alternative methods of cleanup would be considered. In all cases, the danger of possible recontamination must be considered as the benefits of a cleanup operation may be nullified if a shoreline is re-oiled.

8.4 SHORELINE CLEANUP METHODS

Shorelines contaminated by oil will clean themselves naturally in time. Where this process is slow, it may be desirable to

TABLE 31. SHORELINE CLEANUP INFORMATION CHECKLIST

A. OIL AND THE SHORE ZONE

Type of Oil: ______________________________

Depth of Penetration: ______________________________

Volume of Stranded Oil (from Table 19, p. 167): ____________________

Shoreline Type (see Table 21, p. 184): ____________________

Shore-Zone Sediments (see Table 24, p. 188): ____________________

Shore-Zone Exposure and Wave-Energy Levels (see Table 24, p. 188):

____

Is ice present in the shore zone? YES/NO

B. CLEANUP OR NATURAL RECOVERY?

Expected Persistence of Oil:
Days ____ Months ____ Years ____ Decades ____

Would continued presence of oil be undesirable in terms of?

(a) Biological Processes YES/NO

(b) Recreational Activities YES/NO

(c) Commercial Activities YES/NO

Is the level of contamination unacceptable? YES/NO

Would oil migrate onto other shoreline sections? YES/NO

Is immediate cleanup necessary? YES/NO

What is the most effective/efficient cleanup method for the shoreline section? ______________________________

C. CLEANUP FEASIBILITY

Are satisfactory equipment and sufficient manpower available? YES/NO

Is the shoreline accessible for equipment and/or personnel? (see Table 24, p. 188) YES/NO

TABLE 31 (Cont'd)

Can the equipment operate effectively in the shore zone?	YES/NO
Would the degree of cleanup be satisfactory?	YES/NO

If the most preferred cleanup method is unfeasible or would incur damage (see "D" below), what is the next suitable alternative method?

____

D. <u>CLEANUP DAMAGE</u> (see Section 8.5)

Would the level of biological damage be acceptable?	YES/NO
Would the level of geological damage be acceptable?	YES/NO

Impact of Cleanup on Unique Cultural Features:

None ____ Low ____ Moderate ____ Severe ____ Critical ____

Impact of Cleanup on Recreational Activities:

None ____ Low ____ Moderate ____ Severe ____ Critical ____

Impact of Cleanup on Commercial Activities:

None ____ Low ____ Moderate ____ Severe ____ Critical ____

<u>NOTES</u>:

clean the shoreline, in which case a variety of methods to remove or reduce the volume of oil is available.

The various methods can be conveniently grouped into: (a) dispersion, (b) removal, and (c) *in situ* cleaning. Each method is reviewed briefly and the information is summarized in Table 32. The applicability of the shoreline cleanup methods is related to the major shoreline types in Table 33.

8.4.1 Dispersion

(i) Chemical Dispersion. The use of dispersants applied to stranded oil is regulated to low-toxicity products and permission of the regulatory agency in Canada is required (Ruel, *et al.*, 1973; Environment Canada, 1976). In Ontario the Ontario Ministry of the Environment must be contacted prior to any use of chemical treating agents.

Dispersants increase the oil's mobility by reducing the surface tension of oil so that the dispersed oil can be flushed from the shore zone. The increase in the mobility of the oil can also result in an increase in the penetration of the oil into the beach sediments. Therefore, although dispersants are potentially useful on shorelines with sediment, they are more effective and have less impact on rock surfaces and on man-made structures.

(ii) High-Pressure Hoses. This method has proved to be effective in removing oil from the surface of boulders, rock and man-made structures. On cobble or pebble beaches the sediment can be cleaned but the oil is washed into the sub-surface sediments. On sand beaches the sand itself is flushed from the beach.

