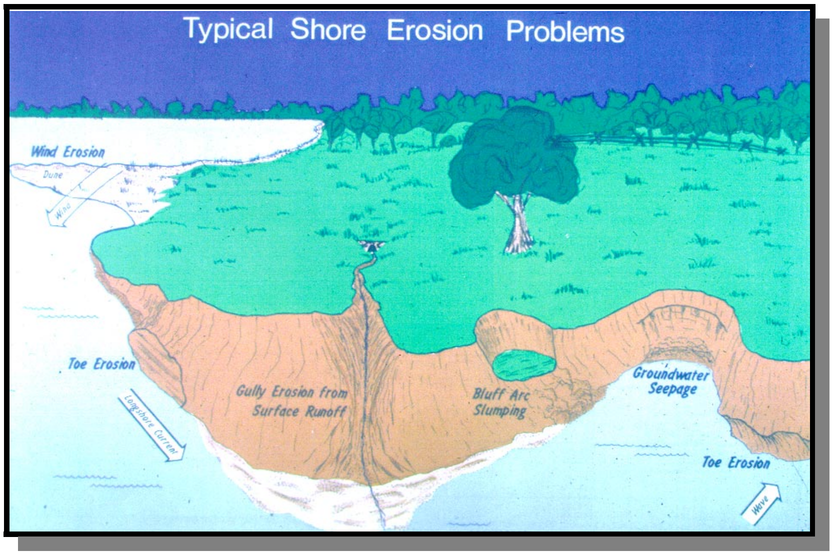
PART 1

THE GREAT LAKES - ST. LAWRENCE RIVER SYSTEM:

PHYSICAL FEATURES AND PROCESSES



GREAT LAKES - ST. LAWRENCE RIVER SYSTEM:
PHYSICAL FEATURES AND PROCESSES

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1.1 INTRODUCTION

Although the *Great Lakes - St. Lawrence River System* constitutes one of our most precious natural resources, their effects on shoreline residents are not always benign. Like other natural phenomena, the behaviour of the lakes and their connecting channels is often unpredictable and beyond human control.

Of fundamental importance to developing effective shoreline management and land use planning and management approaches to addressing shoreline flooding, erosion and dynamic beaches is the need to better understand the system, particularly its formation, evolution and potential impacts.

The primary focus of Part 1 is to provide background information on the *Great Lakes - St. Lawrence River System* and introduce the dynamics of *flooding, erosion and dynamic beach hazards*. This introductory information is supported by Appendices A1.1 and A1.2 which describe in more detail the origin and evolution of the *Great Lakes - St. Lawrence River System* and the processes that control and influence shoreline changes. This discussion is outlined through:

· **Section 1.2**	providing an introduction to the *Great Lakes - St. Lawrence River System*, describing the main components of the physical and biological system as well as human occupation of the Great Lakes basin.
· **Section 1.3**	providing an introduction to the dynamics of *flooding, erosion and dynamic beach hazards* as they relate to the manner and location of human occupation and encroachment into the *Great Lakes - St. Lawrence River System* shorelines.
· **Appendix A1.1**	providing background information on the most important processes and factors that control shoreline dynamics and evolution in the *Great Lakes - St. Lawrence River System.* This material is designed to provide an understanding of the nature of shoreline hazards and of the potential impacts of various approaches to hazard mitigation. To understand the processes currently affecting the evolution of the existing *Great Lakes - St. Lawrence River System* shoreline, this appendix provides a description of the relationship between the underlying bedrock geology and the development of the Great Lakes basin supported by a brief description of the history of ice sheets and the formation of glacial and post-glacial lakes within the basin. The section concludes with a brief description of the present lakes, including those features located within the United States.
· **Appendix A1.2**	providing an overview of the interactions occurring between lake and land features and the factors controlling these interactions. To complement the discussion of lake/land interactions, this appendix reviews the effects of winds, waves and currents in controlling erosion, transport and deposition of sediments along the shoreline; the modifying effects of other factors such as ice and weathering; the sources of sediment supply to the shoreline; and concludes with a description of littoral cells, sediment budgets and shoreline sources and sinks.

1.2 THE GREAT LAKES SYSTEM

The *Great Lakes - St. Lawrence River System* is an extensive, significant, and physically and biologically diverse environmental resource. The system, consisting of a series of large lakes connected by channels or rivers, outlets into the Atlantic Ocean through it's largest connecting channel, the St. Lawrence River (Figure 1.1). Each of the system's lakes and connecting channels are considered to have their own unique combinations of interrelated and interdependent sets of terrestrial, wetland and aquatic environments.

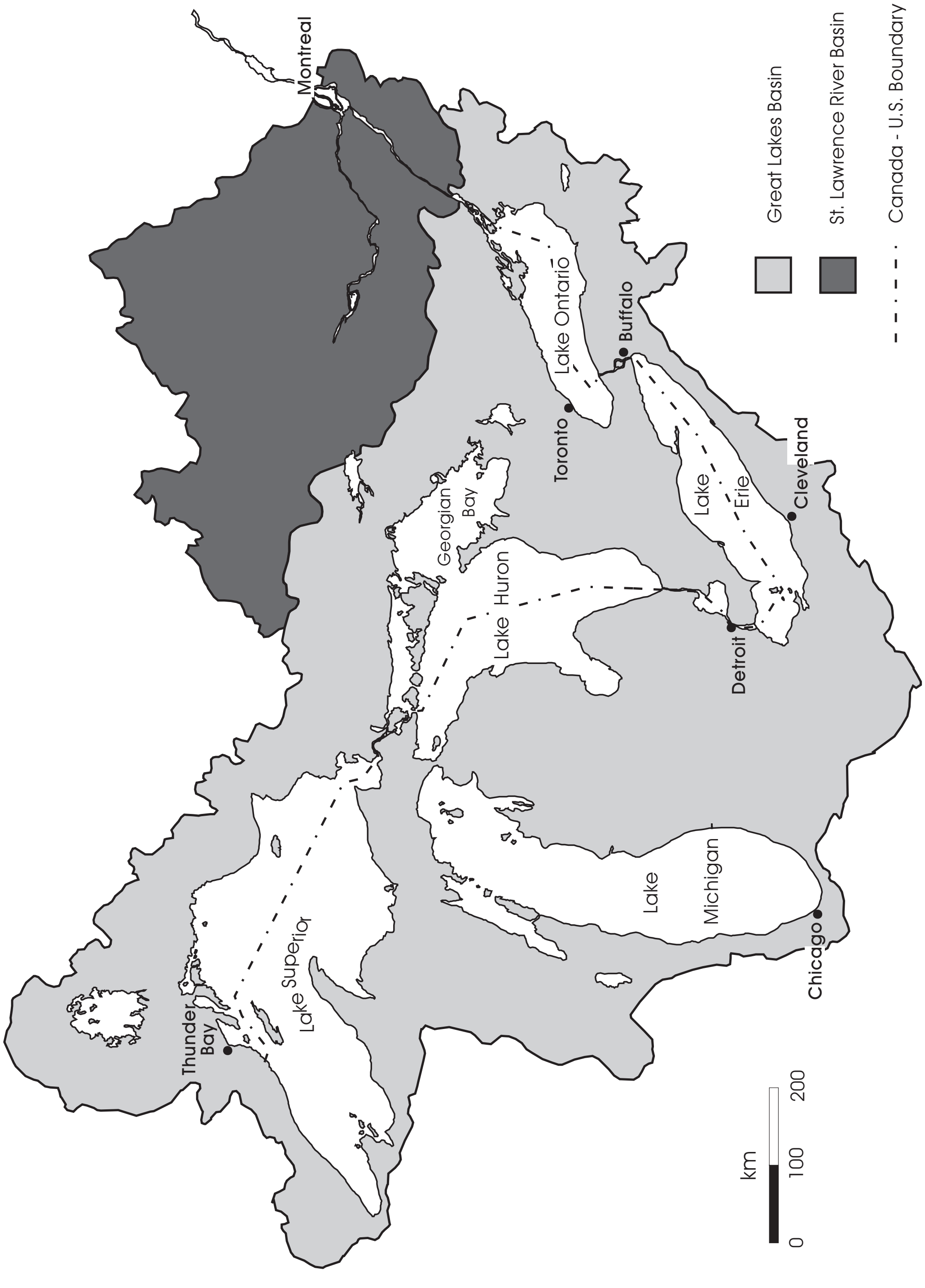
The shoreline of the Great Lakes, roughly 15,700 km in length, is complemented by an additional 4,800 km of shoreline along its connecting channels. The terrestrial, or landside portions of the shoreline consist of a diversity of shore types from erosion-resistant bedrock to highly erodible cohesive bluffs, to beach, dune and wetland complexes.

The Great Lakes, themselves, occupy about 244,000 km^2 or one-third of the 766,000 km^2 of the basin, and range in size from 82,100 km^2, Lake Superior, to 19,000 km^2, Lake Ontario. The lakes contain a variety of aquatic habitats, from deep, cool, oxygen-rich oligotrophic basins to shallow, warm eutrophic embayments. These habitats support numerous fish species and the many organisms upon which fish depend.

More than half of Ontario's population live within the shoreline communities of the Great Lakes - St. Lawrence River basin. Within the lower Great Lakes, the entire population of the basin lives within approximately two hours drive of one or more of the Great Lakes shorelines. This, in addition to the transportation capability, water supply availability, recreational opportunities and aesthetic features of the Great Lakes, attracts a wide variety of shoreline interests. Competition for use of the shoreline, by this diverse and growing range of shoreline interests, has and is continuing to place considerable strain on this limited and fragile resource.

In areas susceptible to flooding, erosion, dynamic beaches and to environmental degradation, the effects of ever increasing development pressures and competing interests have resulted in extensive and mounting property damages, risks to public safety as well as detrimental impacts to the shoreline ecosystem.

Figure 1.1: The Great Lakes - St. Lawrence River Basins



1.3 FLOOD, EROSION AND DYNAMIC BEACH SUSCEPTIBILITY AND HAZARDS

Having been developed and evolved from the naturally occurring processes of glaciation, ice retreat, isostatic rebound, water inundation, surface weathering (i.e., erosion, recession, accretion/deposition) and wind action, much of the *Great Lakes - St. Lawrence River System* shoreline continues to experience and provide evidence of these ongoing, naturally occurring processes.

In determining the appropriate shoreline management strategy for a given shoreline an assessment of these natural processes, the current status or factors impacting on the shoreline, and the intended or proposed use of the shoreline must be examined and balanced.

Evaluations of hazard existence, management and remediation are often based on two distinct and somewhat differing perspectives. These being that:

- flooding, erosion and dynamic beaches are naturally occurring processes which in and of themselves are not hazards, that they only become hazards when humans activities and development encroach within shoreline environments influenced by these natural processes. Activities which in some instances have accelerated the severity of the resulting hazards.

- flooding, erosion and dynamic beaches are hazards which must and can be addressed through various remediation measures (i.e., shore protection, lake regulation, floodproofing), and that the siting of development within shoreline environments is a right and should not be limited by the existence and/or susceptibility of hazards within the defined stretch of shoreline.

The distinct and subtle differences in these positions must be recognized when determining, interpreting and delineating such things as areas of hazard susceptibility, the degree of risk, options to hazard mitigation, and ultimately, in the development of an overall shoreline management strategy.

In general, the inundation of low-lying shorelines (i.e., flooding) and the loss of material from non-lithified shorelines (i.e., erosion) and the continuous adjustment of beach profiles (i.e., dynamic beaches) are considered to be natural processes rather than hazards. Early mapped information for the *Great Lakes - St. Lawrence River System*, has tended to generalize the existence and magnitude of hazards by defining all low-lying shorelines as flood hazards and all shorelines composed of non-lithified sediments as erosion hazards. The degree of hazard susceptibility and severity used in defining these areas has often been very subjective and can depend upon a number of factors including the presence or absence of human occupation.

For discussion purposes, the depiction of flood and erosion susceptible shorelines is provided in Figures 1.2 to 1.7. These depictions of flood and erosion susceptibility along the shorelines of the *Great Lakes - St. Lawrence River System* are based on the synthesis of a number of, often site specific, studies and investigations. These maps should be viewed as general representations of shoreline flood and erosion susceptibility and should not be considered as conclusive.

Flooding, in general, is a phenomenon which is sensitive to and influenced by water level fluctuations. Inundation of low-lying *Great Lakes - St. Lawrence River System* shorelines in and of itself does not necessarily constitute a significant hazard, depending of course, on the type, design, location and density of any development which may exist in or near the flood inundated shorelines. However, where flooded lands are coupled with storm events their cumulative impact can and frequently does pose significant degrees of risk, often over extended periods of time. Of importance in managing a potential flood susceptible shoreline is the need to understand the interrelationship between pre-storm flooding, storm setup, wave height, wave uprush and other water related hazards (i.e., wave spray, ice). If the area of inundation is a wetland or an undeveloped area, the resultant "damage" caused by a storm event may be minimal if measured in terms of human losses (i.e., property and life). Indeed, periodic flooding of wetland complexes have been found to be beneficial for the continued maintenance and enhanced diversity of wetland vegetation itself, by helping to eliminate the invasion of water sensitive upland vegetation into low-lying