TABLE 32. Shoreline Cleanup Methods

METHOD	DESCRIPTION	APPLICABILITY	IMPACT
Dispersion			
CHEMICAL DISPERSION	- applied to oil, reduces surface tension	- use requires approval of regulatory agency - may require mixing with oil - oil/dispersant mixture flushed from beach, rock or man-made surfaces	- increased oil mobility can result in penetration of dispersed oil into the sediments - potentially toxic to land and aquatic flora & fauna
HIGH-PRESSURE HOSES	- high-pressure stream of water washes oil from the substrate	- can be effective on rock, boulder, and man-made surfaces, but is expensive - oil flushed onto water surface for removal or channeled to beach collection site	- can damage flora & fauna - can flush oil into sediments - if beach is backed by unconsolidated cliffs, hosing of cliff can cause slumps, falls, or slope failure
STEAM OR HOT-WATER CLEANING	- steam or hot-water washes oil from the substrate	- very effective on rock, boulder, and man-made surfaces - oil flushed onto water surface for collection or channeled to beach collection site - expensive method	- can be very harmful to flora & fauna - can flush oil into sediments
SANDBLASTING	- high velocity sand removes oil from the substrate	- effective but slow method for rock, boulder, and man-made surfaces - can remove oil stains - expensive method	- can be very harmful to flora & fauna - scatters oil and sand - can cause deeper penetration of oil into sediments
LOW-PRESSURE HOSES	- low-pressure stream of water washes oil from the substrate	- effective but slow method for rock, boulder, and man-made surfaces - oil flushed onto water surface for collection or channeled to beach collection site	- biologically preferable to high-pressure hoses, steam cleaning, or sandblasting - can flush oil into sediments
MIXING	A-mechanical equipment such as rakes, discs or harrows used to break up oil cover and mix surface sediments	- accelerates natural cleaning - useful for light grade oils or to break up "asphalt pavements" - increases surface area of exposed oil and increases dispersal and degradation rates	- does not remove oil - can cause burial of the oil
	B-mechanical equipment used to push oil/sediment down beach into the water	- accelerates natural cleaning - wave action disperses and degrades oil - sediment is returned to the beach - applicable for "asphalt pavements" or coarse-sediment beaches	- does not remove oil - should not be used if storm waves are expected before sediment is returned to the beach; could result in waves overtopping the beach and/or causing backshore erosion

TABLE 32 (Cont'd)

Removal			
GRADERS, SCRAPERS	- remove thin layer of oiled sediments - graders form windrows for scraper or front-end loader to remove - scraper removes oil/sediment layer directly	- effective on sand or pebble beaches with low oil penetration depths (<3 cm) - scraper can remove up to 25 cm layer of oil/sediment - some spillage which can be removed manually	- removes sediment from the beach, amount of sediment removed usually not sufficient to affect beach stability
FRONT-END LOADERS	- loader removes material directly from beach to collection sites	- used on beaches with poor traction or for high oil penetration depths (25 cm or more) - high spillage - usually large amounts of uncontaminated sediment are removed - rubber-tired vehicles are preferred to tracked vehicles	- can result in excessive sediment removal that could cause beach or backshore erosion - grinds oil into the beach
BULLDOZERS	- push material into collection sites for removal	- can remove oil/sediment where penetration is 25 cm or greater - not recommended unless other equipment unavailable or traction is too low for other equipment	- can result in excessive sediment removal that could cause beach or backshore erosion - large spillage and grinds oil into sediments
DRAGLINE, CLAMSHELL	- sediment collected in bucket dragged towards equipment, or by crane-operated bucket	- useful where beach access or trafficability is poor	- can result in excessive sediment removal that could cause beach or backshore erosion
SUMP COLLECTION AND PUMP REMOVAL	- sump excavated and used to collect oil which is then removed by pump or vacuum system	- useful for large spills with oil washed ashore over a period of days	- does not remove all the oil from the beach
MANUAL	A-oil scraped from the substrate B-oil collected with buckets, shovels, rakes, forks, etc. (with or without sorbents)	A/B useful for areas inaccessible to equipment or small spills A/B/C labour intensive methods; slow rate of oil removal	A-selective oil removal, not all oil is removed
	C-cutting of oiled vegetation	C-oil/vegetation collected in containers for removal	C-labour intensive method; pedestrian traffic can disturb marsh vegetation and can cause oil/sediment mixing
In Situ Cleaning			
BURNING (A) INCINERATION (B)	A-oil ignited, usually with ignition agents -continued burning may require wicking agents B-incineration machines use heat source to burn oil	A-seldom completely successful -useful for oil on surface of ice -can be used in marshes with appropriate biological advice -oil residues remain B-useful for sand, pebble, and cobble beaches -sediment returned to beach after incineration	A-can cause heavy air pollution -can increase the penetration of oil into the sediments -could damage root systems of marsh vegetation B-little or no impact
BEACH CLEANING MACHINES	- cleaner picks tar lumps from the beach	- useful on beaches with tar balls	- little sediment removal

TABLE 33. CLEANUP METHODS AND SHORELINE TYPES

	CHEMICAL DISPERSANTS	HIGH-PRESSURE HOSES	STEAM CLEANING	SANDBLASTING	LOW-PRESSURE HOSES	MIXING	GRADER/SCRAPER	FRONT-END LOADER	BULLDOZER	DRAGLINE/ CLAMSHELL	SUMP/PUMP	MANUAL REMOVAL	MANUAL CROPPING	BURNING/ INCINERATION	BEACH-CLEANING MACHINES
Rock	+	+	+	+	√	−	−	−	−	−	+	√	−	−	−
Man-Made	+	+	√	√	√	−	−	−	−	−	−	√	−	−	−
Mud	x	x	x	x	x	x	x	+	x	x	+	√	−	x	x
Sand	x	x	x	x	x	+	√	+	+	+	+	√	−	+	√
Pebble	+	x	x	x	x	+	x	+	+	+	+	√	−	+	√
Cobble	+	+	x	x	+	+	−	+	+	+	+	√	−	x	−
Boulder	+	+	+	x	+	−	−	−	−	−	−	√	−	x	−
Mixed Sediment	+	x	x	x	x	+	x	+	+	+	+	√	−	x	+
Marsh	x	x	x	x	√	x	−	x	x	x	+	√	√	+	−

x NOT Recommended	− Not Applicable
√ Recommended	+ Applicable and possibly useful

To be effective this method involves either flushing of the oil onto the adjacent water surface for collection or channelling of the oil/water mixture into a ditch or sump for collection (Bender, 1978). Care should be exercised to prevent oil being splashed onto clean surfaces. The cleaning should begin at the farthest point from the collection area and systematically flush the oil downslope for collection.

In locations with a cliff of unconsolidated sediments, care must be exercised to avoid disturbance to the base of the cliff. If the cliff is unstable, a situation that may not always be readily apparent, washing of the basal sediments could cause slope failure and slumping.

(iii) Steam or Hot-Water Cleaning. The method is essentially the same as high-pressure flushing except that it is more effective in removing oil, is more expensive, and is more harmful to flora and fauna. The advantage of the method is that, in addition to the mechanical energy introduced by flushing, the temperature of the oil is raised and the oil, therefore, becomes more mobile and flows downslope. The method is applicable for man-made surfaces and may be useful on rock surfaces.

(iv) Sandblasting. The use of sand to abrade oil from the substrate is particularly effective in removing all oil, including stains, from contaminated surfaces. However, the method also removes all flora and fauna, and it is an expensive and slow process. Once blasting is complete the sand-oil mixture must be removed for disposal. The method is applicable for man-made structures and may be useful on rock surfaces.

(v) Low-Pressure Hoses. Similar in operation to the high-pressure hose system, this method is biologically preferable and can be used in marsh environments without incurring damage to the vegetation (Westree, 1977). The method is applicable for man-made structures, rock surfaces and marshes. It may be useful to disperse oil on coarse-sediment beaches but can cause flushing of oil into the sediments.

(vi) Mixing. The objective of this method is to use machinery to break up the oil cover on beaches in order to increase the rates of evaporation, degradation and dispersion. The method does not involve the removal of oil and is, therefore, primarily applicable in situations where sediment removal may result in an unstable beach or on low-priority non-recreational beaches. Two basic techniques can be used:

(A) The first mixing technique involves the use of rakes, discs, harrows, or bulldozers to break the oil cover, to increase the exposed surface area of the oil, and to leave the oil to degrade naturally. It is particularly effective for light-grade oils that evaporate readily upon exposure, provided that the use of equipment does not create a potentially hazardous situation (by the ignition of highly volatile oils such as avgas or diesel). To avoid burial of oil which would reduce the rates of degradation, the depth of disturbance should not exceed the depth of the oil penetration. The method is applicable on any type of beach and particularly useful in low-energy, sheltered beach environments where sediment removal is inadvisable or unnecessary, and on beaches where the sediments and oil have formed an "asphalt pavement".

(B) The second mixing technique involves use of machinery to push contaminated sediments from the beach into the zone of wave activity. The purpose is to allow normal wave action to abrade and disperse the oil and to return the sediment back onto the beach (Owens, 1977; Bender, 1978). The method is applicable to all types of beach and again is useful where sediment removal is inadvisable or when an "asphalt pavement" has formed.

The method is best applied on exposed beaches where levels of wave activity are relatively high so that waves can clean and return the sediments rapidly. The operation should not be implemented if storm or high-water level conditions are expected before the beach sediments are returned. The operation temporarily reduces the effectiveness of the beach to protect the backshore, so waves could overtop the beach and cause backshore inundation or erosion.

8.4.2 Removal

(vii) Graders and Scrapers. The removal of surface oil from sand beaches can be achieved effectively and efficiently by the use of graders and scrapers (Sartor and Foget, 1970). This equipment can also be used on mud or pebble shores where bearing capacities of sediments are favourable. In all cases, the primary limitations are trafficability and, for the grader, a maximum oil penetration in the order of 2.5 cm (Fig. 34). Elevating scrapers, either motorized or towed, can remove sediment to greater depths (up to 25 cm).