Figure 1.2: Flood and Erosion-Prone Areas: Lake Superior

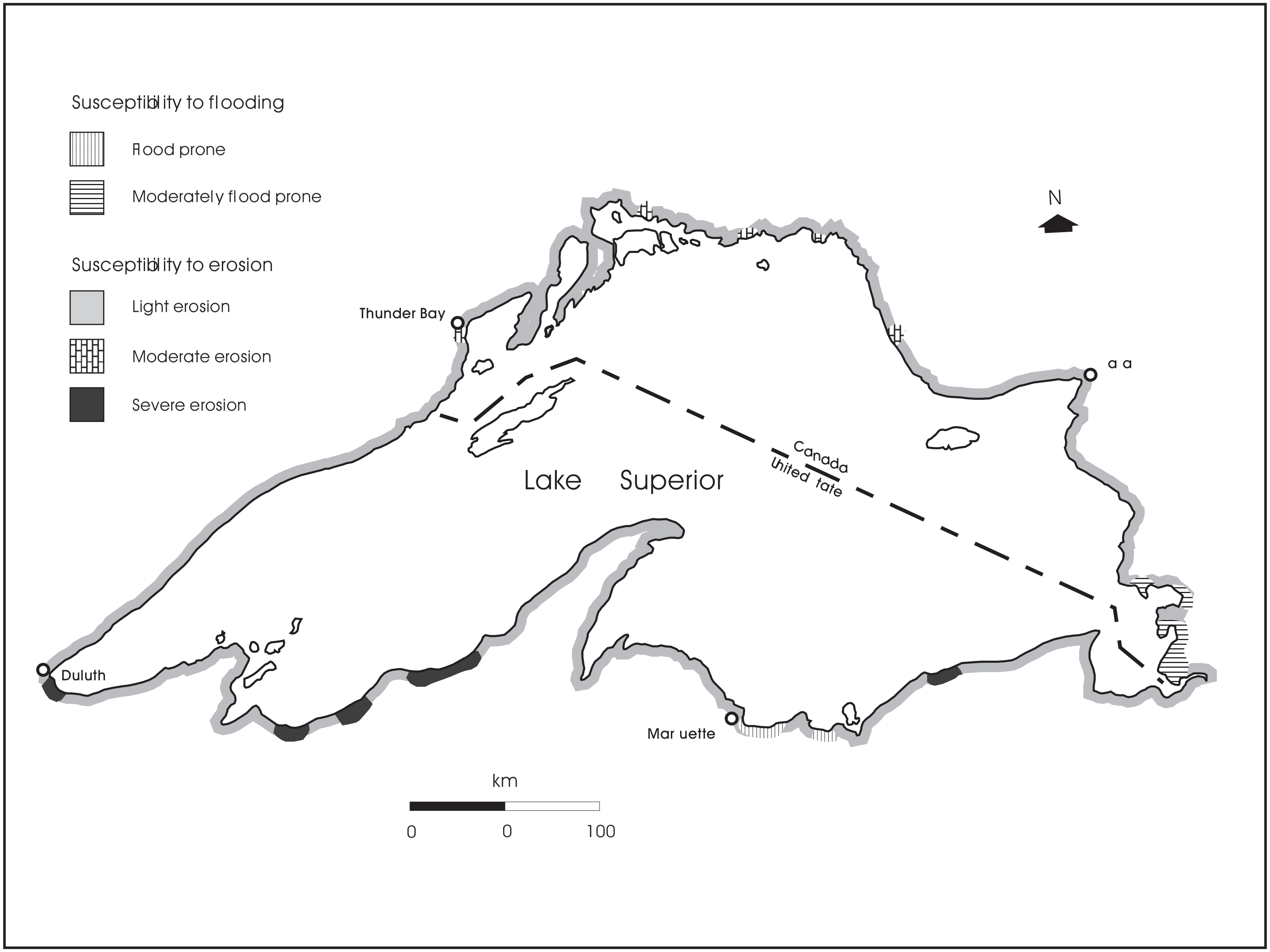


Figure 1.3: Flood and Erosion-Prone Areas: Lake Huron

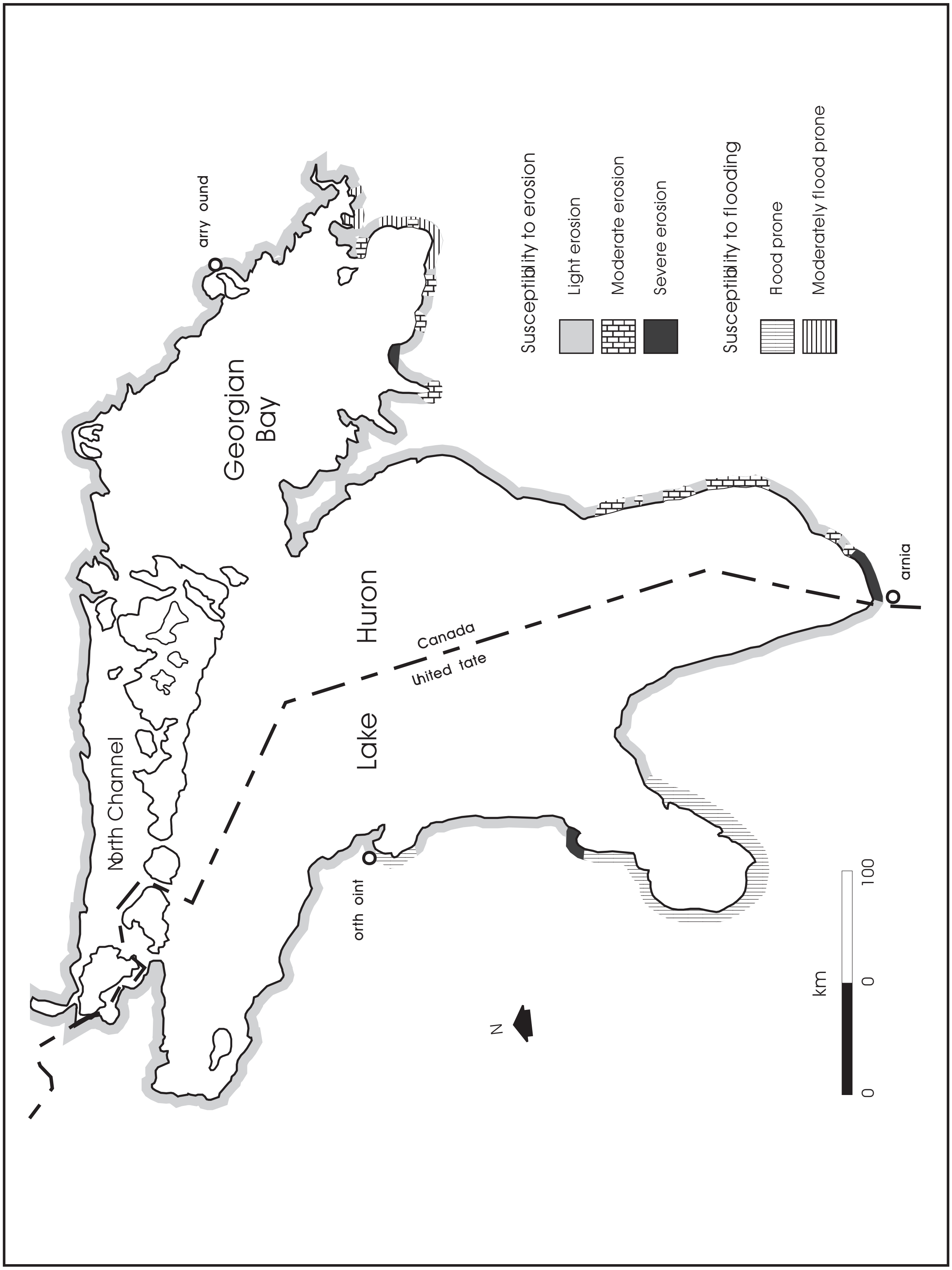


Figure 1.4: Flood and Erosion-Prone Areas: Lake Michigan

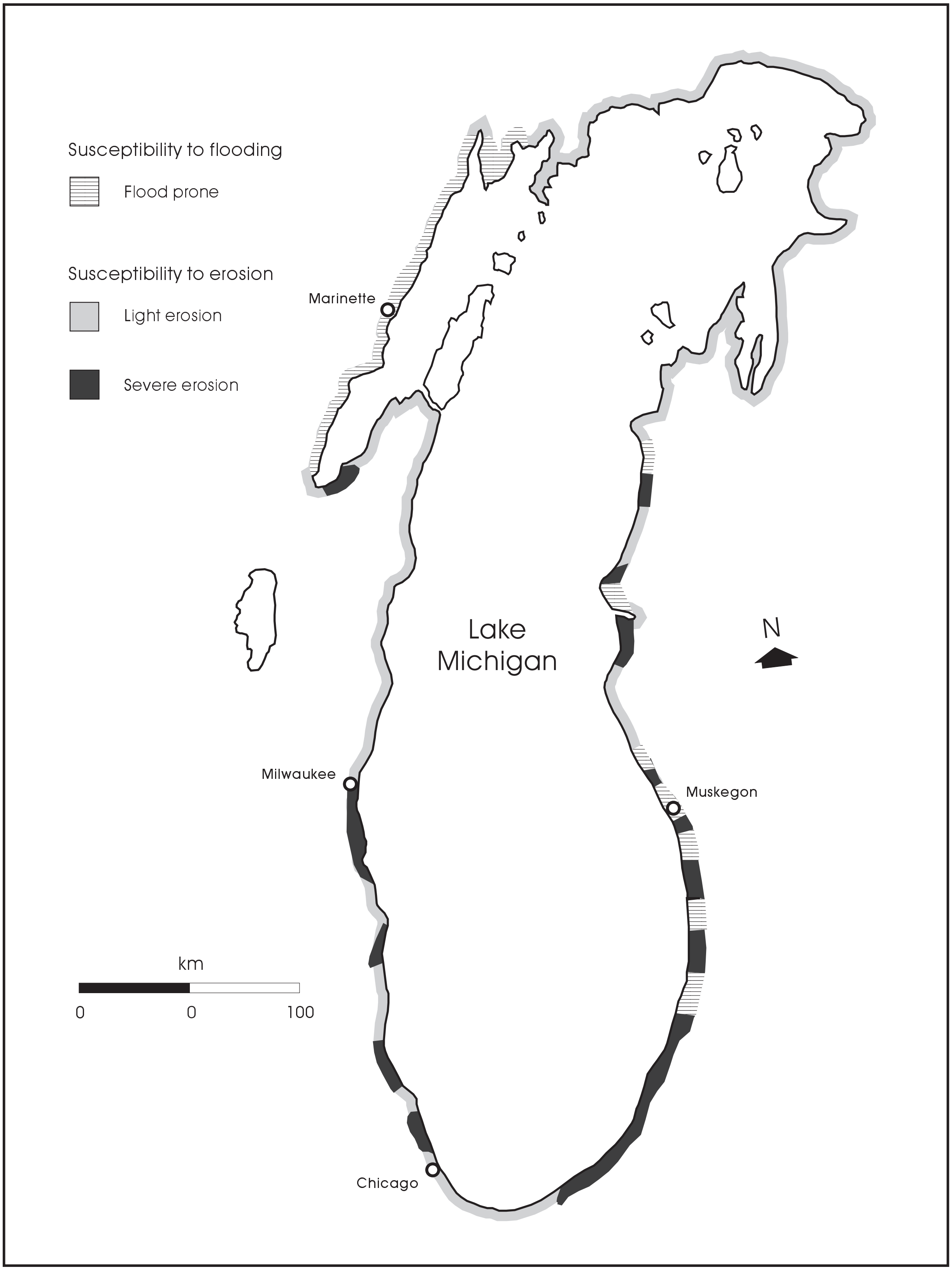


Figure 1.5: Flood and Erosion-Prone Areas: Lake Erie

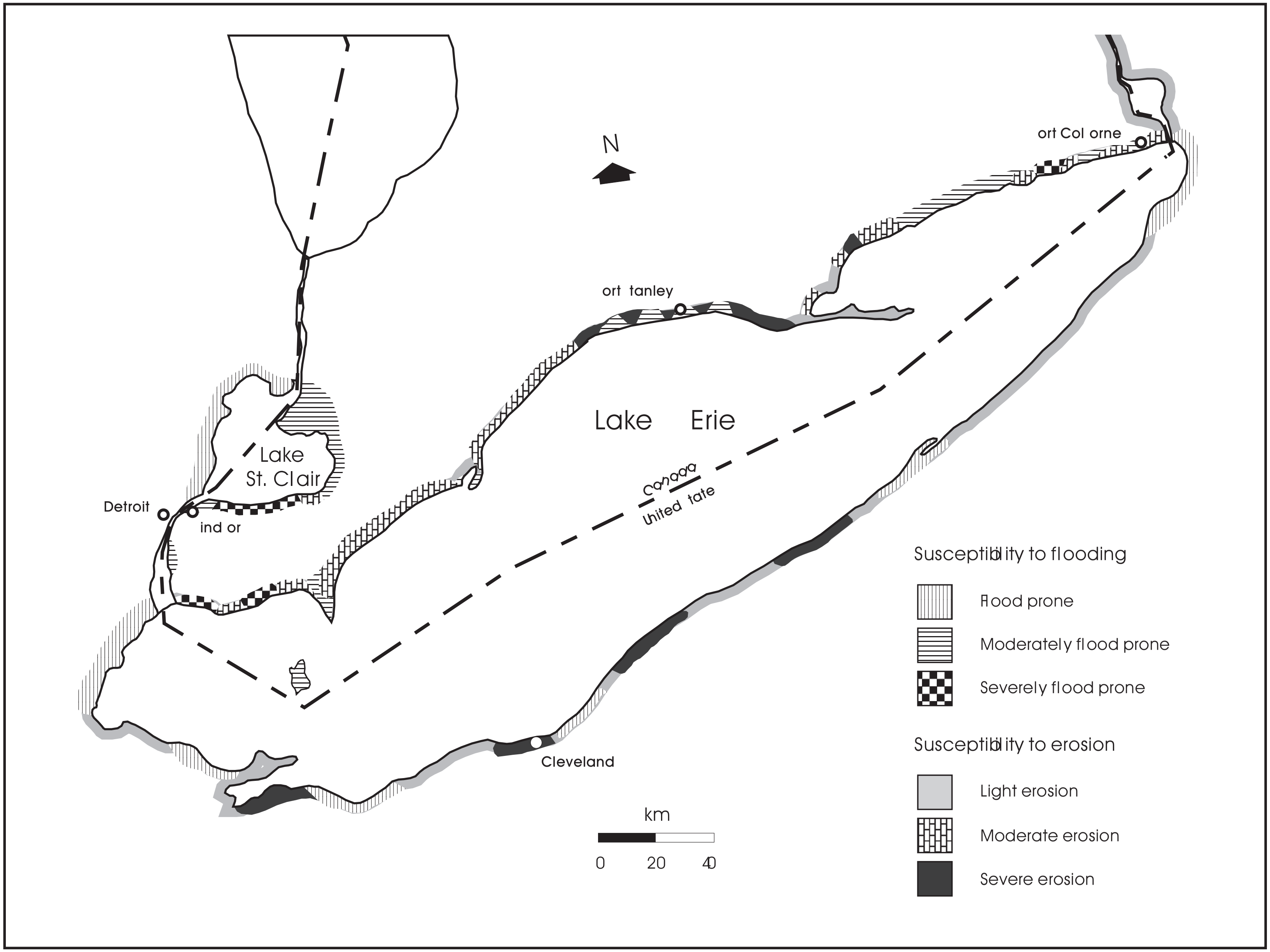


Figure 1.6: Flood and Erosion-Prone Areas: Lake Ontario

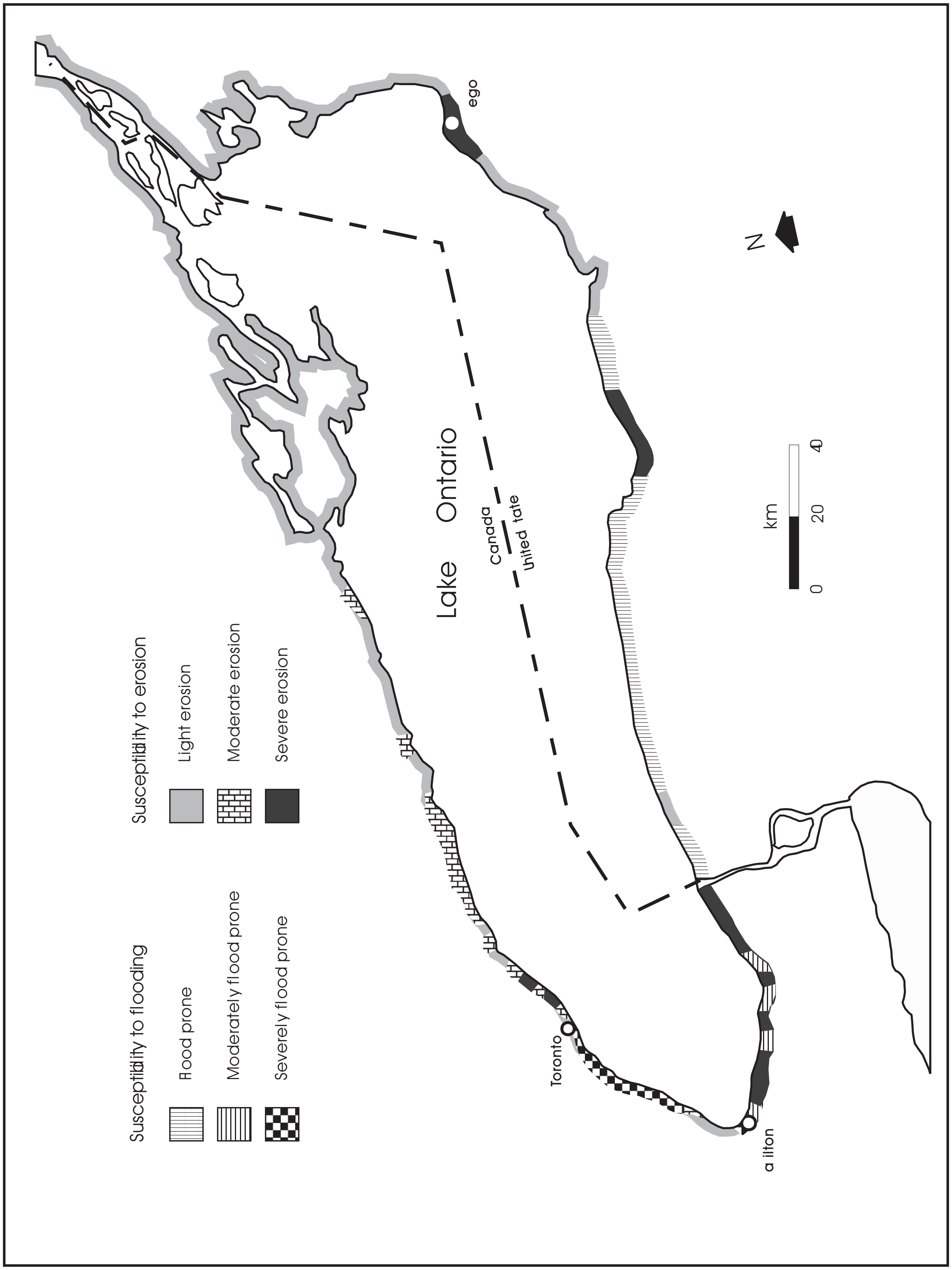
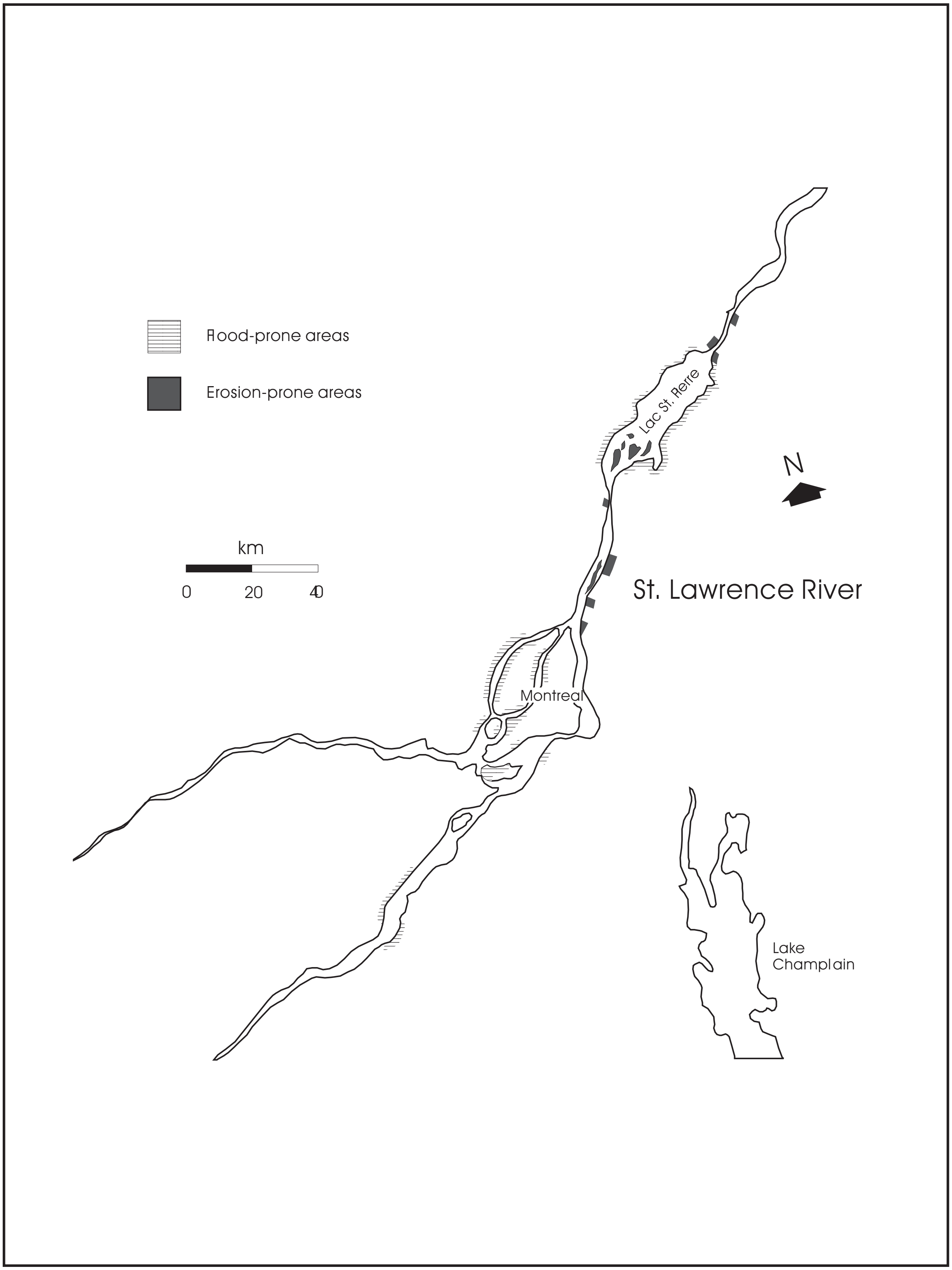


Figure 1.7: Flood and Erosion-Prone Areas: St. Lawrence River



shorelines during periods of low water levels. In terms of human use and occupation of the low-lying *Great Lakes - St. Lawrence River System* shorelines, development decisions based on or during periods of low water levels ironically present the most serious problem. During lower water levels, the potential flood hazard to homes, cottages and other development often goes unrecognized. Consequently, when water levels return to long-term averages or high water levels, flood damages are sustained, damages which are frequently quite significant.

Erosion within the *Great Lakes - St. Lawrence River System* is a major concern, particularly within the lower Great Lakes where a high percentage of the shorelines are experiencing significant rates of retreat. Erosion rates are dependent upon a number of lake and land processes as well as the composition and morphology of the shore. In general terms, identification of erosion susceptible shorelines is rather simple in that erosion of bedrock and cohesive shores involves a unidirectional process. In the absence of human intervention and/or the installation of remediation measures, once material is removed, dislodged or extracted from the shore face and nearshore profile it cannot reconstitute with the original material and is essentially lost forever. Even with the installation of remedial measures (i.e., assumed to address the erosion hazard), the natural forces of erosion, storm action/attack and other naturally occurring water and erosion related forces may prove to be such that the remedial measures may only offer a limited measure of protection and may only reduce or address the erosion hazard over a temporary period of time.

Given the naturally complex and dynamic nature of beach environment, determining hazard susceptibility of a given beach formation requires careful assessment of a wide range of parameters. Over the short term, beach environments, impacted by flood and erosion processes, may undergo alternating periods of erosion and accretion as they attempt to achieve a dynamic equilibrium with the forces acting up on them. Over the long term, beaches experiencing a positive sediment budget (i.e., more sand and gravel is incoming than outgoing) are generally in fact accreting shore forms while those experiencing a negative sediment budget are eroding. As such, the depiction and evaluation of the hazard susceptibility of dynamic beaches should be dependent on the level of information, knowledge and understanding of the beach sediment budget and the cross-profile width over which most of the dynamic profile changes are taking place.

As has been alluded to in above discussions and will be discussed more fully throughout later Parts of this Technical Guide, the degree of risk associated with flood and erosion hazards are naturally intensified with the introduction of storm events. Storm impacts, generally assessed in terms of wave action/attack as well as measurable and sometimes rapid increases in water levels (i.e., resulting from wind setup; seiche effect), often pose significant increased threats of flooding, increased rates of local erosion, and in turn, increased threats to shoreline developments.

TECHNICAL GUIDE FOR
GREAT LAKES - ST. LAWRENCE RIVER SHORELINES

APPENDIX A1.1

ORIGIN AND PHYSICAL FEATURES

OF THE GREAT LAKES

ORIGIN AND PHYSICAL FEATURES OF THE GREAT LAKES

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A1.1 ORIGIN AND PHYSICAL FEATURES OF THE GREAT LAKES

The purpose of Appendix A1.1 is to provide background information on the most important processes and factors that control shoreline dynamics and evolution in the *Great Lakes - St. Lawrence River System*. This material is designed to provide an understanding of the nature of shoreline hazards and of the potential impacts of various approaches to hazard mitigation.

To understand the processes currently affecting the evolution of the existing *Great Lakes - St. Lawrence River System* shoreline, Appendix A1.1 provides a description of the relationship between the underlying bedrock geology and the development of the Great Lakes basin supported by a brief description of the history of ice sheets and the formation of glacial and post-glacial lakes within the basin. Appendix A1.1 also includes a brief description of the present lakes, including those features located within the United States. For more detailed information, a listing of suggested references is provided in the bibliography supporting this Technical Guide.

A1.1.1 Formation, and Glacial and Post-Glacial History

The basins that form the Great Lakes-St. Lawrence River System owe their existence to erosion by ice sheets that have repeatedly developed over the past 2-3 million years over the northern half of North America. Each time an ice sheet developed, ice flowed into the basins resulting in the erosional deepening and widening of the basin. Much of the sediment that was deposited in the basins during interglacial periods was then eroded and deposited in the form of glacial tills along the margins of the basins.

a) Bedrock Geology

The development of the Great Lakes was controlled in part by the underlying bedrock geology which consists of:

- the complex metamorphosed sedimentary and igneous rocks of Precambrian Age (i.e., greater than 1 billion years Before Present - B.P.) that form the Canadian Shield; and

- relatively unaltered sedimentary rocks, consisting of limestones, dolomites, shales and sandstones of Palaeozoic Age (i.e., 350-500 million years old).

The geology and age of the bedrock of southern Ontario is shown in Figure A1.1.1 with a more detailed regional geology of the area provided in Figure A1.1.2.

In general, the beds of the Great Lakes occupy areas consisting of weak shale, siltstone and sandstone outcrops, while their shorelines and topographic highs (i.e., current landforms) are formed in the more-resistant Precambrian shield rocks, dolomites and limestones (Figure A1.1.3). As a result, Lake Ontario, central and eastern Lake Erie, Georgian Bay and the northern part of Lake Huron are all oriented roughly parallel to the strike of the major rock units with the deeper parts of the lakes themselves being eroded in Ordovician shales (e.g., Ontario and Georgian Bay) and Devonian shales (e.g., Huron and Erie). The more-resistant Precambrian shield rocks form the shorelines along much of Lake Superior, and the west and north shoreline of Georgian Bay and a small section of the St. Lawrence River between Kingston and Brockville. In southern Ontario resistant bedrock shorelines, associated with dolomite outcrops that form the caprock of the Niagara Escarpment, are found along the north shoreline of Lake Huron from the Straits of Mackinac, through Manitoulin Island and the Bruce Peninsula, and along the south shoreline of Lake Ontario.