The grader is the most efficient equipment as it removes the least uncontaminated sediment. The recommended technique is to

SIZE OF AREA	TYPE OF OIL	DEPTH OF PENETRATION	TYPES OF BEACHES		
			FINE SAND	COARSE SAND	GRAVEL
LARGE	HEAVY	SHALLOW, 1cm to 2.5cm	GRADER and ES or FFL	GRADER and ES or FFL	--
		MODERATE, 2.5cm to 25cm	ES	ES	ES
		DEEP, 25cm+	WFEL'	WFEL	WFEL
	LIGHT	--	BEACH CLEANING MACHINES		
SMALL	HEAVY	--	MANUAL REMOVAL OR WFEL'		
	LIGHT	--	MANUAL REMOVAL, RAKE		

ES – Elevating Scraper
FFL – Forced Feed Loader
WFEL'– Wheeled Front-end Loader, firm gr. only
Tracked front-loader for low bearing cap. soils

Figure 34. Method and equipment for cleanup of sand and gravel beaches (adapted from Der and Ghormley, 1975).

form windrows with a 50° blade angle (Fig. 35, Table 34). The windrows are then removed by the scraper. If scrapers are not available a front-end loader can be used to remove the windrows,

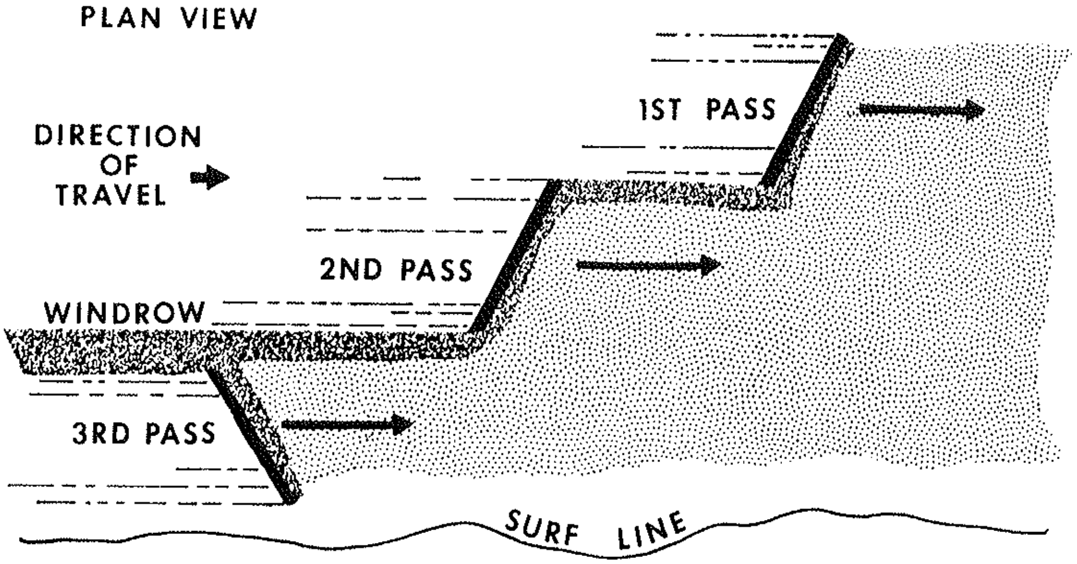


Figure 35. Sequence of windrow formation for removal of surface oil from sand beaches by a motorized grader (from Sartor and Foget, 1970).

TABLE 34. Recommended Cleanup Procedures For Equipment on Sand Beaches (from Sartor and Foget, 1970)

Equipment	Method of Operation
A. Combination of motorized grader and motorized elevating scraper	Motorized graders cut and remove surface layer of beach material and form large windrows, which motorized scrapers pick up and haul to disposal area for dumping or to unloading ramp-conveyor system for transfer to dump trucks. When large amounts of debris are present, a screening system is used to separate beach debris, such as kelp, from sand.
B. Motorized elevating scraper	Motorized elevating scrapers, working singly, cut and pick up the surface layer of beach material and haul it to disposal area for dumping or to unloading ramp-conveyor system for transfer to dump trucks. When large amounts of debris are present, a screening system is used to separate beach debris, such as kelp, from sand.
C. *Combination of motorized grader and front-end loader	Motorized graders cut and remove surface layer of beach material and form large windrows, which front-end loaders pick up and load into following trucks. Trucks remove material to disposal area or to conveyor-screening system for separation of large amounts of debris from sand.
D. *Front-end loader	Front-end loaders work singly to cut and pick up surface layer of beach material and load it into following trucks. Trucks remove material to disposal area or to conveyor-screening system for separation of large amounts of debris from sand.

*Use C and D only when motorized elevating scrapers are not available. Operation of front-end loaders on oil-contaminated beaches should be kept to a minimum.

but spillage is greater and the operation is slower. Spillage occurs in any of the techniques but it can be recovered by manual pick-up. If graders are unavailable, scrapers can be used to remove the contaminated material directly without forming windrows. On beaches with poor trafficability, traction can be increased by reduction of tire pressures or by installation of flotation tires (Sartor and Foget, 1970).

(viii) Front-End Loaders. A front-end loader can be used if graders or scrapers are unavailable, if beaches have poor traction, or if oil penetration is greater than 25 cm. The front-end loader can be used on all but boulder beaches but the equipment generally involves high spillage rates and the removal of large amounts of uncontaminated sediments, as this machine is designed for digging rather than for removing thin layers of sediment. Spillage can be reduced if the bucket is filled to only one-quarter capacity. Rubber tires are greatly preferred over tracks, as the tracks tend to grind oil into the sediment. When front-end loaders are used alone in a beach cleanup operation, the use of a multi-task bucket is preferable.

(ix) Bulldozers. This equipment is not recommended unless other machines are unavailable. If used, a bulldozer can push material up the beach for later collection, however, the use of this equipment causes excessive removal of uncontaminated sediments. The vehicle tracks grind oil into the beach and spillage around the blade is high. Spillage can be reduced by using an angled rather than straight blade.

(x) Dragline or Clamshell. In situations where the bearing capacity of the sediments is extremely low, this equipment can remove contaminated sediment. The operation is slow and inefficient and should only be considered if other options are impractical. Apart from the relative inefficiency of the operation, this technique also involves large-scale removal of uncontaminated sediments.

(xi) Sump Collection and Pump Removal. Excavation of a sump on sand, pebble, or mixed sediment beaches to collect oil is applicable for large amounts of mobile oil (O'Sullivan, 1978). The sump should be located at the water line in order to permit oil to collect. A pump system or vacuum truck is used to remove the oil/water mixture from the sump (*e.g.*, Ruby, *et al.*, 1977).

Booms attached to the shore can be deployed to direct the oil to a sump, particularly in channels or rivers where there is a unidirectional water current.

(xii) Manual. Manual removal can be effective for spills involving small amounts of oil or in locations inaccessible to or unsuitable for machinery. Oil can be scraped or scrubbed from rock or man-made surfaces, and oil particles or contaminated sediments can be removed from beaches with shovels, rakes, forks or buckets. This removal can be carried out with sorbent materials used to collect mobile oil (see p. 210). If vegetation is contaminated, manual cutting may be effective (Vandermeulen and Ross, 1977). In marsh environments care must be exercised to avoid damaging plant root systems and to prevent the grinding of oil into the sediments.

Manual methods of scraping, removal or cutting are labour-intensive operations. The efficient use of manpower requires good organization. In marsh environments the labour force should be carefully briefed and close supervision may be necessary to prevent damage to the environment.

Sorbent materials have been designed largely for oil removal from water surfaces but can also be used on shorelines. Pads or rolls of synthetic sorbents are very effective but more expensive and usually less readily available than natural organic materials. Loose fibre sorbents are labour-intensive as they must be spread, mixed with the oil, and removed for disposal. One method of harvesting loose fibre sorbents from rocks, coarse-sediment beaches or marshes is to use low-pressure hoses to flush the material onto water surfaces for collection. During the *"Arrow"* spill, peat moss was spread manually and with snowblowers and then harvested using rakes. The peat had a maximum sorbtion capacity of 17 gms oil/gm peat moss, similar to that of sheet or mat polyethylene fibres (Schatzberg and Nagy, 1971).

8.4.3 *In Situ* Cleaning

(xiii) Burning and Incineration. Direct cleaning of shorelines can be undertaken by burning if the stranded oil is of a suitable character. An ignition agent may be required to obtain sufficiently high temperatures; a wicking agent may also be necessary to maintain combustion (e.g., Ruby, *et al.*, 1977). The method is of particular use for pools of oil or for oil on the surface of ice. However, the burning process can result in deeper penetration of oil into the sediments and can produce residues which may be difficult to remove. The method also causes heavy air pollution that may be undesirable (Coupal, 1976). Few attempts at burning have been completely successful (Der and Ghormley, 1975). Suitable types of oil spills in marsh environments can be successfully burnt in autumn or winter months, provided that the root systems of the vegetation are not damaged.

Several incineration techniques are in the developmental stage. These techniques basically involve (i) the transfer of contaminated material into a kiln, (ii) incineration, and (iii) replacement of the clean material on the beach. The equipment is being designed to be portable and to be able to handle coarse as well as fine-grained sediments.

(xiv) Beach Cleaning Machines. Although several types of equipment have been developed to remove, clean and replace contaminated sediments, the only techniques that have proven to date to be cheap, portable and efficient involve either sieving devices for removal of tar lumps (Cormack and Jeffrey, 1975; Wardley-Smith, 1976, p. 185) or rotary brushes to spike the tar lumps (Wardley-Smith, 1968). Although effective on sand or pebble beaches, the equipment is frequently not readily available. Sediment/oil pick-up and sieving devices can be built with little difficulty and the equipment can be towed behind a tractor or front-end loader.