Figure A1.1.1: Geology and Age of Rocks: Southern Ontario

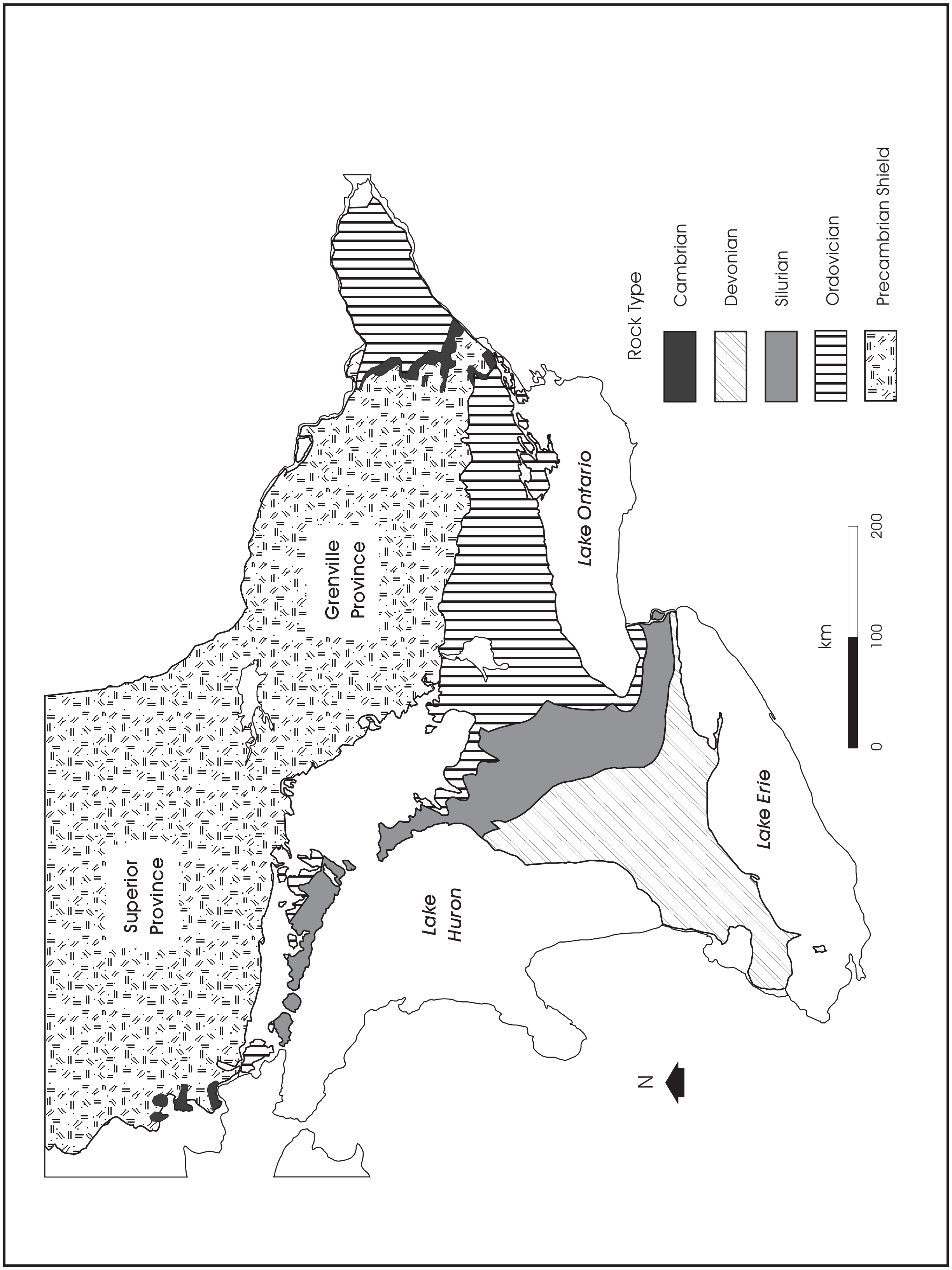


Figure A1.1.2: Regional Geology of the Great Lakes Lowland in Ontario

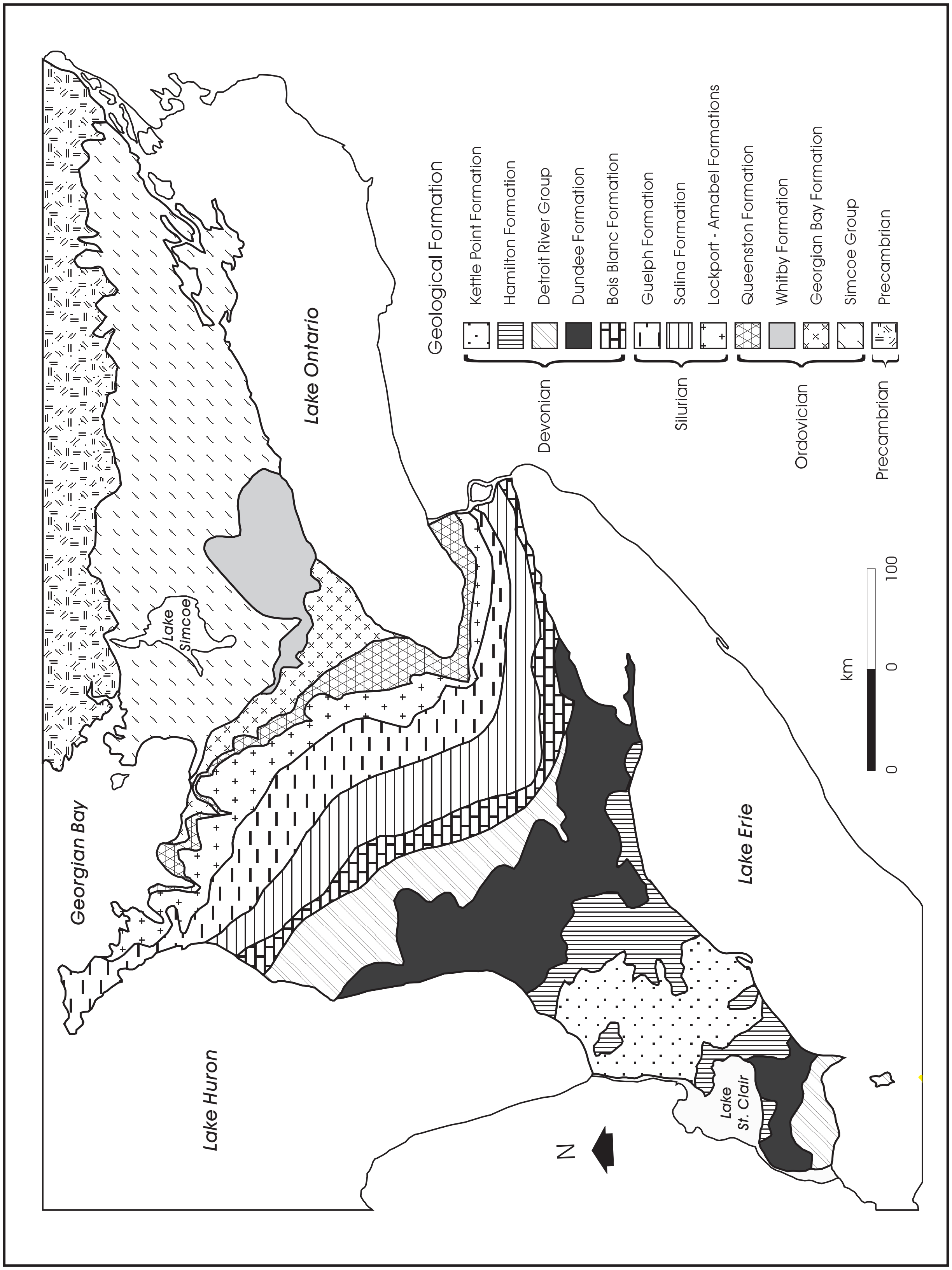
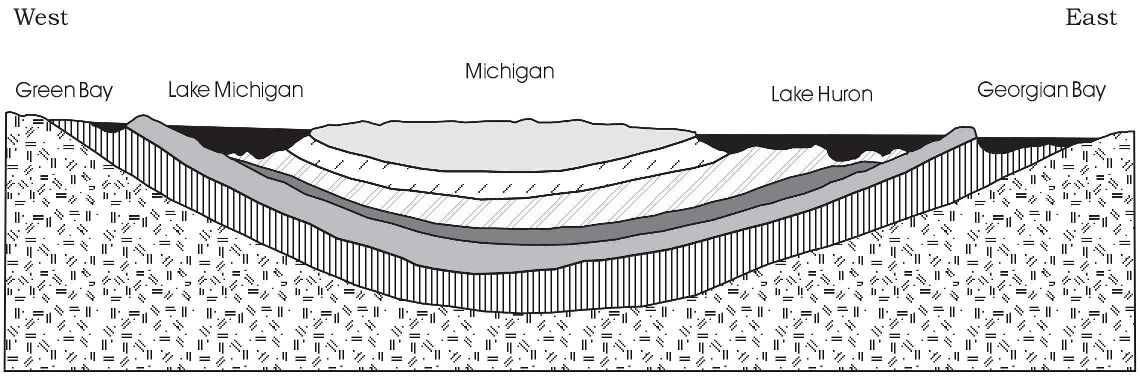


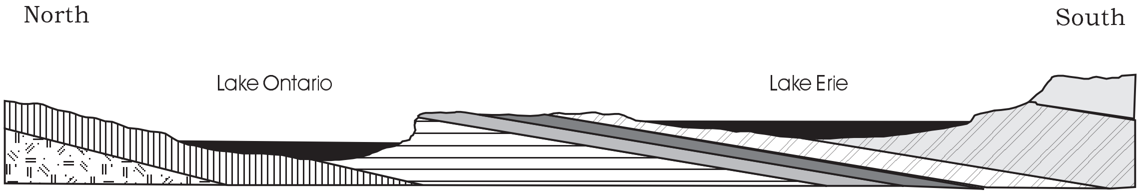
Figure A1.1.3: Cross-Sections of the Bedrock Geology of Ontario Showing the Relation of the Lake Basins to Relatively Weak Rock Formations



Geologic cross-section of the Michigan sedimentary rock basin, showing Lakes Michigan and Huron lying in zones occupied by relatively weak rocks of the Antrim Shale and Salina Group, Green Bay and Georgian Bay lying in zones of weak Ordovician rocks, and the escarpment of the Niagaran Dolomite which separates the lakes from the bay. (Hough, 1958)

Bedrock Type

- ▩ Precambrian rock
- ▥ Ordovician rock
- ▦ Niagara series
- ▨ Devonian and upper silurian rocks
- ■ Salina group
- ▨ Antrim shale
- □ Undifferentiated rock



Geologic cross-section through the western end of the Ontario basin and the eastern end of the Erie basin, showing relations of the basins to weak shales. (Hough, 1958)

Bedrock Type

- ▩ Precambrian rock
- ▥ Ordovician limestone
- ▦ Niagara dolomite
- ▨ Devonian limestone
- ■ Salina shale
- ▤ Queenston shale
- □ Undifferentiated rock
- ▨ Devonian shale

b) Glacial and Post-Glacial Development

In the absence of any major structural controls (e.g., major rift systems) it seems certain that the Great Lakes owe their origin to ice scour during repeated glacial stages during the Pleistocene Era (i.e., last three million years), as do most of the other smaller inland lakes in Ontario. This is reinforced by the fact that all of the Great Lakes except Lake Erie have basins that extend well below present sea level.

Most of the evidence for previous glaciations in Ontario has been removed by ice action during the most recent glacial period (i.e., Wisconsinan), which reached its maximum extent some 20,000 years B.P.. During the Wisconsinan period, the whole of southern Ontario was covered by ice with the dominant regional flow being from the north or north-east although locally, the ice flow direction would have been influenced by the underlying topography. During early glacial retreat, about 14,000 B.P., thinning of the ice sheet eventually led to exposure of the upland areas in southern Ontario (i.e., around present-day Orangeville) which were surrounded on three sides by ice with ice meltwater draining southwest into the early glacial lakes in the Erie basin and beyond to the west (Figure A1.1.4a). Local ice flow patterns were from the northwest and north out of the Huron and Georgian Bay basins and from the east and south-east out of the Erie and Ontario basins. As further retreat of the ice sheet occurred, distinct lobes associated with each lake basin developed, with the main ice sheet located to the northeast and with the Oak Ridges kame moraine developing north of Lake Ontario between the northern and southern ice lobes (Figure A1.1.4b). During the ice retreat a succession of glacial lakes formed between the ice and the drainage divide to the south. Fluctuations in the margins and elevations of these glacial and subsequently the post-glacial lakes reflect the complex pattern of local ice retreat and isostatic uplift which together controlled the location and elevation of drainage exits for the lakes (Figure A1.1.5).

Along much of the shoreline of the Great Lakes in southern Ontario extensive sedimentary deposits were created, first by deposition of tills from the ice sheets and later by meltwater rivers draining the ice and by sediments deposited in the glacial and post-glacial lakes (Figure A1.1.6).

c) Lake Level History

The lakes that occupied the Great Lakes region from the late Wisconsinan (i.e., 14,000 B.P.) to the present have left considerable evidence of their existence in the form of wave-cut notches and bluffs, lag boulder deposits, and a range of nearshore, beach and dune sediments. The most conspicuous and extensive features are shoreline bluffs cut in glacial and glacio-fluvial sediments, notably those of Lake Iroquois in the Ontario basin, and lakes Algonquin and Nipissing in the Huron/Georgian Bay basins, and extensive dune fields such as those in Georgian Bay, the east shoreline of Lake Huron and in some embayments on Lake Superior. The size and extent of these old shoreline features reflects the extent of the lake and the length of time that it was in existence, but is also dependent on factors such as sediment availability, resistance of the shoreline to erosion, local topography and subsequent preservation.

Lake level histories for each of the lake basins have been reconstructed from a variety of shoreline features, sedimentary deposits and other sources of evidence. The actual history is usually depicted relative to present sea level (i.e., as an absolute change in elevation). However, much of this elevation change results from isostatic uplift of the whole land mass, including the lake basin and its exit. The relative change in the level of the water and land along the shoreline is often a lot smaller and is controlled by the relative rates of change between the point on the shoreline and the exit from the lake.

Isostatic uplift is the uplift of the land surface following removal of an overlying weight (e.g., in this case the weight of the glacial ice sheet). The uplift is produced by the inflow of partially molten material at a depth of several hundred kilometres. It is usually modelled as being quite rapid initially and diminishing to very low values after 8-10,000 years. Because thinning of the ice and retreat from the Great Lakes Basin took place over several thousand years, some areas were still undergoing rapid uplift while others had entered a much slower phase. One effect of this differential is that shorelines that mark glacial and post-glacial lakes which were originally horizontal are now tilted (i.e., they increase in elevation away from some point; this is in itself an indication of isostatic uplift). Along the Lake Ontario shoreline, for example, the Lake Iroquois shoreline bluff increases in elevation and distance from the modern shoreline between Toronto and Kingston.

Figure A1.1.4: Stages in the Deglaciation of Southern Ontario

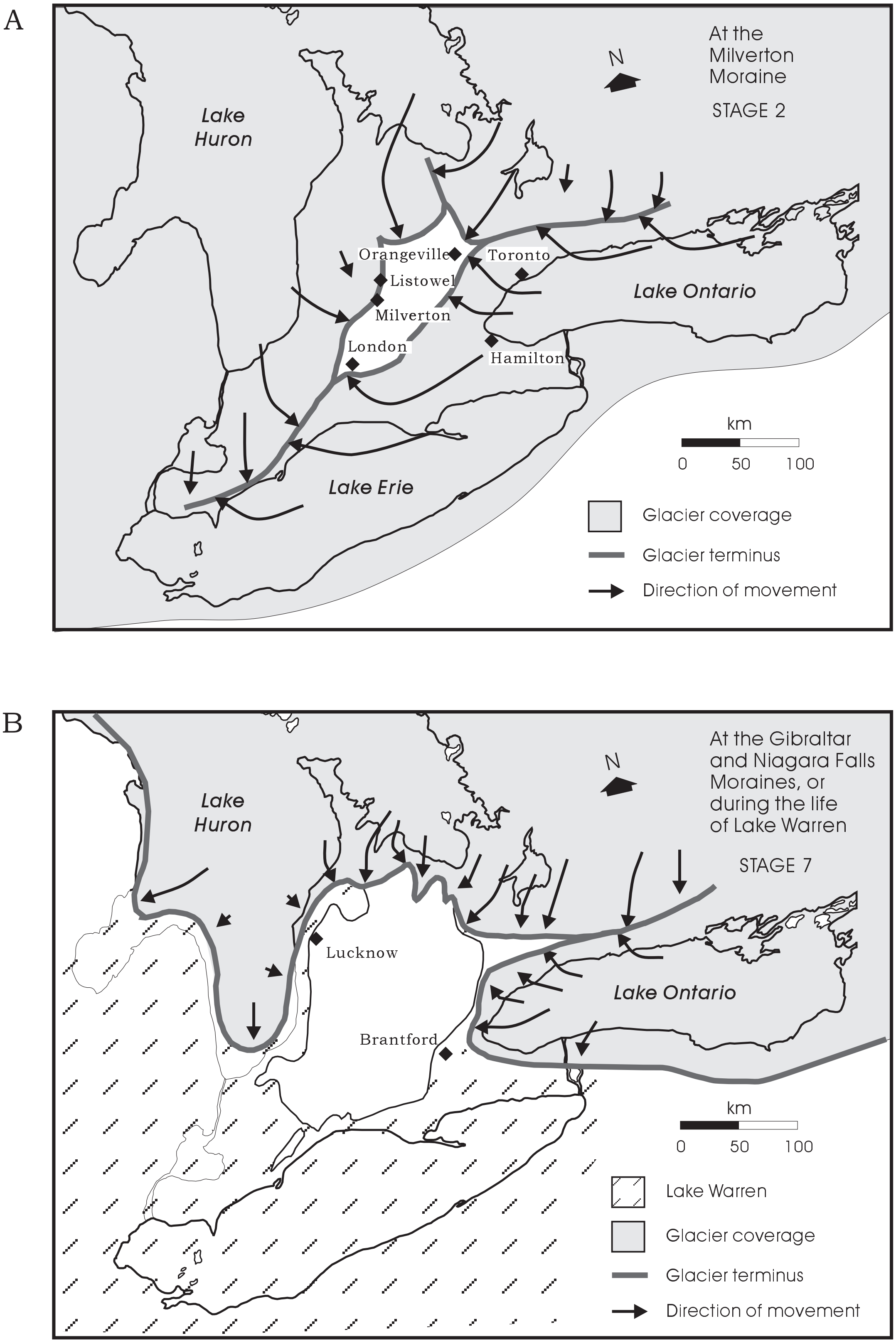


Figure A1.1.5: Stages in the Deglaciation of Southern Ontario

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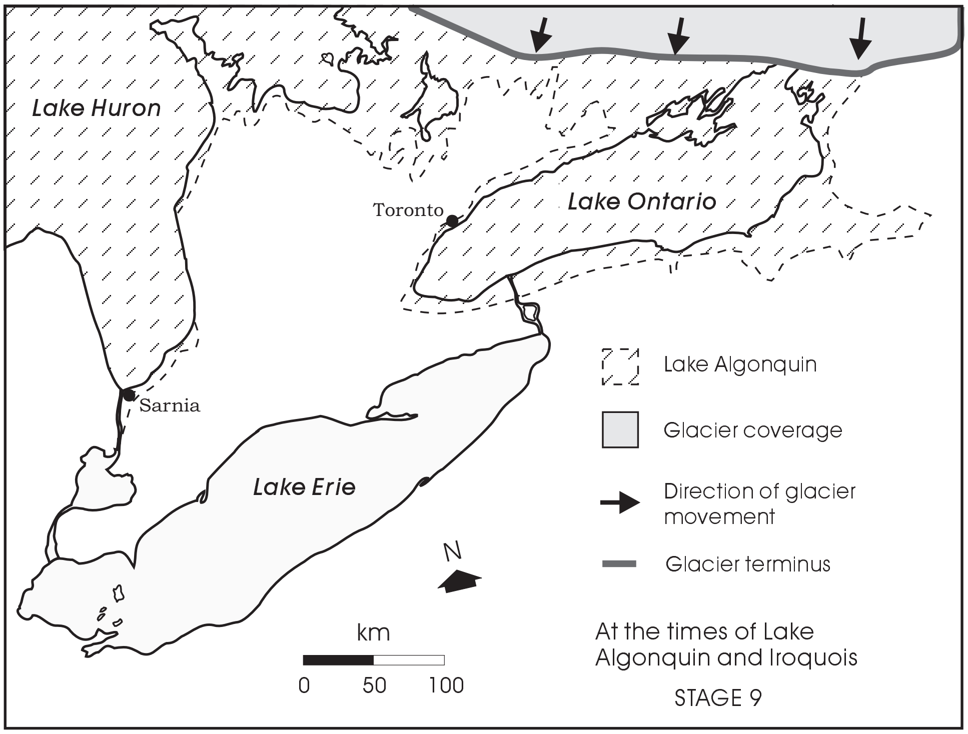

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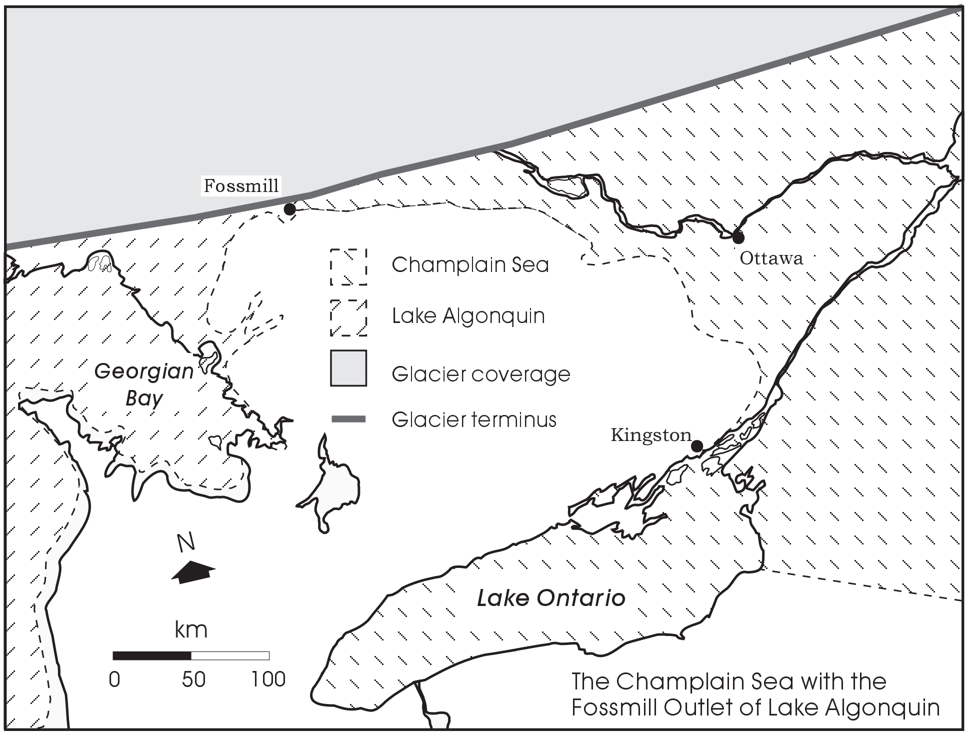
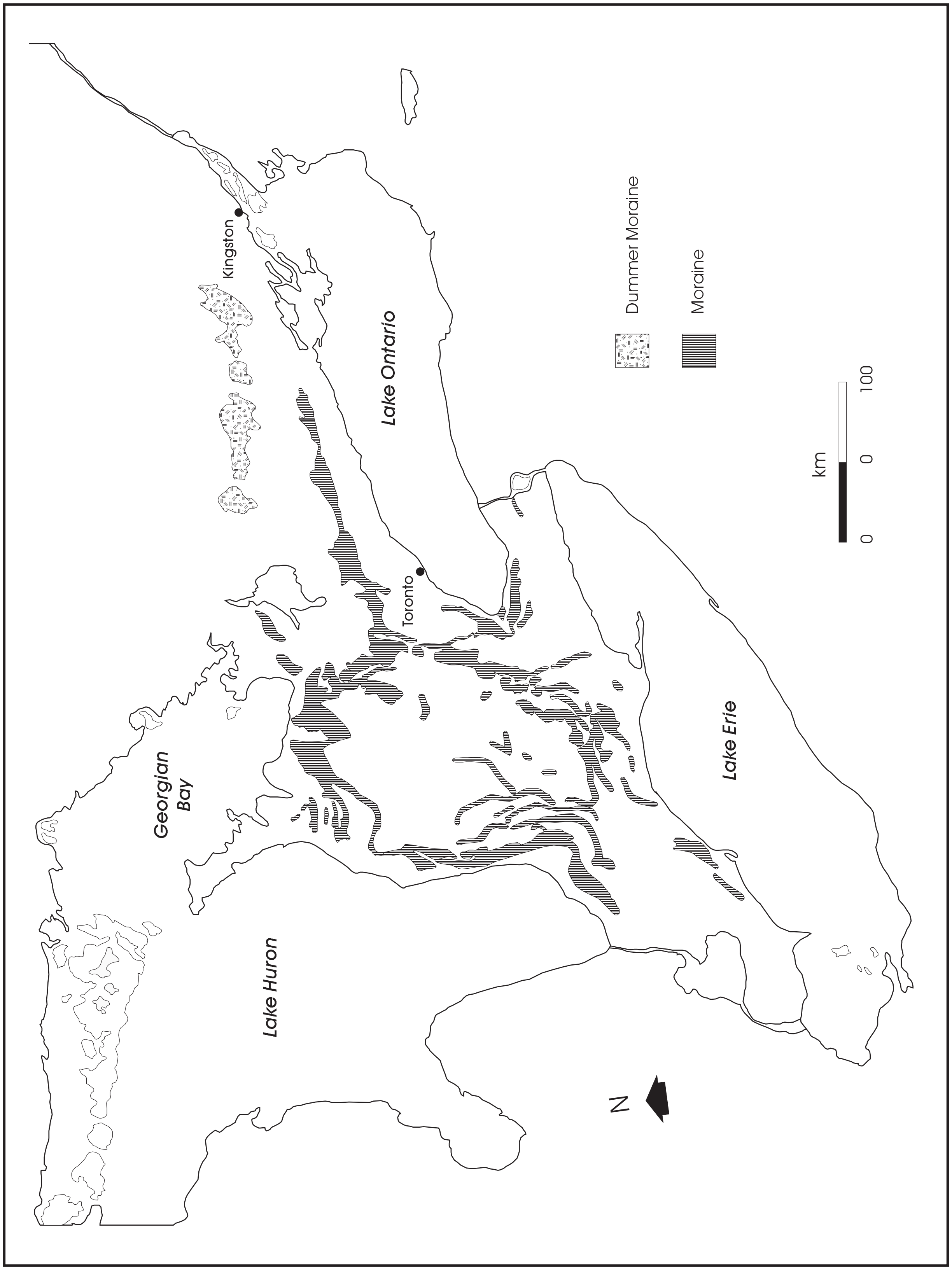


Figure A1.1.6: Physiographic Features Associated with the Deglaciation of Southern Ontario



With the retreat of the ice sheet, generally towards the north and north-east, those areas became ice-free much later than areas to the south and west and as a result are still undergoing some isostatic uplift. Rates of present isostatic uplift in Ontario are shown in Figure A1.1.7, with changes being depicted relative to sea level. Of greater significance, however, is the rate of uplift relative to uplift at the outlet of the lake. Those areas that are being uplifted at a greater rate than their outlet (e.g., Lake Huron/Georgian Bay and Lake Superior north of the St. Mary's River) are experiencing shoreline regression (i.e., the shoreline is moving lakeward), and as such, there are only a few areas where shoreline erosion and recession is significant. The eastern end of Lake Ontario, including the outlet to the St. Lawrence River, is still undergoing some small isostatic uplift with the result being a small lake level rise at the western end of the lake causing the drowning of the mouths of small rivers and an increase in shoreline erosion rates. For the Lake Erie basin, being one of the first areas to become ice free, the isostatic uplift has essentially ceased with most changes now being controlled by alterations in the location and depth of the outlet to the Niagara River.

i) Lake Ontario

As the ice sheet retreated northeastward out of the Lake Ontario basin, glacial Lake Iroquois was formed about 12,500 B.P. (Figure A1.1.5a; A1.1.8, A1.1.9). With the St. Lawrence River blocked with glacier ice, the outlet for the Lake Iroquois was to the south through the Mohawk River at Rome, New York. The Lake Iroquois shoreline, marked by beaches and particularly by bluffs cut in cohesive sediments, is visible along the north shore of Lake Ontario, between Toronto and Trenton, approximately 1-10 km inland from the present shoreline. East of Trenton Lake Iroquois flooded extensive areas to the north of the current Lake Ontario shoreline (Figure A1.1.9).

Between 12,000 and 11,500 B.P. lake levels fell as ice retreat opened up drainage outlets into the St. Lawrence River valley and Champlain Sea which occupied the current St. Lawrence and Ottawa River valleys for a short period of time (Figure A1.1.5b). Between 10,500 and 5,000 B.P. the flow of meltwater from the upper lakes was diverted through the Ottawa River valley causing Lake Ontario to experience a long period of reduced water supply. During this same time period, the absolute elevation of the lake rose as the outlet through Cornwall rose isostatically (Figure A1.1.8), however, there was a much smaller change in the relative position of the shoreline.

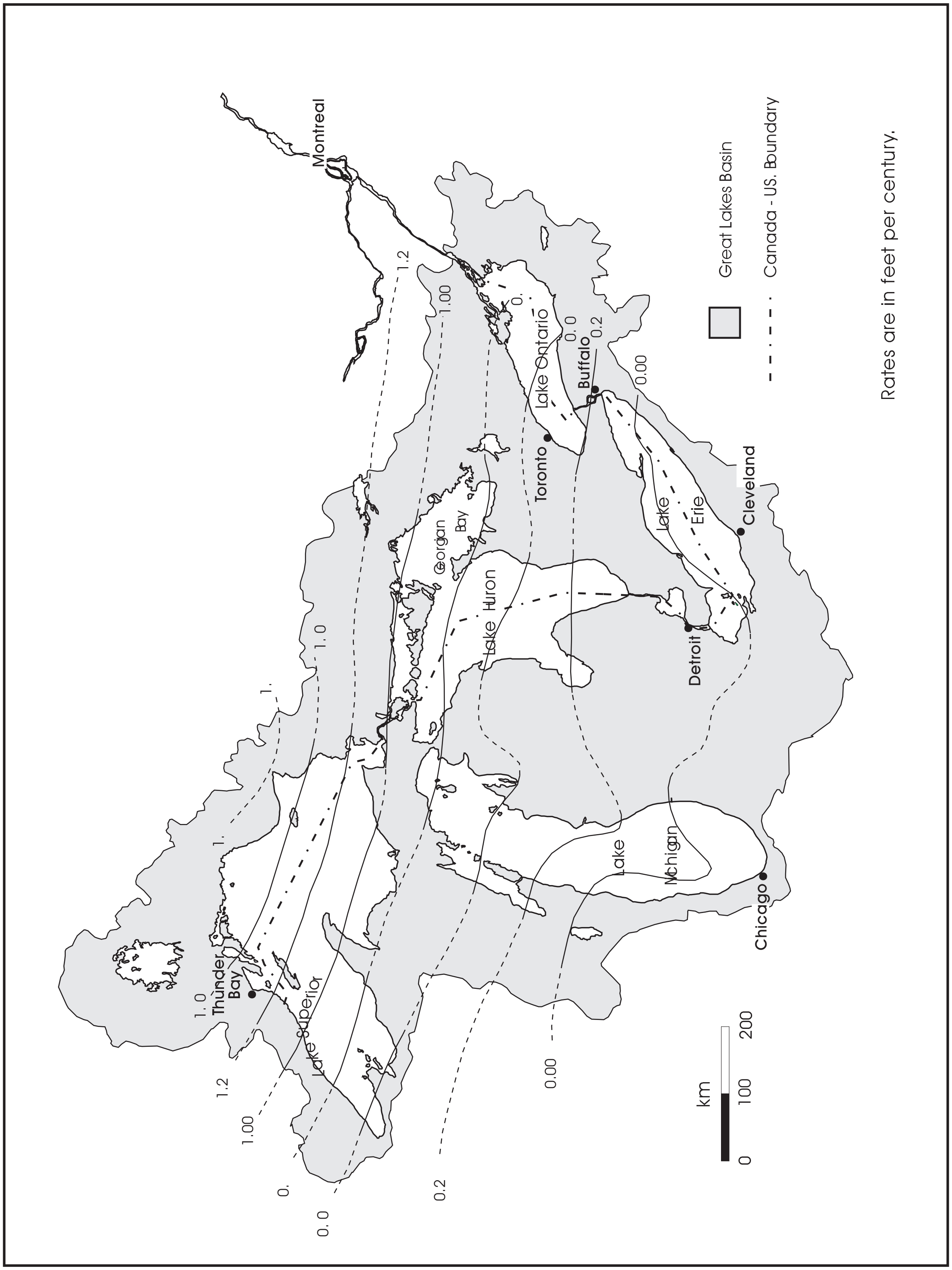
When flow from the upper lakes was restored between 5-4,000 B.P. water levels in Lake Ontario rose significantly and then later fell as the outlet channels adjusted to the new larger flows. At present time, water levels at the western end of Lake Ontario are rising slowly with the continued slow isostatic uplift of the eastern end of the lake basin, including the outlet to the St. Lawrence River near Kingston. This continued isostatic uplift has the effect of drowning the mouths of rivers flowing into the lake and of accelerating the rate of recession along the cohesive portions of the current Lake Ontario shoreline.

ii) Lake Erie

Deglaciation began first in Lake Erie basin with the development of a series of post-glacial lakes at the western end of the basin as the ice margin retreated northward and eastward (Figure A1.1.4b; Figure A1.1.10). Lakes Maumee, Warren and Whittlesey, the most important of these post-glacial lakes, each left prominent bluffs along parts of the western and central basins as well as along southern Lake Huron basin.

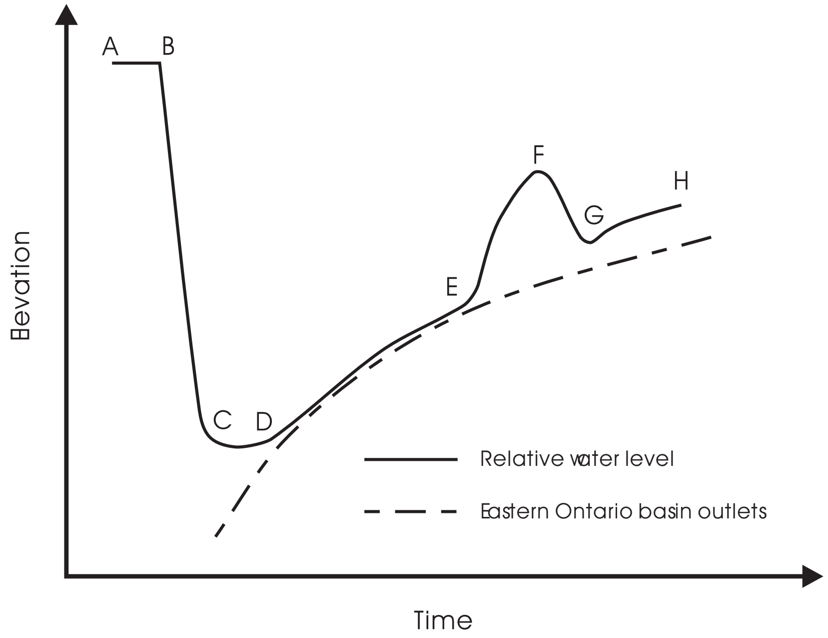
With the opening up of the Niagara River gorge about 12,500 B.P. early Lake Erie, possibly consisting of separate lakes in the eastern and western basins, was formed having shorelines well below the present level. Subsequent isostatic uplift of the outlet at the Niagara River led to the gradual rise of lake levels in the Lake Erie basin. A rapid acceleration of this rise, associated with re-establishment of flow from the upper lakes through the St. Clair-Detroit river system, occurred between 5-4,000 B.P. Since 4,000 B.P. lake levels within the Lake Erie basin have remained essentially stationary with little indication of any remaining isostatic effects being evident.

Figure A1.1.7: Rates of Isostatic Uplift in the Great Lakes Basin



Rates are in feet per century.

Figure A1.1.8: Model of Relative Lake Level Change for the Lake Ontario Basin



A proposed summary model of relative lake-level change for Ontario basin showing early rapid decline due to retreat of a glacial dam (ABC), stillstand due to sea level control (CD), progressive rise at steadily diminishing rates due to differential uplift of outlets (DE), and superimposed flooding with outlet adjustments due to capture of upper Great Lakes drainage (E-H).

AB (12,500 to 12,000 B.P.) Glacial Lake Iroquois - glacier dam in northeast part of Ontario basin, drainage via Mohawk River at Rome, New York.

BC (12,000 to 11,500 B.P.) Post-Iroquois falling lake phases - Frontenac, Sydney, Belleville (Sandy Creek), Trenton-Skinner Creek - retreat of glacier and release of lake waters by newly opened lower outlets, expansion of glacial lake waters into the Ottawa and upper St. Lawrence valleys.

C (11,500 B.P.) Fall to sea level (Gilbert Gulf phase) - Trenton-Skinner Creek or later lower phases are confluent with Champlain Sea Level. Relative lake-level changes are reduced, depending on net effect of basin uplift and sea-level rise.

D (11,500 B.P. to 10,500 B.P.) Early Lake Ontario (Duck-Galloo phase) - separation from Champlain Sea.

DE (10,500 to 5,000 B.P.) Rising early Lake Ontario - Following diversion of upper Great Lakes drainage to the Mattawa and Ottawa Rivers (drainage of glacial Lake Algonquin in the Huron Basin), the Ontario basin experienced a long period of reduced water supply causing lake

EF (5,000 to 4,000 B.P.) "Nipissing Flood Phase" - With return of upper Great Lakes drainage through Lakes Erie and Ontario, increased outflow overtaxed the capacity of outlet channels, causing water levels to rise significantly. The "Nipissing Flood", peaking about 4,000 B.P., surpassed present levels in eastern Lake Ontario. This stage probably corresponds with the North Pond phase of Sutton et. al., (1972).

FG (4,000 to 3,500 B.P.) Levels subsided as outlet channels adjusted to increased outflow from upper Great Lakes discharge.

GH (3,500 B.P. to present) Levels increase gradually but more slowly than in early Holocene under the influence of rising outlets.

The RLL interpretation of this study is similar to other recent models (Karrow et al.,1961; Sutton et al., 1972; Sly).

Figure A1.1.9: Areal Extent of Lakes in the Ontario Basin 12,000-4,000 B.P.

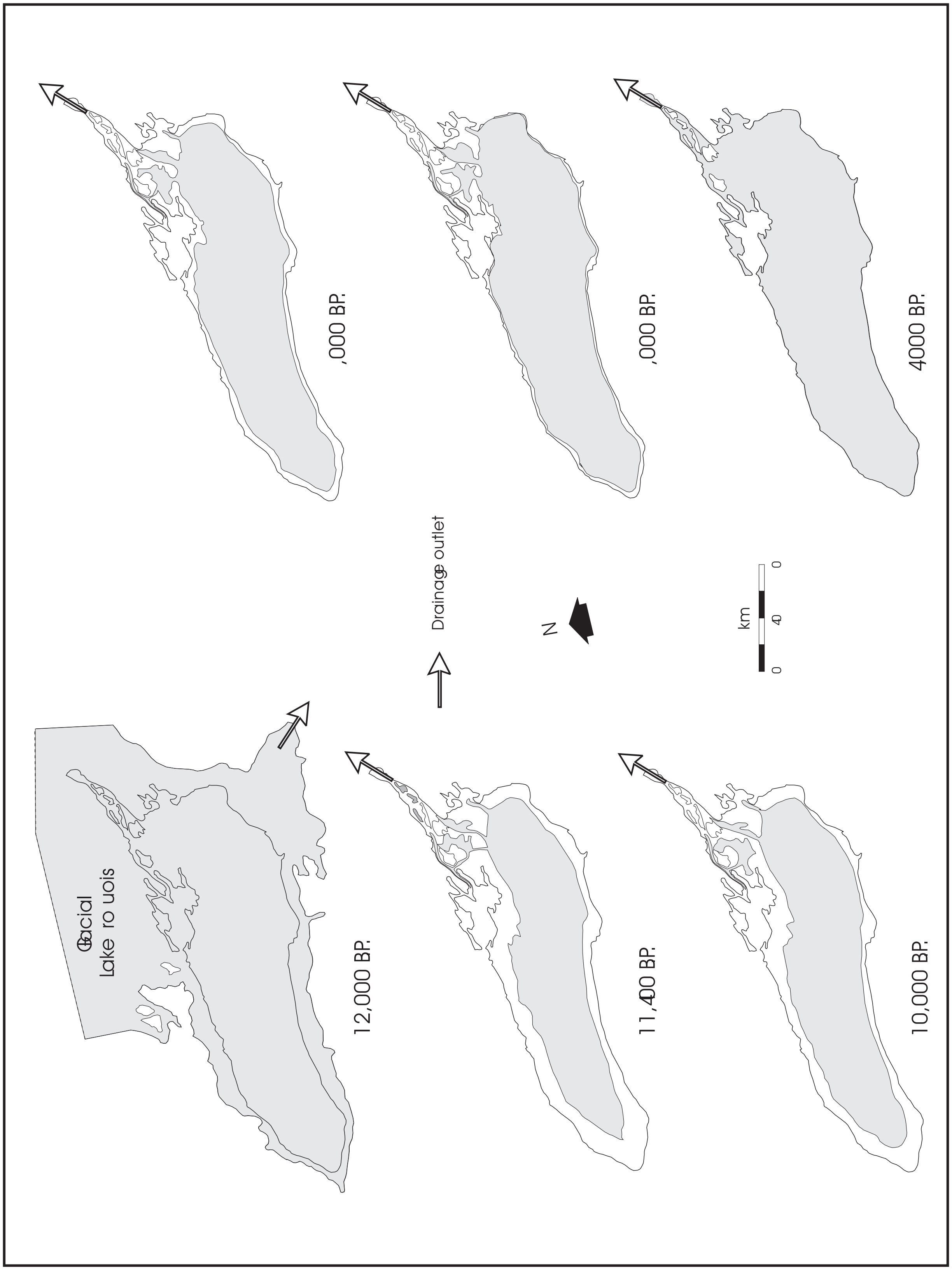
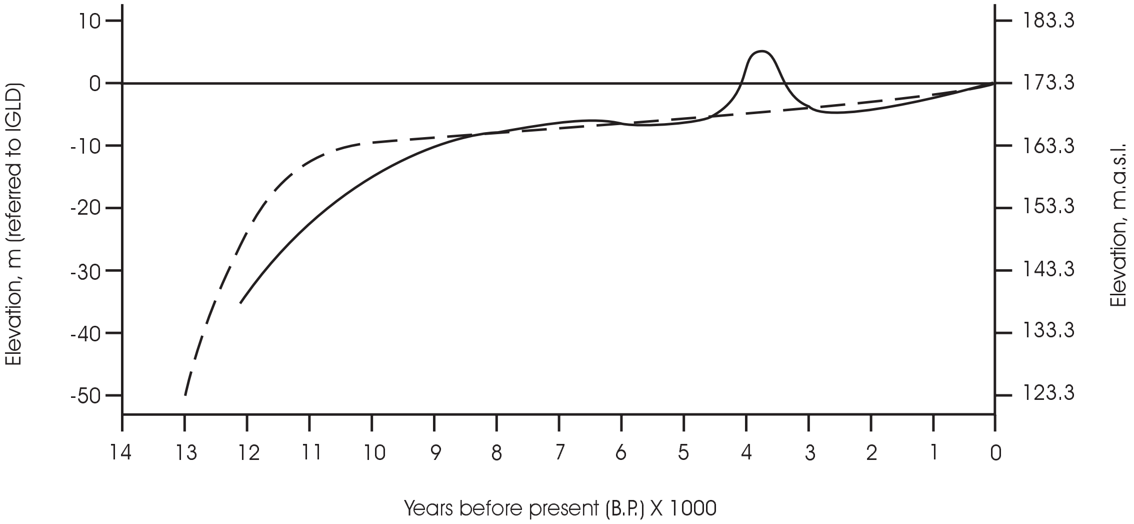


Figure A1.1.10: History of Lake Levels in the Erie Basin



Revised interpretation of lake level history in Lake Erie (central sub-basin), indicated by the solid line. The dashed line represents the theoretical lake level at the outlet sill (assuming on overlying depth of water similar to that at present) based on a composite model of sill rebound.

iii) Lake Huron and Georgian Bay

Early glacial lakes Maumee, Warren and Whittlesey, which occupied the southern end of the Lake Huron basin and parts of the Lake Erie basin, were followed by rapid inundation of the whole Michigan, Huron, Georgian Bay and Lake Simcoe areas as the ice retreated rapidly northwards forming early Lake Algonquin about 13,000 B.P. (Figures A1.1.4b; A1.1.5a; A1.1.11). The outlet from this early Lake Huron basin was to the south through the Lake Michigan basin at Chicago.

Following some small fluctuations in water levels, the main phase of Lake Algonquin development was completed by about 12,500 B.P. Sediments and shoreline bluffs, evidence of the existence of Lake Algonquin shoreline are visible inland and along many sections of the present Lake Huron shoreline. In some areas (e.g., between Goderich and Grand Bend), evidence of Lake Algonquin has been removed as erosion has extended inland beyond the Lake Algonquin shoreline.

Continued northward retreat of the ice sheet exposed a series of successively lower outlets around North Bay which permitted Lake Huron to drain eastward into the Ottawa and St. Lawrence River valleys. The development of these outlets resulted in a dramatic fall in lake levels (Figures A1.1.5b; A1.1.11). At the lowest point, Lake Huron and Georgian Bay basins probably existed as separate lakes, Lake Stanley in the Lake Huron basin and Lake Hough in the Georgian Bay basin, with a river channel located between the Bruce Peninsula and Manitoulin Island connecting the two basins.

Between 10,500 B.P. to about 5,000 B.P., isostatic uplift around the North Bay area led to a continuous rise in lake levels to where levels reached an elevation several metres higher than present, forming Lake Nipissing. The transgression associated with these rising lake levels resulted in the "rolling over" of large quantities of sediment as the shoreline migrated inland. Eventually this led to the formation of extensive dune systems along many parts of the Lake Huron/Georgian Bay shoreline, including those south of Grand Bend, at Sauble Beach and Red Bay, and around Nottawasaga Bay.

As water levels continued to rise, outlets through Chicago and later through Sarnia/Port Huron, and eventually through Lakes Erie and Ontario to the St. Lawrence River were re-established. Subsequent erosion of the outlet at Sarnia/Port Huron has led to a small drop in lake level. Some isostatic uplift continues to occur in the northern part of the Lake Huron and Georgian Bay basins while this has essentially ceased around the outlet at Sarnia/Port Huron (Figure A1.1.7). As such, the shorelines in Georgian Bay and north of Goderich show evidence of present emergence, reducing the effects of shoreline recession due to erosion in these areas.

iv) Lake Superior

With deglaciation occurring much later in the Lake Superior basin than in other lake basins to the south, isostatic changes within the Lake Superior basin are still very important and causing continued, and significant modification of the current shoreline.

Around 11,800 B.P. narrow marginal lakes first formed the beginnings of the Lake Superior basin. Re-occupied by ice during the Marquette advance, around 10,000 B.P., thick red till was deposited, particularly at the western end of the basin. The ice retreated, first from the south-eastern end of the basin forming Lake Minong and later extended into the whole of the Lake Superior basin by about 9,500 B.P.. As the ice retreated and glacial deposits around the outlet from Lake Minong were eroded water levels fell until erosional downcutting at the outlet was halted by the bedrock sill in the St. Mary's River at about 9,000 B.P. (Figure A1.1.12).

During this same time period, as retreating ice uncovered successively lower outlets, there were a number of catastrophic floods resulting from the sudden draining of glacial Lake Agassiz, which covered extensive areas of northwestern Ontario, most of Manitoba and parts of Saskatchewan, through the Lake Nipigon basin and into the Lake Superior basin. It has been estimated that 4,000 km^3 of water could have flowed into Lake Superior over the space of two years in one of these events. The extensive grey clay deposits found in Lake Superior probably resulted from the huge volume of sediment that was transported by these floodwaters.