The beach cleaning machines referred to in Figure 34 have been designed to collect, wash and replace contaminated sand-size sediments. The machines utilize a variety of methods to separate the sediment and the oil, but to date the techniques and equipment developed have not proven to be cheap, portable and efficient.

8.5 SHORELINE TYPES AND CLEANUP OPERATIONS

The use of personnel or machinery to remove stranded oil can have an impact on the ecological and geological stability of the shore zone. This aspect of cleanup operations is reviewed and guidelines are presented so that any adverse effects from cleanup may be avoided. Normal cleanup operations can be seriously hampered by the presence of ice in the shore zone and in this context winter cleanup operations are discussed at the end of this section.

8.5.1 Ecological Impact of Cleanup

The frequency distribution of plant and animal life in the shore zone varies considerably. Bare rocky or man-made surfaces are virtually inert, whereas, marsh systems have high levels of biological activity. The effects of cleanup operations can involve removal of species, burial of oil in sediments, extension of the contaminated area, and habitat disruption.

On rocky coasts or man-made structures, hand-cropping rarely presents a serious impact, whereas, high-pressure hoses, steam cleaning, and sandblasting can remove entire populations of existing species. Recovery rates may be relatively rapid (1 or 2 years) depending on the extent of the damage.

Sand, pebble, cobble and boulder beaches can be severely affected by sediment disturbance or mixing of oil and sediment, but in general the impact is short-lived. Recolonization is likely to be rapid unless the depth of disturbance is great (>25 cm). Backshore dune vegetation is sensitive to the traffic of personnel and machines; this environment is discussed under geological impact (8.5.2). Mud environments are more sensitive than coarse-grained beaches, particularly if oil is mixed into the sediments, as many burrowing organisms live within the sediments. Mixing should be avoided in this environment.

Marshes are particularly susceptible to damage by cleanup operations. Great care must be exercised to avoid oil becoming compacted or mixed into the sediments by personnel or equipment (Westree, 1977). Machinery should not be used as it can cause extensive damage to the vegetation. Also, personnel can spread or bury oil simply by walking across contaminated then clean areas. If access across a marsh is necessary, mats can be used to reduce the damage level. Cleanup operations need not have a severe impact if personnel are well-briefed and well-supervised.

An adequate assessment of potential cleanup damage, as well as advice on implementing the operations on shore zones with a high biological sensitivity, should be obtained from qualified local or regional biologists/ecologists.

8.5.2 Geological Impact of Cleanup

The two primary geological problems that can occur from cleanup are related to sediment removal and dune disturbance.

The removal of any sediment from the shore zone reduces the total volume of beach sediments. This is not a problem if the sediments are in abundance or if natural processes can replace the sediment. If excessive amounts of sediments are removed (>50 cm depth) or the volume of beach sediment is small, beach retreat can follow as the waves attempt to reestablish an equilibrium. In particular, sheltered or pocket beaches usually have relatively little sediment and low sediment re-supply rates and, therefore, are very susceptible to damage by sediment removal. The effect of beach retreat is either: (i) a general landward movement of the beach, if the beach is wide or if it is backed by a marsh or lagoon, or (ii) backshore erosion if the beach is backed by cliffs or dunes. In cases where a narrow beach is backed by cliffs of unconsolidated sediments, erosion can be rapid until the shore zone establishes a new equilibrium with the waves.

In all cases the cleanup operation should aim to remove as little beach material as possible. To achieve this the oil should be removed as soon as is practical after a spill to prevent burial or greater penetration of the oil into beach sediments. If large-scale removal is necessary, it is advisable that the material be replaced by an equal volume of the same-size sediment. Replacement of sediment on pebble, cobble, or boulder beaches is particularly important as natural sediment replacement rates are very slow.

Dune systems can be severely damaged if personnel and equipment destroy the dune vegetation that naturally stabilizes the sand. The trampling or removal of the vegetation can cause serious erosion if "blow-outs" (removal of sand by wind action) develop before the vegetation can restabilize the sand. If access across a dune system is necessary, personnel or vehicles should be restricted to as few routes as possible and mats can be used to improve traction as well as reduce the damage level.

8.5.3 Ice and Winter Cleanup Operations

The cleanup of spills in ice-infested waters or on ice-covered beaches presents unique problems. Normal shoreline cleanup techniques usually cannot be applied, and, if applicable, these methods are often difficult to implement (Ruby, *et al.*, 1977).

The presence of ice on the shore usually prohibits the use of mechanical cleanup equipment. Removal of contaminated ice with equipment involves large volumes of ice and very little oil. Oil trapped in pools can be removed manually with sorbents or buckets or with pumps if the volume of oil is large. Oil can be flushed from the ice onto the water surface for collection if the water is ice-free. Ice floes or brash ice on the water would seriously hamper removal, and working conditions could be dangerous.

Allowing the oil to remain on, or trapped in, shore ice merely delays the cleanup problem. During spring melt the oil is released onto the beach or onto the water surface. If cleanup is not possible during the winter months, this may be a viable alternative for areas of low sensitivity provided that release of the oil would not endanger adjacent, more sensitive environments.

PART 9 - CONCLUSIONS

1. The Canadian Great Lakes have a wide range of shoreline types that include the rocky, complex coasts of Lake Superior and Georgian Bay as well as the extensive beach-dune systems of Lakes Erie and Ontario. Shoreline sensitivity to oil spills varies considerably, depending not only on the impact of oil on the various shoreline types but also on the different pressures imposed by man's activities and use of the shore zone.

2. A significant feature of the shore zone throughout the Great Lakes region is the general scarcity of beach sediments. This has an important bearing on cleanup operations and on shoreline sensitivity, as large-scale sediment-oil removal could result in shoreline damage by beach or cliff erosion.

3. Another feature of the Great Lakes region is the relatively short fetch distances which result in low levels of shore-zone energy, by comparison with open-ocean coasts. In addition, many regions have an extremely irregular shoreline configuration so that there is considerable local wave-sheltering and low shore-zone energy levels. The persistence of stranded oil in the shore zone is closely linked to the level of mechanical wave energy so that rates of natural self-cleaning are low in the many low-energy sections of coast.

4. Ice plays an important role in all regions for four to five

months each year, reducing wave-activity at a time when wind velocities and potential wave-energy levels are at a maximum. Cleanup operations in ice-infested water would be more difficult and hazardous should a spill occur during winter months.

5. There is considerable variation in available shore-zone process and character information. Many sections of the "upper" lakes (Superior, North Channel-Georgian Bay, and Huron) have virtually no data base so that spill-response decisions would be more difficult in these regions. To date, no programmes have been developed that focus on the collection of relevant shoreline information at the local level for oil spill contingency planning. This type of programme, that could initially focus on local information gathering for high-risk areas, would provide the basis for spill impact assessment and for the selection of appropriate protection and cleanup procedures.

6. The experience of the NEPCO 140 spill in June 1976 in an area of high recreational impact and complex, low-energy shorelines provided many lessons that can be applied to other sections of the Great Lakes. In particular, the cleanup operations showed that despite severe operational difficulties cleanup can be successful, although the process may be time-consuming and expensive.

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APPENDIX

DEFINITION OF TERMS

ASPHALT: Refers to the heavy fractions of oil that have a high boiling point (see Table 35, p. 249).

BACKSHORE: That part of a beach above the maximum limit of normal wave action that extends landward to the limit of storm-wave activity (Fig. 36).

BACKWASH: The movement of water down the beach-face slope after a wave has broken and has surged up the beach face (see swash).

BEACH: An environment of unconsolidated sediments in the coastal zone between the junction of water and land to the landward limit of storm-wave activity. The upper limit is usually marked by vegetation, dunes or a cliff.

BEACH FACE: That part of the beach that is exposed to swash action. Usually the beach face has the steepest zones (up to 40°) in the beach zone.

BERM: A zone above the beach face that is nearly horizontal and is above the limit of normal wave action.

BERM CREST: The seaward limit of the berm.

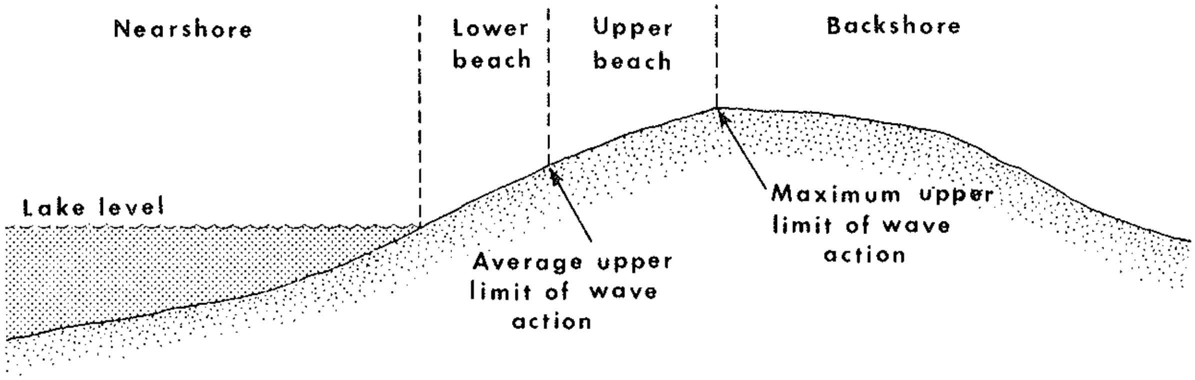

Figure 36. Sketch of beach profile with terminology.