Figure A1.1.11: History of Lake Levels in the Huron Basin

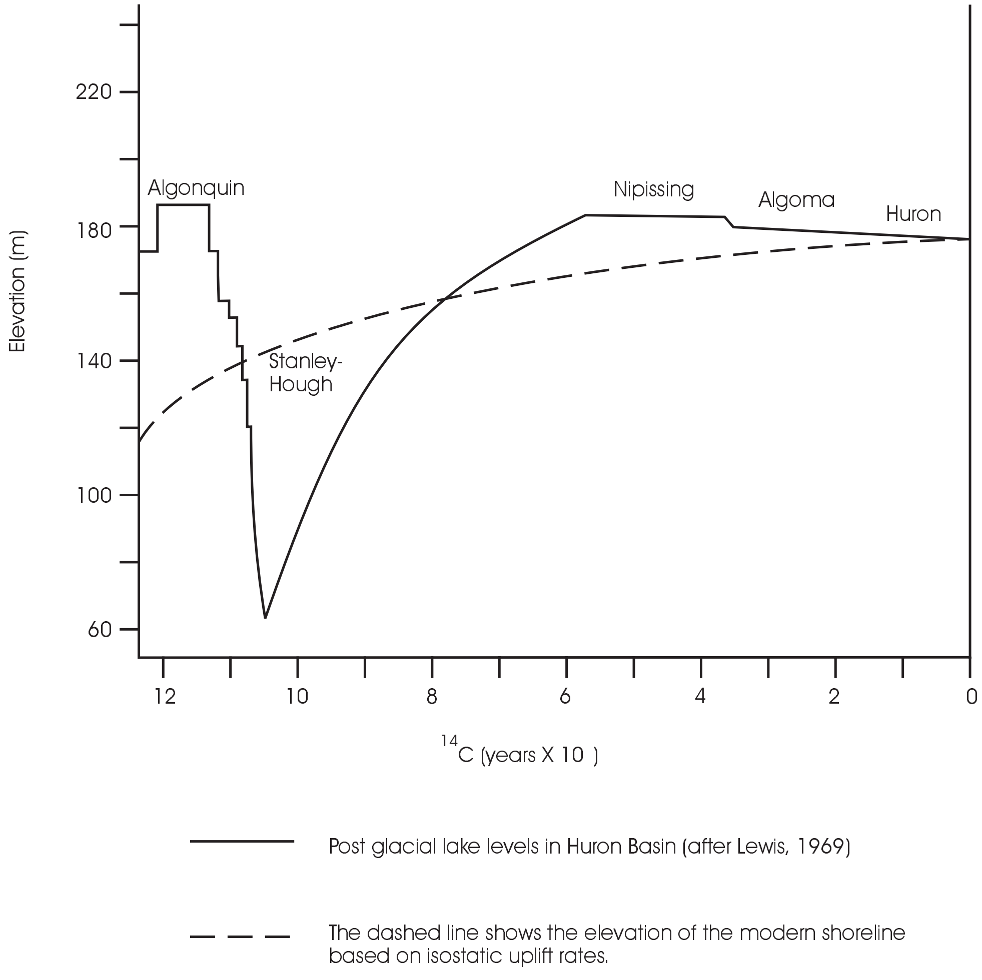
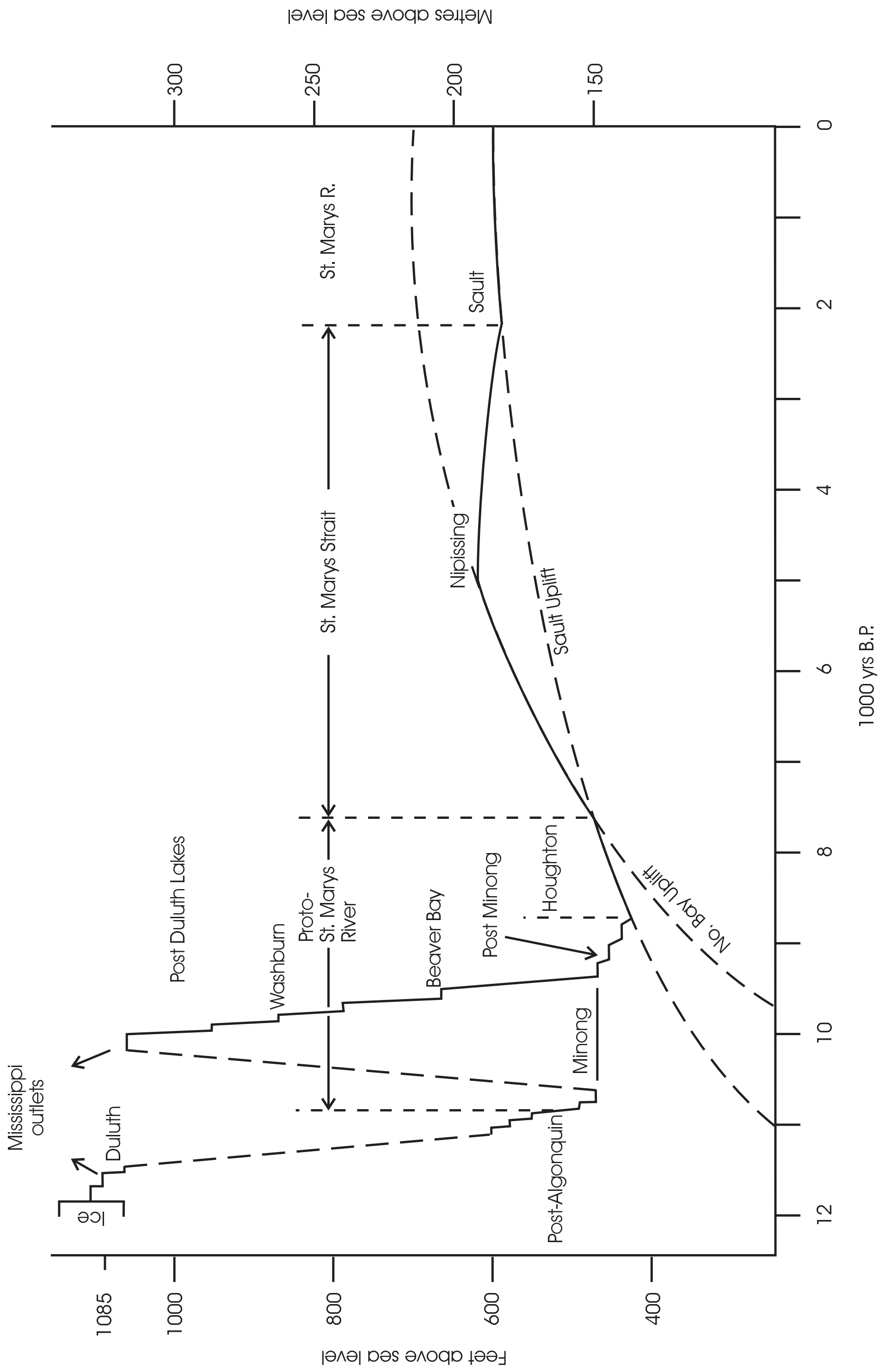


Figure A1.1.12: History of Lake Levels in the Superior Basin



Curves of water level in the basin prior to rebound. The "spike" at 10 000 B.P. occurred only in the western basin, while the eastern remained at the Minong level. Modified from Farrand (1969)

Between 9,500 and 5,000 B.P., the isostatic rebound of the North Bay outlet of the Lake Huron-Georgian Bay basin was occurring faster than the Lake Superior outlet at the St. Mary's River. By 5,000 B.P., this differential in isostatic rebound resulted in rising water levels in Georgian Bay, the flooding of the area around Sault Ste. Marie, and the connecting of Lake Superior with the Michigan-Huron-Georgian Bay basin to form one continuous water body known as Lake Nipissing. As downcutting of the outlet of Lake Huron into the St. Clair River occurred and as the uplift of the sill on the St. Mary's River continued the two basins became separated again around 2,200 B.P. (Figure A1.1.12).

Isostatic rebound is still occurring in the Superior basin, with the rate of uplift increasing from south-west to north-east. At any point on the existing Lake Superior shoreline the significant control is the rate of uplift relative to that at the outlet (Figure A1.1.13). Most of the Lake Superior shoreline is experiencing some relative isostatic uplift, with the shoreline around Michipicoten and Marathon being uplifted at a rate of about 30 cm per century. In general, this leads to the emergence of existing wetlands and the stranding of beach sediments above the present lake level.

A1.1.2 Description of Great Lakes Physiography

The physical characteristics of the shorelines of the *Great Lakes - St. Lawrence River System* have resulted from the development of the Great Lakes basin since the last ice age. The physiography of these shorelines range from high bluffs composed of clay, till, shale and rock, to low rocky shorelines, dune complexes and sandy beaches, to low marshy clay flats. From a regional perspective, the northern shorelines of Lakes Superior and Huron and the Thousand Islands area of the St. Lawrence River consist primarily of highly erosion-resistant sedimentary and igneous rock. Throughout the remainder of the Great Lakes-St. Lawrence River system the shorelines are mainly composed of glacial sediments which are susceptible to erosion, primarily through wave action.

Given the differences between lake and connecting channel environments, the following sections provide separate discussions on each of the discrete shoreline/lake units.

Although the following descriptions of the *Great Lakes - St. Lawrence River System* shoreline are provided as a collection of discrete units, it should be noted that these units are inter-related and inter-dependent and therefore their influence on and contribution to the entire system should be recognized. For this reason, a description of the United States Great Lakes shoreline has also been included.

The following descriptions of the Great Lakes' shoreline are based primarily on a number of studies including the Great Lakes Framework Study (Great Lakes Basin Commission 1975), the Coastal Zone Atlas (Haras and Tsiv 1976) and The Great Lakes Environmental Atlas and Resource Book (Botts and Krushelnicki 1987).

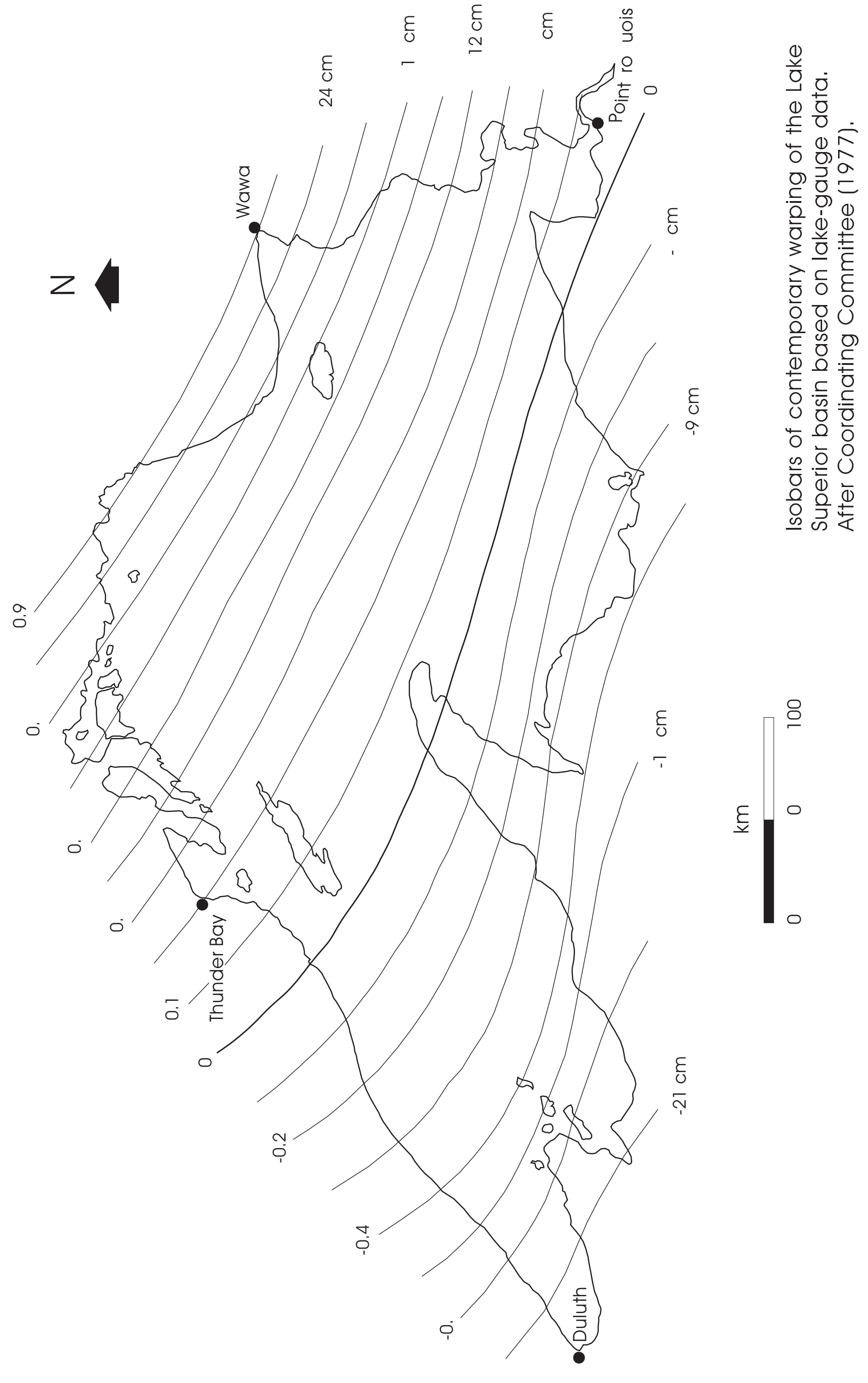
a) Lake Superior and St. Mary's River Shoreline

The majority of the northern shoreline of Lake Superior, cut into the resistant rock of the Canadian Shield, is characterized by low, resistant rock outcrops interspersed with a few areas of sediment accumulation. The northwest and southeast sections of the lake, consisting of complex shorelines involving a series of large sheltered embayments, are the result of erosion of relatively unresistant rock outcrops. The remaining stretches of shoreline are relatively straight interspersed with only small bays and headland features. Beaches are scarce, usually occurring in embayment areas or adjacent to river mouths.

The southern shoreline of Lake Superior is very similar to the northern shoreline, ranging from steep rock cliffs in the Pictured Rocks National Lakeshore area; to sandy beaches at Whitefish Bay; to low lying clay and gravel bluffs near Duluth, Minnesota; and to the wetlands of Munuscong Bay, Michigan. A substantial baymouth bar encloses the harbours at Duluth, Minnesota and Superior, Wisconsin.

There are many islands in Lake Superior and in the St. Mary's River, with Isle Royale, Sugar, St. Ignace and Michipicoten Islands being the largest. Major urban centres include the grain ports of Thunder Bay, Ontario and Duluth, Minnesota, and the border towns of Sault Ste. Marie, Ontario and Michigan.

Figure A1.1.13: Rates of Contemporary Isostatic Uplift in the Superior Basin



Isobars of contemporary warping of the Lake Superior basin based on lake-gauge data. After Coordinating Committee (1977).

b) Lake Michigan Shoreline

Perhaps one of the most impressive natural shoreline types of the entire *Great Lakes - St. Lawrence River System* is the long expanse of sand dunes along the eastern shoreline of Lake Michigan. The dunes, extending from the Indiana border on the southern tip of Lake Michigan north to near the Straits of Mackinac, are the result of prevailing westerly winds causing an almost continuous washing and grading of shoreline materials. Wide sandy beaches are common along this shoreline, especially during periods of low water levels.

All forms of shoreline types which can be found throughout the *Great Lakes - St. Lawrence River System* are found along Lake Michigan's approximately 2,300 km of shoreline. The majority of this shoreline consists of highly erodible bluff and dune complexes within the states of Michigan and Wisconsin with the non-erodible shoreline being located within the northern section of the lake along the Upper Peninsula of Michigan and Door County, Wisconsin. Extensive shoreline wetlands have developed along Green Bay, Big and Little Bays de Noc, and along drowned river mouths of tributaries draining into Lake Superior. Large, highly urbanized developments are concentrated along the southwest shoreline and include the cities of Chicago, Illinois and Milwaukee, Wisconsin.

c) Lake Huron Shoreline

The highly diverse Lake Huron shoreline ranges from rocky shorelines associated with the Precambrian shield covering the northern and eastern shorelines, to exposed limestone dominating the shorelines of Manitoulin Island and the Bruce Peninsula, and to the glacial deposits of sand, gravel and till dominating the southern and eastern portions of the Lake. Igneous or limestone rock comprises the majority of the shoreline from Sault Ste. Marie to Waubashene in southern Georgian Bay and most of Huron County in Michigan. Small sand beaches and wetland areas occur in embayments and river mouths.

The southern shoreline of Georgian Bay and southeastern shoreline of Lake Huron are characterized by long, wide beaches backed by dunes or bluffs at Ipperwash and Wasaga and high and low erodible bluffs with limited beach development through Huron and Lambton Counties. Rock outcrops occur at Kettle Point.

Within the State of Michigan, the northwestern shoreline of Lake Huron consists mainly rock and boulder features with some high bank beaches extending landward into rolling uplands. Toward the south, the western shorelines of Lake Huron are dominated by sandy beaches backed by low dunes and bluffs. Saginaw Bay, one of the largest embayment along the western Lake Huron shoreline, consists of extensive shoreline wetlands in the Inner Bay and predominately low sandy beaches backed by low dunes and bluffs in the Outer Bay.

Islands within Lake Huron-Georgian Bay range from the very large (e.g., Manitoulin, St. Joseph, Cockburn, Bois Blanc and Drummond) to the many small islets which combine to form the "30,000 Islands" of eastern Georgian Bay.

d) St. Clair River, Lake St. Clair and Detroit River Shoreline

The shoreline of the Lake St. Clair and St. Clair and Detroit Rivers are generally low lying features consisting of soft deposits of sand and clay of varying depths. For example, along the St. Clair River the shoreline consists of a sandy till bank 1.5 to 5.0 metres high, topped by clay deposits.

The islands of the St. Clair delta cover almost one half of the shoreline within this region. The very low lying delta islands are dominated by broad marshes growing on the sand deposits overlying a clay bed. Along some stretches of these shorelines the shoreline marshes have been dyked and drained for agricultural purposes.

The northern and eastern shorelines of Lake St. Clair are dominated by marshland on sand beds backed by low clay plains. Extensive areas of the Lake St. Clair shoreline have been dyked and drained for agricultural purposes. By comparison, the south shoreline of Lake St. Clair consists of narrow sandy beaches backed by very low flat till plains while the western shoreline is predominantly artificial fill onto which shoreline residential development have been placed.

The Detroit River shoreline consists generally of 1.5 to 5.0 metre high clay banks. Shoreline development is heaviest within this area with many areas having been artificially filled and involving varying forms of shoreline protection, particularly within the cities of Detroit, Michigan and Windsor, Ontario.

e) Lake Erie and Niagara River Shorelines

The north shoreline of Lake Erie consists primarily of highly erodible deposits of glacial till, with some sections of clay and sand deposits. At the eastern end of Lake Erie, bedrock is exposed at or near the waterline in many locations. Except for the rocky portions of the eastern section, and the large sand spits at Point Pelee, Rondeau, and Long Point, most of the north shoreline of Lake Erie consists of soft eroding bluffs ranging from 3 to 30 metres in height. Extensive wetland complexes exist at various creek mouths and behind sandspits with a large portion of these wetland areas, particularly along Point Pelee, Pelee Island and Rondeau having been dyked and drained for agricultural purposes.

Within the boundaries of the United States, wetlands interspersed with artificial shoreline types in developed areas dominate the southwestern shoreline of Lake Erie (e.g., Monroe County, Michigan). From the western portion of the Ohio shoreline, characterized by wetlands, low erodible bluffs and erodible plains, the shoreline type shifts to some of the most highly erodible glacial till and soft shale bluffs within the eastern extent of the Ohio shoreline. Within Pennsylvania, bluffs ranging from 15 to 25 metres in height, consist of silt, clay, and granular material with shale bedrock at or above water level. In the eastern portion of Pennsylvania, the shale bedrock frequently rises to 10 metres above the lake level with the upper portion of the bluff being composed of silt, clay and granular material. Sand and gravel beaches frequently extend along the toe of these bluffs. One feature of particular note, a large sand spit known as Presque Isle, occurs at Erie, Pennsylvania. The remainder of the Lake Erie shoreline to the Niagara River is characterized by erodible, 10 to 15 metre high bluffs consisting of shale overlain by unconsolidated material.

The Niagara River shoreline, composed of low banks in the upper portion of the river, transforms into a deep gorge cut through sedimentary deposits in the lower river below Niagara Falls. Extensive filling activity has occurred in the Buffalo area.

Highly urbanized developments within the Lake Erie-Niagara River area are focused on the American side of the Lake Erie shoreline, particularly within the shoreline communities of Toledo and Cleveland, Ohio; Erie, Pennsylvania; and Buffalo, New York.

f) Lake Ontario Shoreline

The southwestern shoreline of Lake Ontario from the Niagara River to Hamilton consists of consolidated clays, silt and sand features of varying height and forms. In the Niagara area, 3 to 7 metre high bluffs predominate, while the shoreline in the Hamilton-Wentworth area is characterized by low-lying sandy beaches. A prominent sand bar (i.e., baymouth barrier), known as the Burlington Bar, encloses the western end of Lake Ontario containing the heavily industrialized Hamilton-Burlington Harbour. The north-western shoreline from Burlington to Toronto consists primarily of 3 to 7 metre high shale outcrops covered by glacial till.

Across the Toronto area the shoreline begins at the western end with low bluffs of sand, silt and clay fronted by narrow sand and gravel beaches at the toe. Eastward from the mouth of the Humber River the shoreline is low-lying but well protected by a series of seawall and breakwater structures. Within central Toronto, a large sandy spit, involving a series of naturally and artificially formed islands known as Toronto Islands, coupled with the artificially constructed headland/spit (e.g., Leslie Street Spit), have essentially closed off Toronto Harbour at its eastern end. Eastward from central Toronto, the erodible Scarborough Bluffs rise 90 metres above lake level.

From Scarborough to Presqu'ile Point, the shoreline is dominated by mainly low bluffs of silty sand and boulder clay interspersed with beaches and marshes at the mouths of rivers and creeks outletting into Lake Ontario. The eastern shoreline from Prince Edward County to the St. Lawrence River consists primarily of erosion-resistant bedrock materials with sand beaches and sandy barriers with extensive marshes developing in some of the low-lying areas.

The southern shoreline of Lake Ontario within the State of New York generally consists of 5 to 20 metre high bluffs of glacial material frequently fronted by narrow gravel beaches which are subject to erosion from wave action. Low marshes are interspersed among the bluffs in several places. Within the Rochester and Irondequoit vicinity, the shoreline is quite marshy, with sand and gravel barrier beaches separating the marshes and open ponds from Lake Ontario. From Sodus Bay east to Port Ontario, the shoreline changes from a series of drumlins and dunes separated by marsh areas to rock outcroppings interrupted by only a few pockets of beaches and marshes at the inner ends of deep bays at the far eastern end of Lake Ontario.

g) St. Lawrence River Shoreline

From the Lake Ontario outlet to Cornwall, the shorelines of the St. Lawrence, as well as the many small islands located within the upper portion of the river, are comprised of generally non-erodible, bedrock features.

Between Cornwall and Montreal the St. Lawrence River widens to include Lac St. Francois downstream of Cornwall, Lac St. Louis upstream of Montreal and the Laprairie Basin adjacent to Montreal Harbour. Within this area the shoreline is generally low-lying (i.e., within 5 metres of the low water plane) and consists primarily of clay materials with till outcrops. Wetlands dominate the low-lying portions of the River, particularly in the Lac St. Francois area, with rock outcroppings altering the shoreline in the Montreal area.

A1.1.3 References

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INDEX - APPENDIX A1.1

ORIGIN AND PHYSICAL FEATURES OF THE GREAT LAKES

TECHNICAL GUIDE FOR
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APPENDIX A1.2

LAKE/LAND INTERACTION

LAKE/LAND INTERACTION

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A1.2 LAKE/LAND INTERACTION

The purpose of Appendix A1.2 is to provide an overview of the interactions occurring between lake and land features and the factors controlling these interactions. To complement the discussion of lake/land interactions, Appendix A1.2 reviews the effects of winds, waves and currents in controlling erosion, transport and deposition of sediments along the shoreline; the modifying effects of other factors such as ice and weathering; the sources of sediment supply to the shoreline; and concludes with a description of littoral cells, sediment budgets and shoreline sources and sinks. For more detailed descriptions, a number of textbooks on coastal geomorphology and coastal engineering listed in the bibliography supporting this Technical Guide should be consulted.

A1.2.1 Definition of the Shoreline Zone

Lake/land interactions generally occur in an area defined as the shoreline zone (Figure A1.2.1). This zone of interaction is normally divided into three distinct units:

- The **onshore** is the area landward of and generally beyond the limit of wave action by a particular water body. This may include shoreline bluffs, sand dune fields, wetlands, and areas subject to occasional inundation.

- The **backshore zone** extends from the landward limit of the nearshore to the point of development of vegetation or change in physiography (i.e., where the bluff or dune starts). The backshore zone is typically only affected during severe storms particularly at high water.

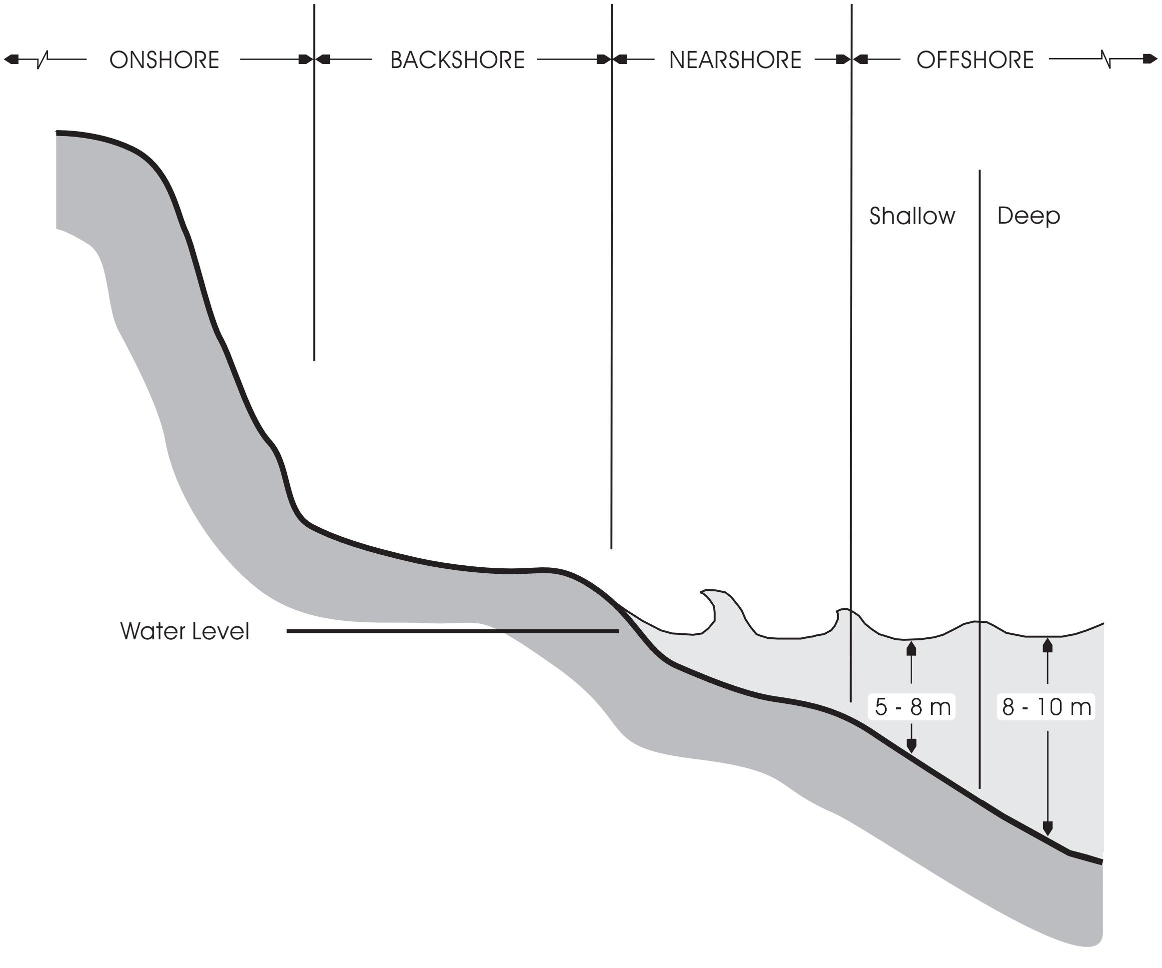
- The **nearshore zone** is an indefinite zone extending from just beyond the breakers zone to the landward limit of the swash zone or the landward limit of the foreshore zone. The swash zone is the portion of the nearshore zone in which the beach face is alternatively covered by the uprush of the wave swash and exposed by the backwash. The foreshore is the sloping portion of the beach profile lying between the berm crest, or in the absence of a berm crest, the upper limit of wave swash, and the lower limit of the backrush of wave swash. The term foreshore is often nearly synonymous with the beach face but is commonly more inclusive, containing also some of the flat portion of the beach profile below the beach face.

The littoral zone is composed of the backshore, nearshore and shallow offshore (i.e., 5-8 metres) which in total extends from the landward limit of storm wave action on a bluff or beach offshore to the maximum depth at which wave action can effectively transport sediment on the lakebed (i.e., roughly 5-8 metres in the Great Lakes).

The "shoreline" is generally defined as the intersection of the stillwater line with the land. Changes or movement of the "shoreline" lakeward or landward can be influenced by a number of factors. Primarily, the shoreline position is determined by the level of water with respect to the level of the adjacent land and by the erosion and accretion processes which occur.

Short-term (i.e., hours, days, years) changes in the position of the shoreline can occur as a result of water level fluctuations due to wind and wave action, to seasonal changes of net basin supply and to changes in net basin supply from abnormally high or low precipitation and evaporation. The resulting shoreline changes can be thought of as oscillations about a mean "shoreline" position. Over a longer period of time (i.e., tens of years to hundreds of years), submergence or emergence of a given shoreline can occur in response to "permanent" changes in water level resulting from post-glacial isostatic adjustments and to changes in the elevation or depth of the lake outlets. The ultimate influence of these "permanent changes" can lead to a landward or lakeward displacement of the shoreline. Finally, horizontal displacement of the shoreline may also occur as a result of net erosion or accretion of the shoreline. Erosion and accretion are littoral processes which primarily occur in the littoral zone, and it is

Figure A1.2.1: Definition of the Shoreline Zone



important to distinguish the effects of erosion and accretion from those associated with the short-term and long-term lake-level fluctuations.

Littoral processes are the result of interactions among winds, waves, currents, water levels, sediment supply and other phenomena in the littoral zone. The dominant processes leading to erosion, sediment transport and deposition within the littoral zone are associated with sediment supply, waves and wave-generated currents. These in turn control the resultant quantity movement of sediment alongshore and on-offshore. Modifications to these littoral processes can result from changes in sediment supply (i.e., protection of updrift bluffs, construction of harbour jetties), changes in lake levels and/or by the presence of ice during the winter months.

On erodible bedrock and cohesive shorelines, the material which comprises the controlling substrate (i.e., predominant material) of the nearshore lakebed is subject to irreversible downcutting (i.e., downwards erosion) and subsequent long term shoreline recession. On dynamic beach shorelines, the shoreline may either be eroding or accreting depending on the supply of sediments, wave action and water levels.

A1.2.2 Shoreline Characteristics and Evolution

Within the area of lake/land interaction, numerous physical and biological processes contribute to the existing characteristics and continue to shape the constant evolution of the *Great Lakes - St. Lawrence River System* shoreline. The interactions between and interdependency among the various components of the Great Lakes ecosystem are controlled by these physical and biological processes. Rather than being considered external forces, these processes, and even those which are human-related, need to be assessed and viewed as an essential part of any implementation option and/or strategy aimed toward effective and proper management shoreline ecosystem.

To understand and ultimately predict how different types of human actions may bring about change in the shoreline system, one must first understand the physical and biological processes influencing a given shoreline and their effects under existing natural and modified conditions. By so doing, one will enhance their ability to predict the potential environmental impacts associated with various human activities or actions within a comprehensive framework of the natural evolution of the *Great Lakes - St. Lawrence River System*.

A basic characteristic which controls the long term, large scale evolution of the *Great Lakes - St. Lawrence River System* shorelines is the controlling substrate. Controlling substrate is defined as the dominant underlying material which makes up the main body of the lakebed in the nearshore and the offshore. Along shorelines where the controlling substrate consists of bedrock (i.e., erodible or erosion resistant) or cohesive material (i.e., cobble/boulder till, fine-grained cohesive), there may also exist a surficial veneer of unconsolidated cohesionless sediment (i.e., sand, gravel, shingle, cobbles). The cohesionless sediment may even extend onshore appearing as a beach deposit. However, the volume of these surficial materials is insufficient or too transient to protect the underlying material from the wave action. Dynamic beach shorelines are composed of such deep sand and gravel deposits that any underlying bedrock or cohesive material is never exposed. Therefore, the dynamic beach material itself can be considered the controlling substrate.

a) Bedrock Shorelines

Bedrock shorelines are areas where the bedrock is at, or very near, the surface of the water. The profiles are generally devoid of sand and are characterized by shallow nearshore profiles. The resistance to erosion varies with the bedrock material. Nonerodible bedrock is bedrock material, such as Precambrian Shield rock that is very resistant to forces of erosion. Other softer bedrock material, such as shale, can be considered as erodible and acts in a similar manner as erosion resistant cohesive material, such as till with a high cobble/boulder content. Some additional factors causing erosion are wetting/drying and freezing/thawing processes.

b) Cohesive Shorelines

Cohesive shorelines mainly consist of cohesive materials such as silts and clays. The controlling process for the recession of a cohesive shoreline bluff is the downcutting, or downwards erosion, of the nearshore cohesive profile by the wave induced forces. The ongoing downcutting of the nearshore profile or lakebed eventually results in the toe of the shoreline bluff being undercut. When the bluff is sufficiently over-steepened it will collapse resulting in recession of the crest. If the backshore composition of the shoreline remains the same, cohesive shorelines recede without change in the shape of their profile. Even though the process is governed by the downward cutting of the nearshore bottom by wave action, the effect is a horizontal translation of the entire shoreline profile at the long term average bluff recession rate (see Figure A1.2.2).

In its simplest form, the downcutting process is a function of the erosion resistance of the nearshore materials and the erosive force of the wave action. As noted, the primary constituent parts of cohesive materials are very small particles of silts and clays. The internal strength of cohesive materials, which in turn provides their resistance to erosion, is derived from the cohesion between their constituent parts and from the consolidation resulting from any glacial action. After the wave action destroys the matrix that holds the cohesive materials together, the individual fine grains of silts and clays are too small on their own to remain in the breaking wave zone at the shoreline. The fine-grained materials are carried out in suspension to the offshore zone, by the waves and currents, where they settle out in the deeper water. Wave action effects at the bottom in deeper water is limited and most of the fine-grained material remains at the bottom. Thus the erosion or downcutting of the cohesive material is irreversible and ongoing. The remaining small volume of coarser materials, or beach materials (i.e., sand, gravel and cobbles which is large enough to remain in the breaking wave zone), is moved alongshore and cross-shore by the wave action. The coarser materials may form a thin veneer over the cohesive substrate, especially in the immediate nearshore and backshore areas. This manifests itself at the shoreline in the form of transient, narrow or even non-existent beaches. These narrow beaches may be particularly evident during the calmer summer months. However, along cohesive shorelines, the wave energy available to move beach materials exceeds the supply of beach materials from erosion of the shoreline. Therefore, the beach material can not accumulate in sufficient volumes to form a protective cover for the underlying cohesive substrate during storms.

Cohesive shoreline profiles in predominantly fine-grained material (i.e., high percentage of silts and clays with relatively low percentages of sand and gravel or cobbles) are characterized as distinctively concave (see Figure A1.2.3a). The constant concave profile shape over time indicates that the downcutting rate is the greatest at the shoreline and gets less towards the offshore. Concave shoreline profiles are characterized (Boyd 1981) by a steep slope of 1:50 in the first 100m, then a slope1:115 to 1:80 from 100 to 500m, followed by a flatter 1:285 to 1:145 slope.

The presence of erosion resistant tills (i.e., greater internal strength and/or high cobble and boulder content) in the nearshore will act to retard the downcutting process with a resultant profile which tends to be convex with a shelf developed in the nearshore (see Figure A1.2.3b). Erodible bedrock shorelines consist of softer rock materials, such as shale, and act in a manner similar to erosion resistant cohesive materials.

The presence of sand and gravel in the nearshore can also affect the downcutting rate. A limited amount of sand acts as an abrasive agent as it is moved across the cohesive material. A substantial volume of sand will cover and protect the underlying cohesive material. Figure A1.2.4 illustrates the role of the sand cover. Where the sand or gravel cover is very thick and stable, the frequency of exposure of the erosion susceptible substrate is reduced, and therefore the downcutting and shoreline recession rate will be lower (see Case A, Figure A1.2.4). As the sand and gravel cover is reduced, and the frequency of exposure of the underlying substrate is increased, downcutting will increase (see Case B, Figure A1.2.4). In the extreme case of no sand cover, laboratory research indicates that downcutting rates due to abrasion by the sand decrease (see Case C, Figure A1.2.4). Research work in understanding the actual process involved in erosion of a cohesive material and the development of procedures for predicting the rate of erosion is still ongoing (i.e., Ollerhead and Davidson-Arnott, 1993; Bishop et al.,1992;Nairn, 1992)

To summarize, the two major factors governing the cohesive and erodible bedrock shoreline forms are:

- the erosive forces of the waves; and
- the resistance of the natural cohesive shoreline materials including the effect of the sand/gravel cover.

Figure A1.2.2: Downcutting of Cohesive Nearshore Profile

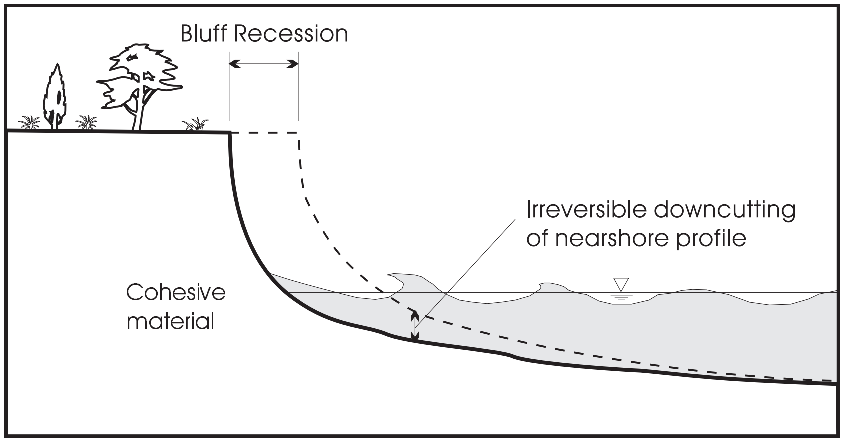
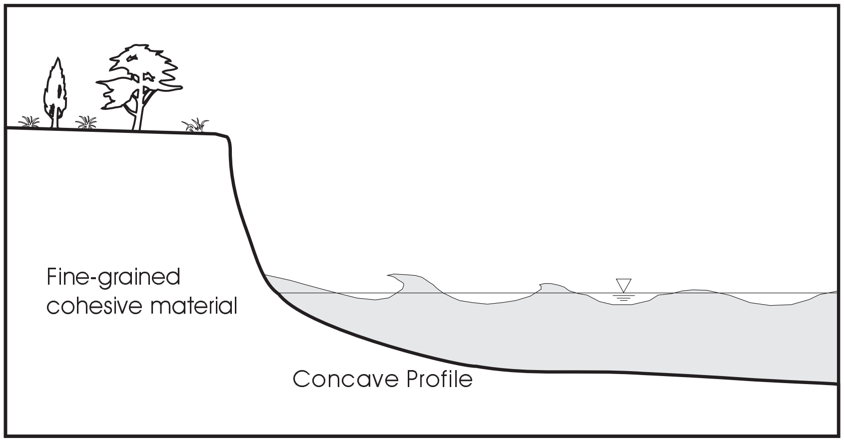


Figure A1.2.3: Typical Cohesive Nearshore Profile Shapes

a)



b)

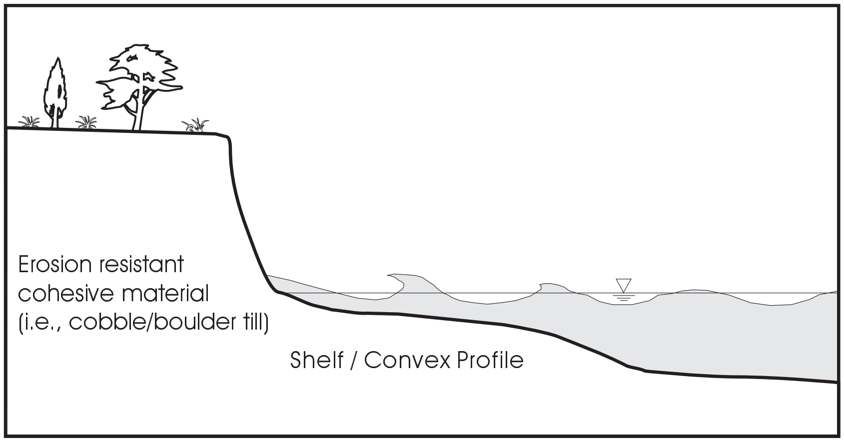
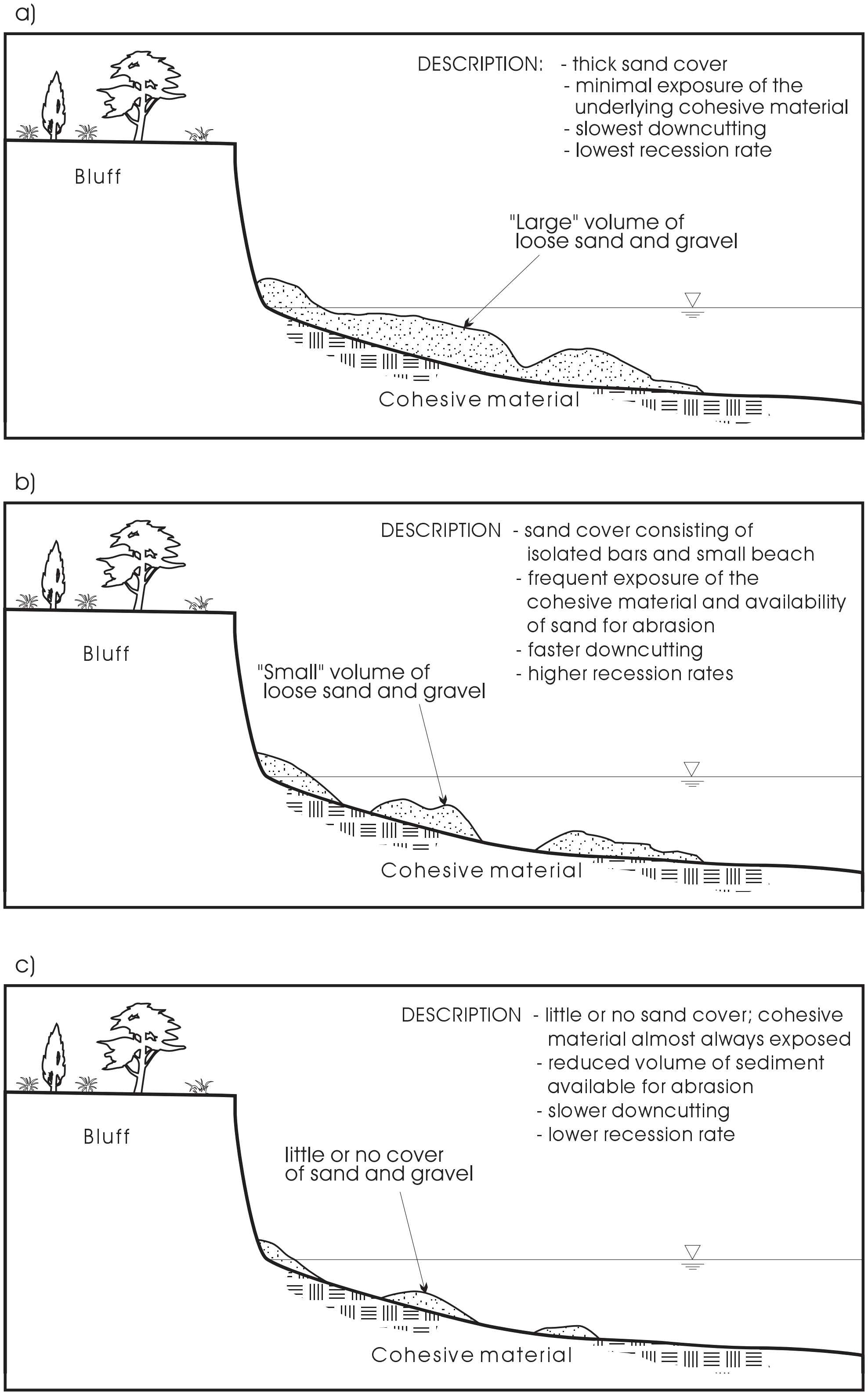


Figure A1.2.4: Cohesive Shores and the Role of Sand/Gravel Cover



a)

DESCRIPTION:
- thick sand cover
- minimal exposure of the underlying cohesive material
- slowest downcutting
- lowest recession rate

"Large" volume of loose sand and gravel

b)

DESCRIPTION
- sand cover consisting of isolated bars and small beach
- frequent exposure of the cohesive material and availability of sand for abrasion
- faster downcutting
- higher recession rates

"Small" volume of loose sand and gravel

c)

DESCRIPTION
- little or no sand cover; cohesive material almost always exposed
- reduced volume of sediment available for abrasion
- slower downcutting
- lower recession rate

little or no cover of sand and gravel

(after WRT, 1994)

c) Dynamic Beach Shorelines

Beach shorelines are simply extensive deposits of cohesionless materials, such as sands, gravel and cobbles, that have been transported and deposited by waves, currents and wind. The backshore can consist of a bluff but the bluff will not be subject to erosion from the lake and will likely be heavily vegetated. The beach may or may not be backed by a dune.

Generally, long term erosion of a beach occurs when the volume of beach sediment being supplied to the area is less than the volume of sediment being removed from the area. These long term changes are generally the result of changes in the alongshore transport. Areas of sand deposition, or accretion, occur where the shoreline orientation reduces the capacity of the waves to transport the sediment being supplied or at points where the transport is blocked by long piers or harbour entrance jetties. Accretion represents a net gain of material.

Beach shorelines can also alternately recede and accrete over the short-term due to changes in the wave climate and water levels. In these instances, beach material is temporarily eroded from the beach and deposited in the nearshore and will be returned to the beach over time (see Figure A1.2.5). This dynamic aspect of beaches can be considered separately from the long-term erosional effects. A discussion of the dynamic aspects of beaches is provided in this Technical Guide (Part 5: Dynamic Beach Hazard) and technical support documents (Beach/Dune Management Guideline (MNR 1996), Cross-Shore Profile Change Models Great Lakes - St. Lawrence River Shorelines Review and Typical Applications (Acqua 1995).

A1.2.3 Shoreline Processes

Continuous change in form and configuration of a shoreline results from the action of natural shoreline processes such as those related to erosion, transport and deposition of material in the nearshore or littoral zone. The primary agents of change are waves and currents. The impact that waves and currents impose on shoreline features are further influenced by water levels and wind action.