TABLE 35. Classification and Components of Crude Oil (from Whitehead, 1976)

Boiling Point Range °C	-200	-10	0	30	150	200	250	350	380	520	1000+
General Classification	← Gases →		← Light Fraction →		← Middle Fraction →			← Heavy Fraction →		← Residue →	
Main Components	← Gases →			← Gasolines →			← Fuel Oils →			← Asphaltenes →	
	dry		*wet*	*light*		*heavy*					
						← Gas Oils →					
		← LPG →			← Kerosines →			← Lubricating Oils →			
					Naphthas						
Hydrocarbon Range	← C_4 and lower →		← Pentane Plus →		← Liquid →			← Solid →			
	C_1		C_4	C_5	C_8		C_{14}	C_{16}			C_{60}
US Bureau of Mines Correlation Index	Paraffinic-Paraffinic			Paraffinic-Naphthenic			Naphthenic-Paraffinic			Naphthenic-Naphthenic	
Base Classification	Paraffinic (Light)			Mixed (Aromatic)				Naphthenic (Heavy)		Asphaltic	
Typical API Gravity Range		38° – 47°			37° – 30°					25° – 15°	
Specific Gravity		0.835 – 0.800			0.840 – 0.876					0.900 – 0.970	

Note: The classifications shown in this table are intended to be representative, and no precise demarcations are implied.

CRUDE OIL: Naturally-occurring undistilled or unrefined oil (see Table 35).

EMULSION: A mixture of two fluids that do not usually mix, in this report this term refers either to a water-in-oil or an oil-in-water mixture.

FETCH: The area of open water over which waves are generated by wind.

ICE FOOT: A feature that is formed by the accumulation of ice that results from freezing of wave spray and swash in the shore zone (Photo 1, p. 30).

IGNEOUS ROCKS: Rocks that are formed by the cooling of lava or molten material in the earth. Intrusive rocks are one type of igneous rock.

INTRUSIVE ROCKS: Rocks formed as molten material solidified before reaching the earth's surface. They are igneous rocks.

LIGHT FRACTION: Hydrocarbon compounds with a boiling below 150°C (Table 35).

LONGSHORE SEDIMENT TRANSPORT: The mechanism by which material is moved parallel to the coast by wave-induced processes.

METAMORPHIC ROCKS. Igneous or sedimentary rocks that have undergone physical changes due to chemical alteration or to heat and pressure.

METASEDIMENTARY ROCKS: Sedimentary rocks that have undergone metamorphic changes.

MORAINE: A deposit of unconsolidated sediments derived from erosion and deposition by glaciers or ice sheets.

NEARSHORE ZONE: That part of the shoreline seaward of the beach that is within the zone of wave-generated processes.

OIL: A liquid mineral compound of hydrocarbons, with minor amounts of other substances that is insoluble with and lighter than water. The physical and chemical properties of naturally-occurring (crude) oils vary considerably (Table 35).

POUR POINT: The lowest temperature at which an oil will not flow (in crudes these can vary between -26°C and +50°C).

SEDIMENTARY ROCKS: Rocks formed by the deposition of sediments in layers by wind, river, ice or marine processes.

SEICHE: A change in the level of the water surface that may or may not be oscillatory. Often formed by winds piling water up against the shore in lakes (see Fig. 9, p. 34).

SIGNIFICANT WAVE HEIGHT: The average height of the highest one-third of the waves.

STORM RIDGE: A ridge formed in the backshore above the limit of normal wave action during storms.

SWASH: The rush of water up a beach face that follows breaking of the wave.

SUBSTRATE: The material(s) of which the shore zone is made.

VISCOSITY: The property of a fluid that tends to resist relative motion or flow within the fluid.

VOLCANIC ROCKS: Rocks that have formed by volcanic action, they may be intrusive rocks or lavas.

VOLUME: The standard unit for volumes of oil is generally the U.S. barrel. However, other commonly used units and the conversion factors are:

VOLUME: (cont'd)

Barrels

1 barrel (U.S.) = 42 U.S. gallons
= 35 imperial gallons
= 159 litres
= 0.159 cu. metres

1 barrel (U.K.) = 36 imperial gallons
= 163.7 litres
= 0.16 cu. metres

Tons

1 metric ton = 1000 kg*

1 long ton = 1016 kg*

1 short ton = 907.2 kg*

Gallons

1 U.S. gallon = 3.785 litres
= 0.024 U.S. barrel
= 0.833 imperial gallon

1 imperial gallon = 4.546 litres
= 0.038 U.S. barrel
= 1.201 U.S. gallon

*The volume-weight conversions involve consideration of the density (or specific gravity) of the oil. In these conversions a specific gravity of 1 (= a density of 1.0 kg/litre) is used. The specific gravity of oils varies in the range from 0.80 to almost 1.0.

WAVE-CUT NOTCH: A notch at the base of a coastal cliff eroded at or near the upper limit of wave action.