The following subsections provide an overview of the shoreline processes and their potential impacts on rates of shoreline erosion and recession.

a) Wind-Generated Waves

Waves are formed by a complex process of energy transfer from wind moving across a smooth water surface, through wind turbulence creating small waves or ripples and then from surface ripples to larger waves. This energy is carried by waves to the nearshore zone and serves as the primary energy source for shoreline changes. Wind-generated surface waves are a major factor in shoreline erosion, damage to shoreline structures, formation of depositional beach features and littoral transport. Waves generated by commercial and recreational boats (i.e., ship/boat wakes) may be a significant part of the total wave action in the connecting channels, contributing streams and small harbours and may also be responsible for erosion in these areas.

Waves are generally defined in terms of their height, period, wave length and direction of travel (see Figure A1.2.6). Wave height is the vertical distance between the top of the crest and the bottom of the preceding trough. Wave length is the horizontal distance between successive wave crests. Wave period is the time that it takes for successive crests or troughs to pass a fixed point. Within the wave, water particles move in a roughly circular orbit as the wave passes, with the diameter of the orbit at the surface being equal to the wave height. This orbital motion decreases exponentially with depth and is negligible below a depth equal to 1/2 of the wave length in deep

Figure A1.2.5: Beach - Dune System

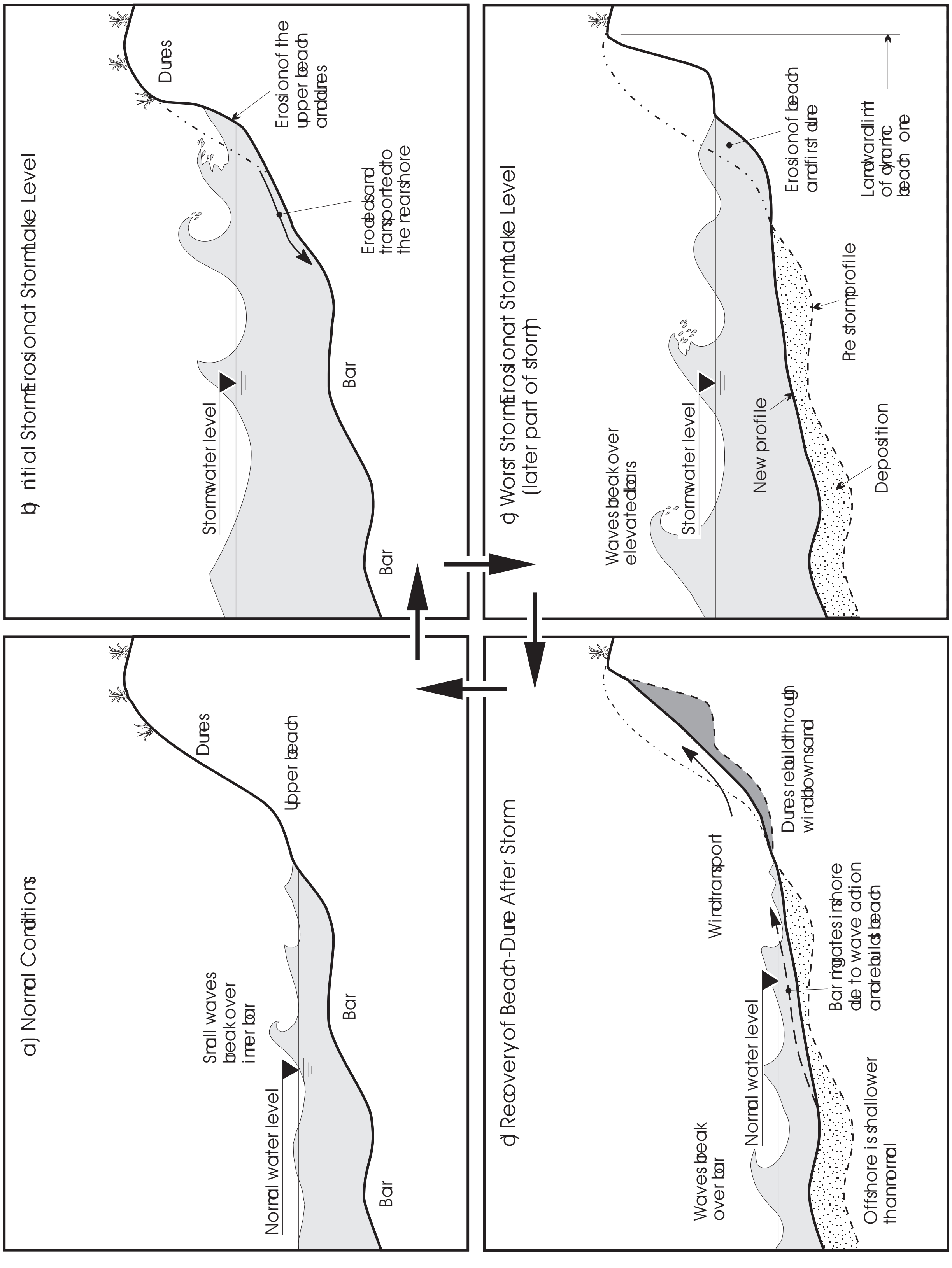
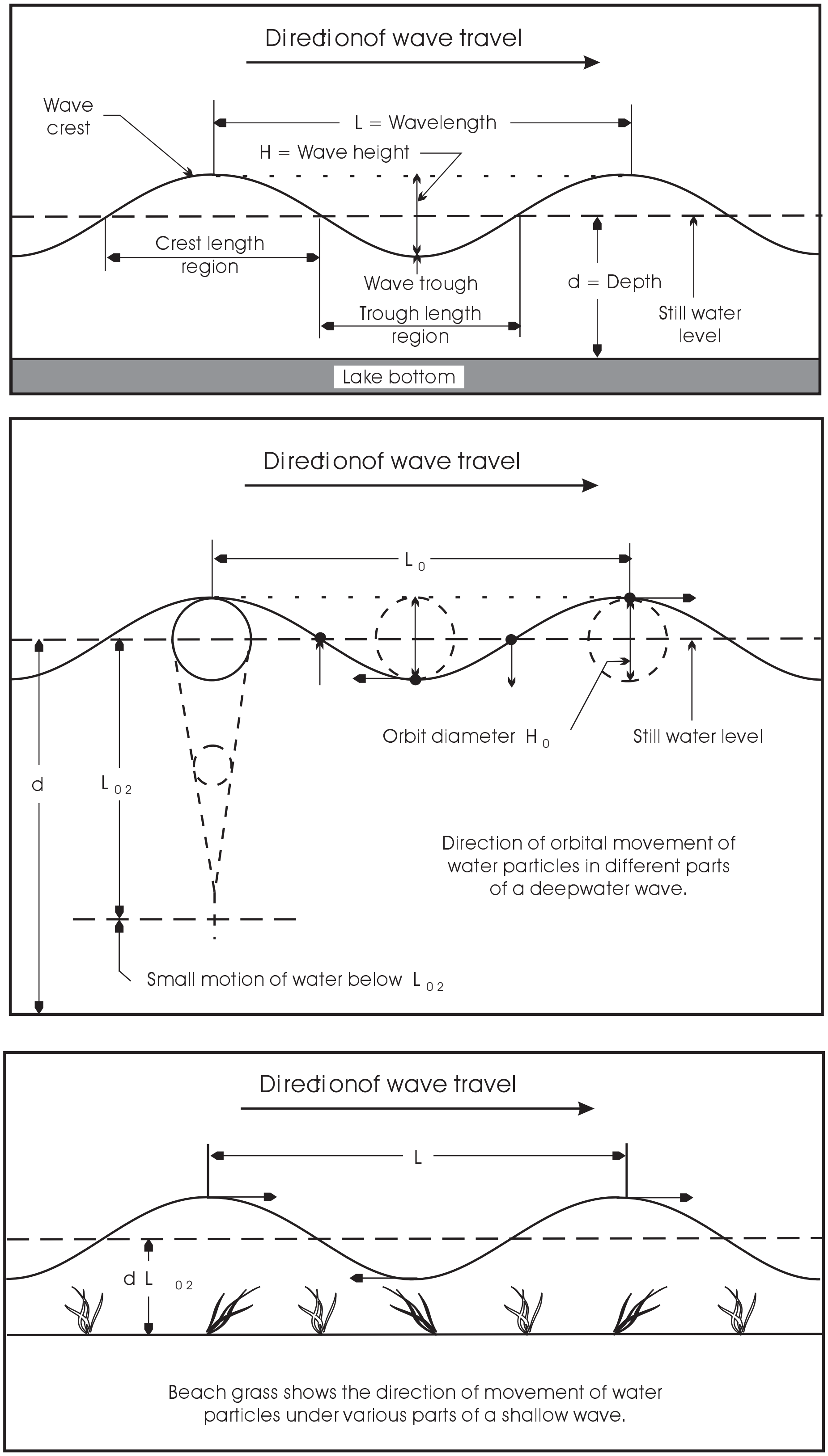


Figure A1.2.6: Wave Characteristics



water. The term deep water is then used for all conditions where the water depth is greater than this value, see Figure A1.2.6. In deep water the wave length is directly proportional to the wave period and can be determined from:

$$L_o = 1.56 \, x \, T^2$$

where:

T = wave period in seconds
L_o = deep-water wave length in metres

(Note: Deep-water conditions are indicated by the subscript $_o$.)

Waves generated by wind are termed progressive since they travel in the direction of the wind that generated them. The speed of an individual wave form is termed the celerity and is determined from:

$$C = \frac{L}{T}$$

and

$$C_o = \frac{L_o}{T} = 1.56 \, x \, T$$

where:

C = celerity in metres/second

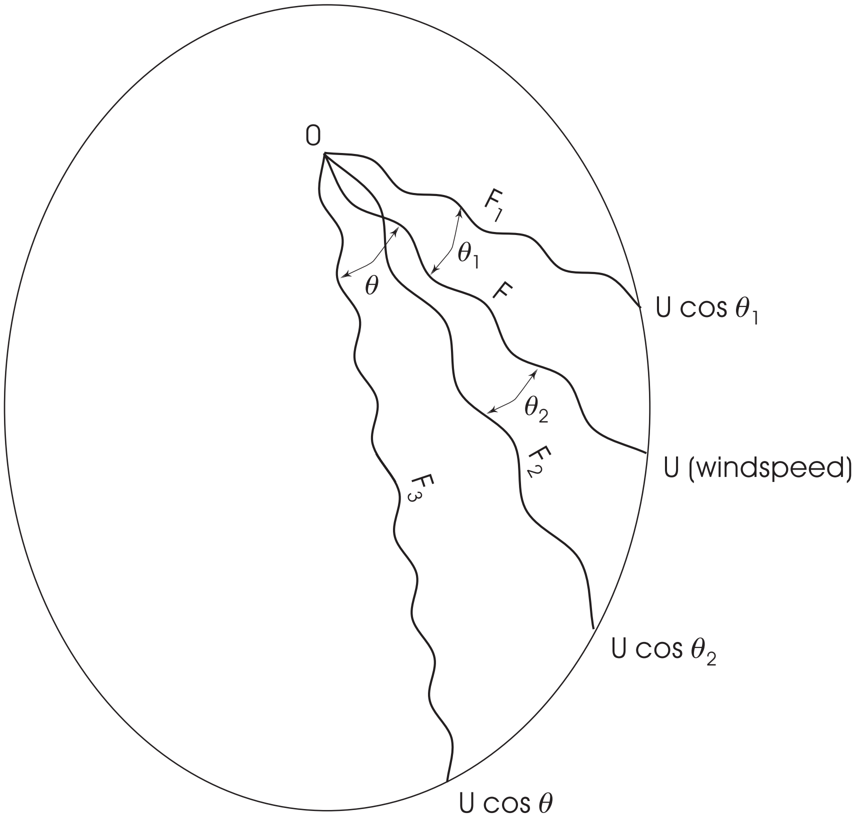
In summary, it can be seen that both wave length and wave celerity increase with increasing wave period. Energy in the wave is proportional to the square of the wave height and to the wave length.

Wave height and period, and thus wave length and celerity, generally increase with increasing wind speed, duration of wind, and with increased fetch length (i.e., the overwater length across which the wind blows). As such, at any given location along a shoreline, the largest waves that can reach the site are usually determined by the longest available fetch. For a given wind speed, there is a maximum wave height and period that can be generated assuming an unlimited fetch and unlimited duration. However, for a given wind speed the resultant wave height and period may be limited by either fetch, wind duration or water depth. Fetch and wind duration, separately or in combination, act to limit the length of time that energy is transmitted from the wind to the water surface. In the case of fetch length, since the wave is travelling in the direction of the generating wind, it may reach the opposite side of the lake before it attains its maximum size. In the Great Lakes, waves associated with intense storms seldom achieve the maximum conditions because the fetch lengths are generally too short. In shallow waters friction on the lakebed and increased wave breaking (i.e., white capping) act to reduce the maximum wave conditions.

Since wind speed and direction are not constant and since the wind continues to generate new waves over the whole length of the fetch, waves of many heights, lengths and periods are generated, resulting in what is commonly called irregular waves. Waves generated by the wind propagate over an arc up to about 45° on either side of the mean wind direction, although wave height decreases rapidly.

Further, it is often assumed that the direction of wave travel in deep water is the same as the wind direction. However, it has been shown that the angle of approach of the largest waves reaching a shoreline may differ by 30° or more from the wind direction in cases where the fetch length increases rapidly away from the direction of the prevailing wind, as can be the case with the elongate form of the Great Lakes. This occurs because the increase in height due to increased fetch length more than compensates for the decrease in height associated with the reduction in the effective wind speed (i.e., cosine of angle away from that of the wind direction, see Figure A1.2.7).

Figure A1.2.7: Schematic Diagram Showing the Effect of Fetch Length and Wind Angle on Wave Development



Plan view showing the combined effect of the effective wind speed, $U \cos \theta$, and the corresponding fetch, F, to the point of observation, O. Note that the rapid increase of fetch, F_2, more than offsets the reduction of effective wind speed so that the largest waves approach from the θ_2 direction.

For ease of description, the complex waves generated by winds are often represented by a single wave height and period.

b) Shoaling and Refraction

The process of shoaling results in significant changes in a number of wave properties as the wave moves into shallow water. Generally, the length and celerity of the wave decreases and the height increases. Some reduction in wave height may also result from energy loss caused by the roughness of the lake bottom in shallow water. This reduction in wave height becomes more significant on gently sloping shorelines where the distance over which the wave shoals is long. In shallow water, the orbital motion in the wave now reaches the bed. At the bed itself the water motion is horizontal, with landward movement under the wave crest and offshore motion under the wave trough. Above the bed the orbital motion becomes increasingly elliptical as water depth decreases. The maximum velocities at the bed increase as wave height increases and as depth is reduced.

By comparison, the process of wave refraction occurs as waves move from deep water into a shallower shoreline region, changing their direction as the wave crests attempt to align themselves parallel to the underwater depth contours (see Figure A.1.2.8). The degree of wave refraction depends on the wave length, water depth and nearshore bathymetry. In addition to changes in the wave direction and alignment to the shoreline, refraction may increase or decrease the wave height at shoreline locations through the concentration or spreading of wave energy.

A graphic description of the process of wave refraction, for explanatory purposes, is provided in Figure A1.2.8. Within this graphic, orthogonals are shown as lines drawn perpendicular to the wave crest at all points. In deep water the orthogonals are equally spaced and thus the wave energy between the orthogonals is also equal. As waves approach the shoreline and the wave crests bend to conform more closely to the underwater contours the orthogonals are concentrated on headland areas and spread out in the bays. If one assumes that energy remains constant between orthogonals then it can be seen that wave energy, and hence wave height, is greatest at the headlands and smallest in the bays.

In summary, wave refraction is a very important consideration in assessing the effects of wave action on the shoreline as opposed to assessing its impact in deep water. Refraction and shoaling, separately or in combination influence the erosion and deposition patterns of materials along the shoreline, and therefore the development of shoreline forms.

c) Wave Diffraction

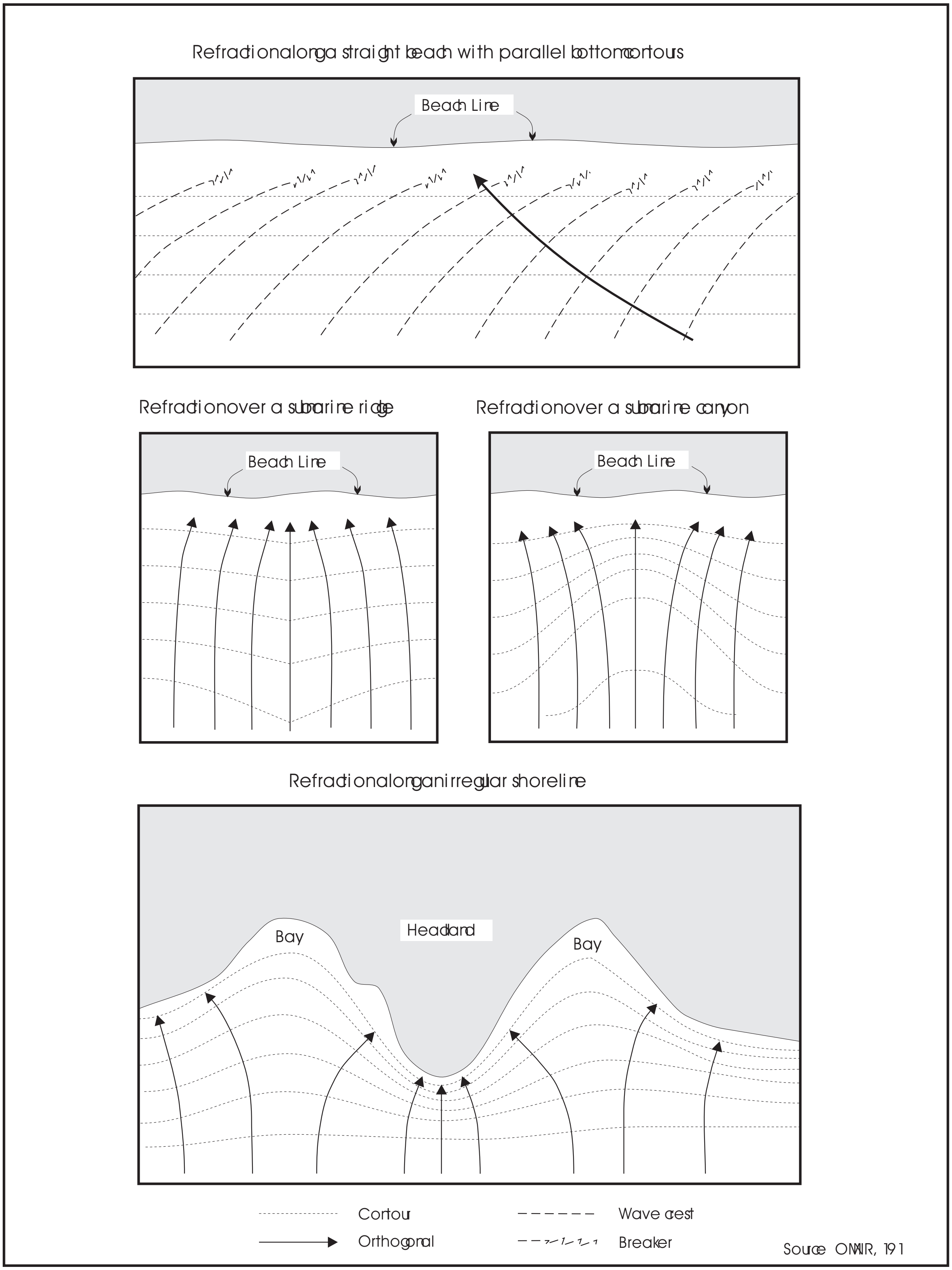
The process of wave diffraction basically involves a lateral transfer of wave energy along the wave crest. Diffraction is particularly important around structures such as harbour breakwalls and groynes and can be an important controlling factor on the deposition of material transported by nearshore currents.

Beyond the influence of wave diffraction on nearshore and offshore structures, wave diffraction may also influence shorelines considered protected by headland features. Although headlands do provide shelter from wave action, waves do bend, to a limited extent, and do transport their energy onto shorelines in the lee of or sheltered by a headland. For this reason, the potential impact of wave diffraction along headland protected embayments and shorelines may warrant assessment.

d) Breaking Waves

The depth at which a wave breaks, and the form of the breaking wave, are determined by the wave height and period, the water depth and the slope of the bottom. For example, in deep water, waves break (i.e., white-capping) when the wave height becomes too large relative to the wave length (i.e., the wave becomes "too steep"). In shallow water, waves break as a result of the limiting water depth.

Figure A1.2.8: Wave Refraction on Simple and Complex Shorelines



Source OMNR, 191

The depth of water shallow enough to initiate breaking of a wave is defined as the breaking depth, d_b, while the height of the breaking wave is defined as H_b. As a simple guide, waves will break when:

$$\frac{H_b}{d_b} = 0.78$$

or when the water depth is just slightly greater than the wave height.

Depending on the wave height and nearshore slope, waves may break:

- some distance offshore, forming a surf zone over which wave energy is dissipated and wave heights are greatly reduced before they reach the shoreline;
- on the beach, with energy being dissipated in the swash and backwash; and
- where there is relatively deep water close to the shoreline, such as on some rocky or bluff shorelines, directly against the toe.

Different scenarios for wave breaking are shown in Figure A1.2.9.

Turbulence produced by wave breaking can lead to suspension of sand and finer sediments and to the erosion of the beach and nearshore profile on cohesive shorelines.

When waves break at the shoreline, or when a wave that has already broken reaches the shoreline, the forward momentum of the wave results in wave uprush, or runup of the water, in the wave form onto the beach and backshore area. As such, this wave uprush ,or runup, extends the effects of the waves both inland and to higher elevations than the shoreline. The factors controlling the maximum elevation and inland distance of wave uprush depends on the height and period of the wave as well as on the width and slope of the beach and backshore. Detailed explanations of wave uprush and the methods for calculating wave uprush are provided in this Technical Guide (Part 3: Flooding Hazard) and technical support documents (Wave Uprush and Overtopping: Methodologies and Applications (Atria, 1997)).

e) Nearshore Currents

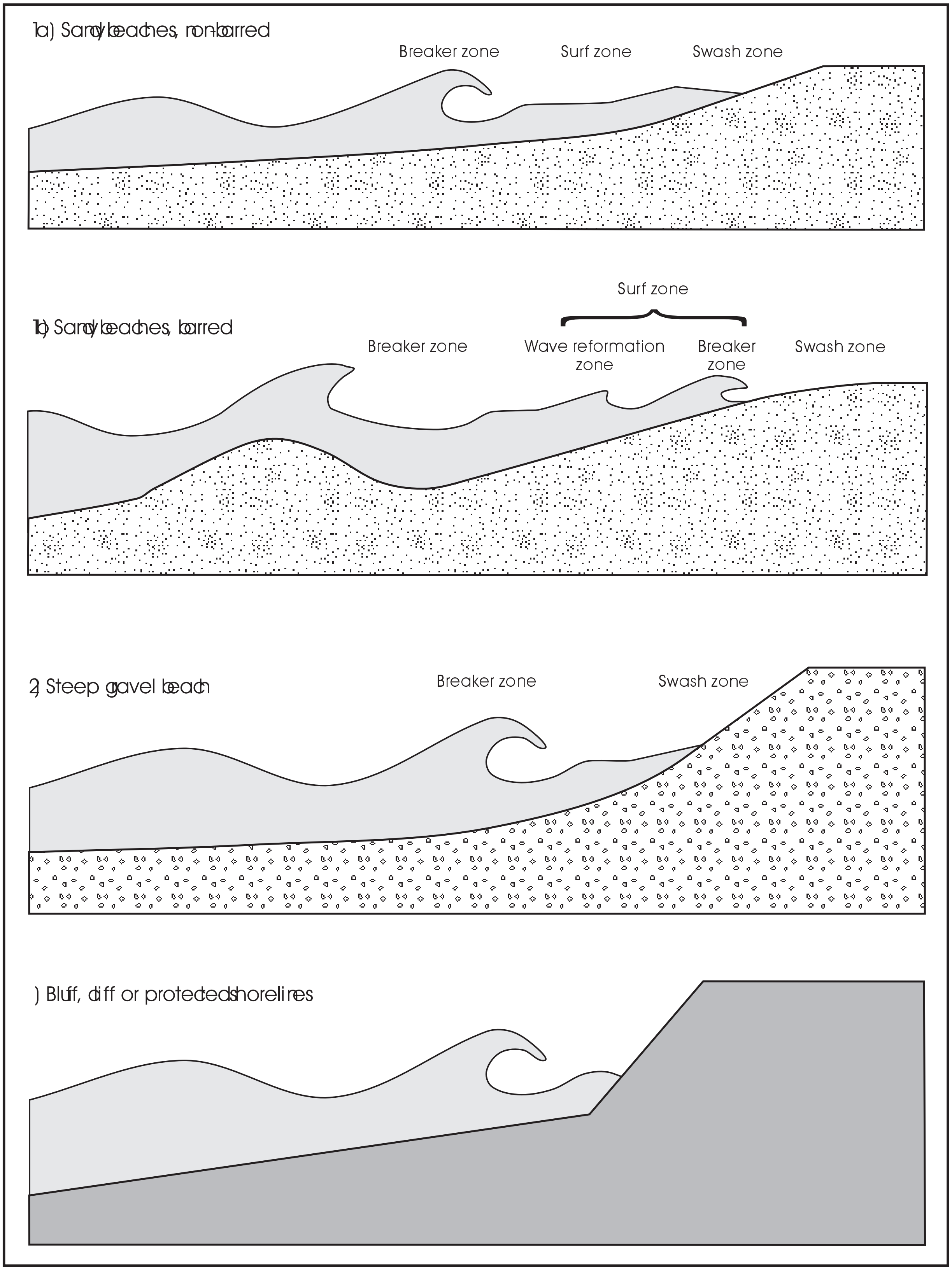
Currents in the Great Lakes occur as a result of the earth's rotation, the inflow and outflow of water within the *Great Lakes - St. Lawrence River System*, wind blowing over the surface of the lakes and, at the shoreline, the process of wave breaking. Lake currents vary from lake to lake and location to location and can be influenced by factors such as the direction of flow through the Lakes and the direction of the predominant or prevailing winds.

Nearshore currents in the littoral zone are predominantly wind and wave-induced motions (i.e., alongshore currents and rip currents) superimposed on the wave-induced oscillatory motion of the water (i.e., mass transport or shore-directed currents).

Alongshore currents flow parallel to the shoreline and are restricted mainly between the zone of breaking waves and the shoreline. Most alongshore currents are generated by the alongshore component of motion in waves that obliquely approach the shoreline. However, waves approaching parallel to the beach will also generate a current from areas of higher wave height to areas of lower wave height. Wind-generated currents can also be important in the nearshore.

In the idealized deep-water waves (i.e., linear waves, see Figure A1.2.6) water particles move in closed orbital paths. As the paths are closed (i.e., the particle returns to its starting point), linear theory does not predict any mass transport. In depths where waves are affected by the bottom, the circular orbit becomes elliptical. In shallower water, the ellipses elongate into nearly straight lines, but with linear theory the orbits are still closed.

Figure A1.2.9: Scenarios for Wave Breaking



However, in reality linear theory is not entirely correct and in general the water particle orbits are not closed. This is particularly true in shallow water where linear theory is really not applicable and water particle motion becomes more complicated. In shallow water, there is net movement of water in the direction of wave propagation, known as mass transport.

Other significant currents in the nearshore zone can be those generated by the momentum of the waves themselves. The momentum and excess water mass carried into the surf zone by breaking waves results in the set-up of water close to the shoreline. This in turn drives an offshore return flow which may occur either as a uniform "undertow" at mid-depth (see Figure A1.2.10, "two-dimensional"), or as a more complex three-dimensional rip cell (see Figure A1.2.10, "three-dimensional").

f) Erosion by Waves

Wherever consolidated material such as bedrock or cohesive material is exposed to wave action, erosion of the nearshore and backshore profile may take place as a result of fluid stresses generated by the wave orbital motion, turbulence due to wave breaking and the direct impact pressures generated by waves breaking at the toe of the bluff. Where sediments are present on the bed, much of the erosion can take place as a result of abrasion by the impact of particles being rolled across or hurled against the underlying substrate. Along shorelines composed of relatively weak materials such as glacial till, wave action can result in recession rates of many tens of centimetres per year, while in areas of resistant rock such as granite, recession rates may be measured in millimetres per thousand years. Recession is the landward retreat of the shoreline by erosion of the shoreline material. As noted earlier, along bedrock and cohesive shorelines, the erosion is irreversible.

A detailed explanation of erosion is provided in this Technical Guide (Part 4: Erosion Hazard) and technical support documents (Geotechnical Principles for Stable Slopes, Terraprobe, 1997).

g) Sediment Transport

Wave orbital motion and wave-generated currents are the primary processes resulting in sediment erosion, transport and deposition in the beach and nearshore zone. As waves shoal and break, the intensity of wave orbital motion on the bed increases, setting sediment in motion across the bed, and ultimately leading to the suspension of the finer sediment. The presence of any nearshore currents superimposed on this oscillatory motion then results in net transport of the sediment in the direction of the nearshore current flow, whether onshore-offshore or alongshore. Sediments present in the nearshore and on the beach can be transported onshore-offshore and/or alongshore by waves and currents as soon as these exceed the speeds necessary to set the particles in motion. Sediments are set in motion at the bed by the oscillatory motion associated with the passage of each wave, by turbulence associated with wave breaking and by the action of swash and backwash on the beach.

Once in motion the sediments may be transported onshore or offshore as a result of direct currents associated with the waves, currents resulting from nearshore circulation, wind driven currents or from the flow of water in connecting channels. Alternatively, sediments are transported alongshore when waves approach at an angle to the shoreline and a portion of the momentum of the breaking waves is directed alongshore resulting in the generation of alongshore currents in the direction of wave approach. These alongshore currents, together with beach drifting on the swash slope, are the primary influences responsible for the transport of sediment alongshore (Figure A1.2.11).

Ice can also be a factor in sediment transport and is discussed in a later section.

h) Wind and Wave Climate

The wave energy (i.e., wave height and period) reaching a given point on the shoreline is determined by the wind climate (i.e., hourly wind speed and direction), by the fetch lengths in each direction, and by the effect of limiting factors such as winter ice cover on the lakes which tends to restrict wave generation.

Figure A1.2.10: Two and Three-Dimensional Nearshore Current Patterns

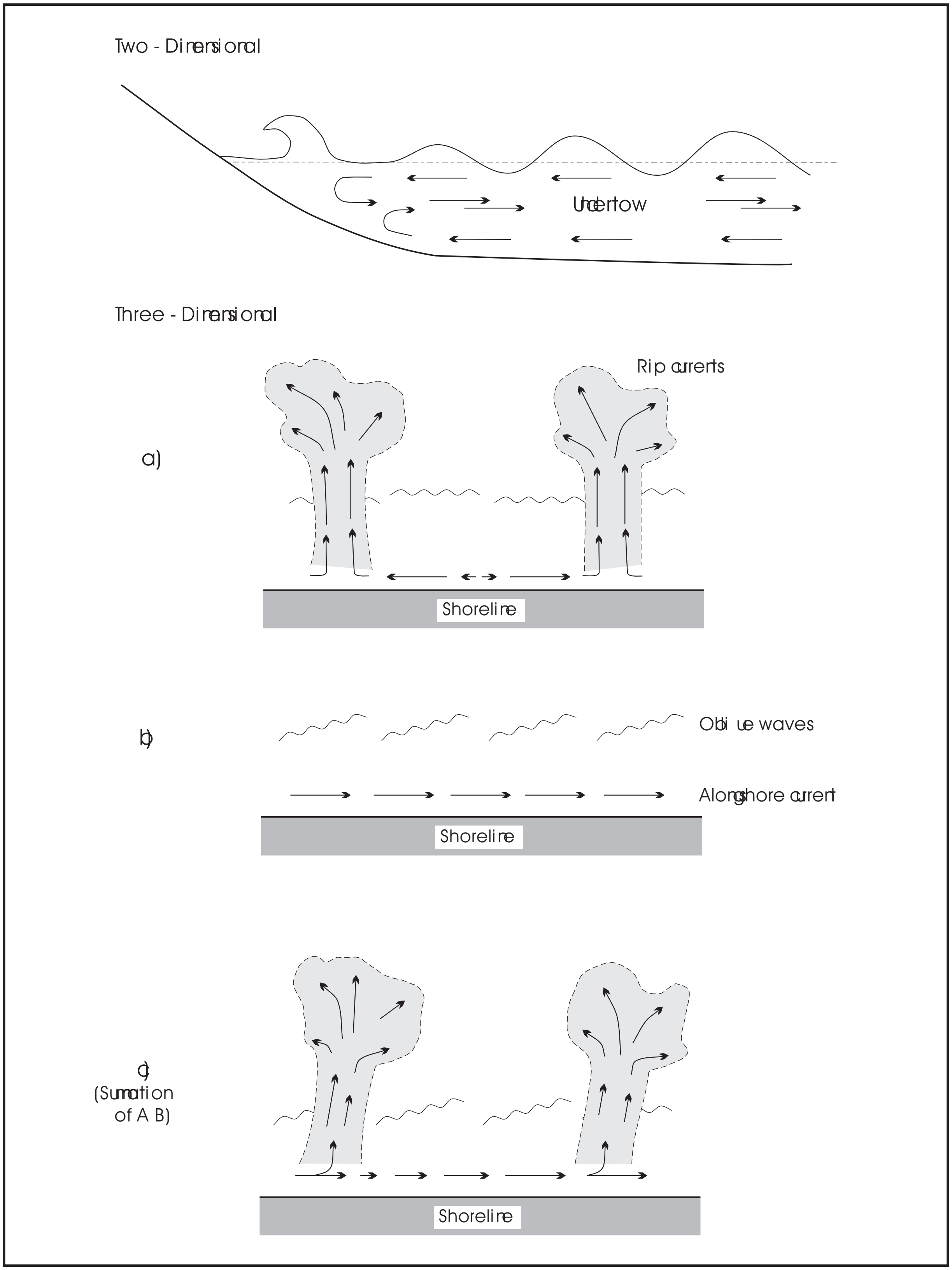
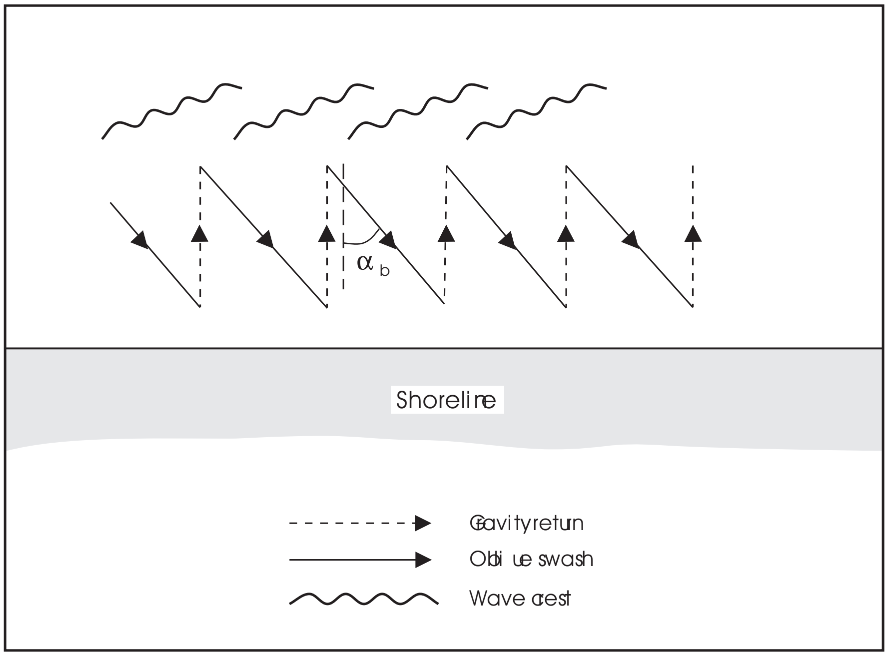
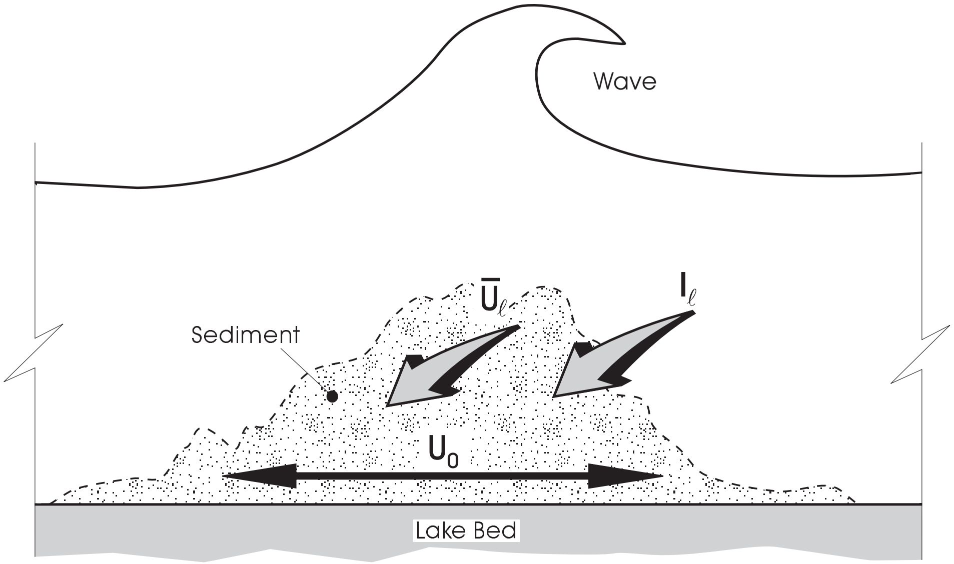


Figure A1.2.11: Models of Alongshore Sediment Transport



a) Beach Drift (planview)



b) Alongshore Transport in Surf Zone (profile view)

Modes of alongshore transport of sediment. a) Beach drift resulting from zig-zag motion of sediment along the swash slope. Sediment moves upslope under the swash at the angle of wave approach and the return flow is nearly perpendicular to the slope under the influence of gravity; b) Alongshore transport in the surf zone where the sediment is set in motion by the orbital velocity of the waves U_o and the alongshore current $\bar{U}_\ell$ provides a net transport of sediment I_ℓ in the direction of $\bar{U}_\ell$.

(after Komar, 1976)

Wave heights and periods can vary hourly depending on the wind conditions. Therefore, typically the wave climate can be specified as the average conditions over a specified period and direction. The average conditions at a given location can be defined as the average annual hourly frequency of waves of different classes (i.e., defined by height, period, and direction). The average is determined based on measured or estimated conditions over a longer period (i.e., 10 or 20 years). The resulting wave climate is often presented as average conditions by direction (i.e., 8 or 16 points of the compass) and by month or season (i.e., summer, fall, winter and spring).

In general, sections of shoreline that are exposed to long fetches in the direction of the predominant winds are likely to experience high wave energy on a frequent basis. Conversely, shorelines that are sheltered from waves from the predominant wind directions and from the severe storm wind direction are likely to experience much lower energy conditions.

The offshore wave climate can be defined for a point in deep water just offshore of a given shoreline location or stretch of shoreline. Using historical wind records and measured fetch lengths it is possible to hindcast, the opposite of forecast, a wave climate for any given location of stretch of shoreline. Studies commissioned by the Ministry of Natural Resources have generated the wave hindcasts for each of the Great Lakes (MNR 1988).

The nearshore wave climate for a specific location can be determined from the offshore wave climate after the effects of wave refraction, diffraction and shoaling are taken into account (see Sections A.1.2.3(b) and (c)). The total wave energy reaching a given location or stretch of shoreline can be expected to exert some control on the potential rates of erosion of rocky and cohesive shorelines, while the magnitude and direction of the net alongshore component of wave energy controls the patterns of littoral sediment transport and potential rates of sediment transport. These in turn are an important control on the sediment budget of beaches (see discussion under Section A1.2.5(a)(ii)).

i) Wind

Wind action has a strong indirect influence on beach dynamics through its control on the wave climate and related wind setup effects. In addition, wind-driven currents in the lake influence sediment transport patterns, particularly the offshore transport of fine sands.

Wind action, as a direct influence on the beach change, is generally defined in terms of aeolian sediment transport. On sandy beaches, onshore winds transport sand landward where it may be trapped by vegetation, leading to the formation of naturally protective shoreline dunes. The development, maintenance and expansion of dune complexes depend in part on the wind climate and in part on the beach width and availability of sediment for transport.

j) Water Levels

Changes in water levels occur as a result of long-term and short-term factors. Long-term factors generally include precipitation, inflow to the Great Lakes, which is dependent on precipitation, outflow from the Great Lakes, evaporation, and to a slight degree by isostatic adjustments to the earth's crust. Short-term factors generally include oscillations caused either by the wind blowing over the lake for several hours or by atmospheric pressure changes.

Seasonal and long-term changes in Great Lakes levels result from variations in the amount of precipitation, evaporation, runoff, storage capacity of the Great Lakes and the discharge characteristics of the connecting channels, including the effects of ice. Long-term changes in levels can be considered random, although it is possible to distinguish cycles of varying lengths from 7-30 years in historic records over the past century. Seasonal changes follow an annual cycle with peaks in the late spring or early summer and lows in the late fall or winter. Due to the size of the Great Lakes and the relatively small discharge capacities of their outflow rivers, extreme high or low lake levels normally exist for some time after the climatological factors which caused them. Historical records of long-term variations, dating back to the late 1800's, show variations in monthly mean levels over a range of 1.2 metres on Lake Superior and about 2 metres on all of the other Great Lakes.

Short-term fluctuations are generally produced by the influence of the wind and by changes in atmospheric pressure. Atmospheric pressure differences between the opposite sides or ends of lakes can produce fluctuations in water levels amounting to 0.2 m in height. The main cause of short-term lake-level fluctuations is strong winds. When winds continue to blow over the lake surface in one direction for a number of hours, an increase in the water level against the downwind shoreline is produced, referred to as "wind setup" or "storm surge" (Figure A1.2.12a).

A similar "wind setdown" is produced at the upwind end of the lake. For a given wind speed and duration, the setup increases with decreased water depth and nearshore slope. The main control is the rate at which water can move back offshore close to the bed, and this is retarded by bottom friction on shallow, gently sloping shorelines.
In the Great Lakes, the greatest impact of wind-induced water levels is experienced at the western and eastern ends of Lake Erie, where short-term changes in water levels can exceed 2 m (Figure A1.2.12b). Given that Lake Erie is relatively shallow and is oriented in an east-west direction parallel to the prevailing westerly winds, Lake Erie is subject to these short-term fluctuations more frequently than the other Great Lakes. Wind setups which may reasonably be expected at typical mid-lake shoreline locations are in the order of about 0.5 metres.

Another phenomena influencing lake levels within the *Great Lakes - St. Lawrence River System* is known as seiche effect. Factors influencing or causing seiche effect and in turn lake levels include both atmospheric pressure and wind-induced water level changes. The return flow of water from the end with an elevated level to the depressed end can result in oscillations of lake levels similar to the sloshing action that occurs in an enclosed tank of water. As such, during seiche effect any given shoreline location may experience alternate periods of elevated and depressed levels over a period of several hours with the initial seiche levels being at much lower elevations than the original wind setup.

In addition to the natural factors, various artificial changes have been made in this century that have had an influence on the levels and flows along the *Great Lakes - St. Lawrence River System*. The most significant projects for managing the lake levels are the Lake Superior and Lake Ontario control structures. Regulation of outflows and levels of Lake Superior was initiated in the early 1900's. Control is achieved by a control structure and hydroelectric plant in the St. Mary's River at Sault Ste. Marie. The outflows and levels of Lake Ontario have been regulated since the completion of the St. Lawrence Seaway and Power project in 1958. The main structure that governs the lake's level is the Moses-Saunders power dam across the St. Lawrence River at Cornwall. The objective of the regulation is to balance the interests on Lake Ontario with those downstream on the St. Lawrence River and at Montreal.

Five diversions have been constructed in the Great Lakes basin. Two of these, Long Lac and Ogoki Diversions, divert some of the tributary flow of the Hudson Bay southward in to the Lake Superior basin. These diversions raise water levels of the Great Lakes by minor amounts.

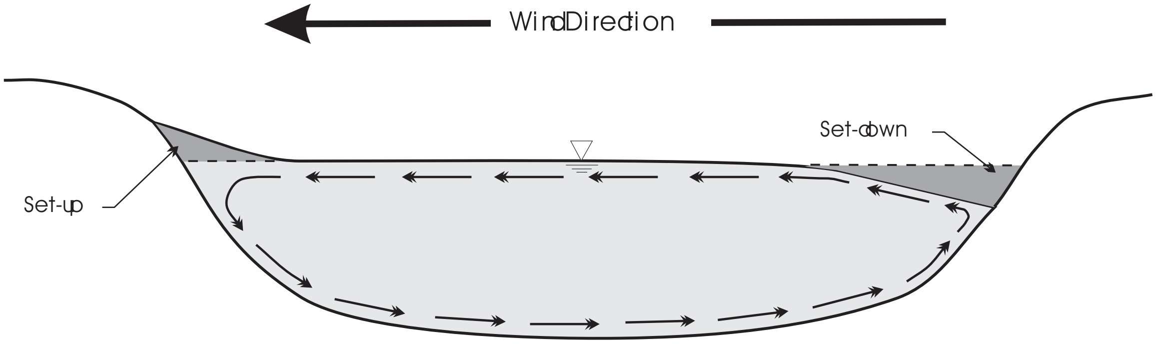
The diversion of water through Sanitary and Ship Canal at Chicago from the *Great Lakes - St. Lawrence River System* to the Mississippi River is for purposes of sanitation, navigation and hydro-electric production. This diversion lowers water levels of the Great Lakes, except Lake Superior, by minor amounts.

The other two diversions, the Welland Canal and the New York State Barge Canal, are interbasinal. These have no overall effect on the *Great Lakes - St. Lawrence River System*, but the Welland Canal lowers the water levels of Lakes Erie and Michigan-Huron.

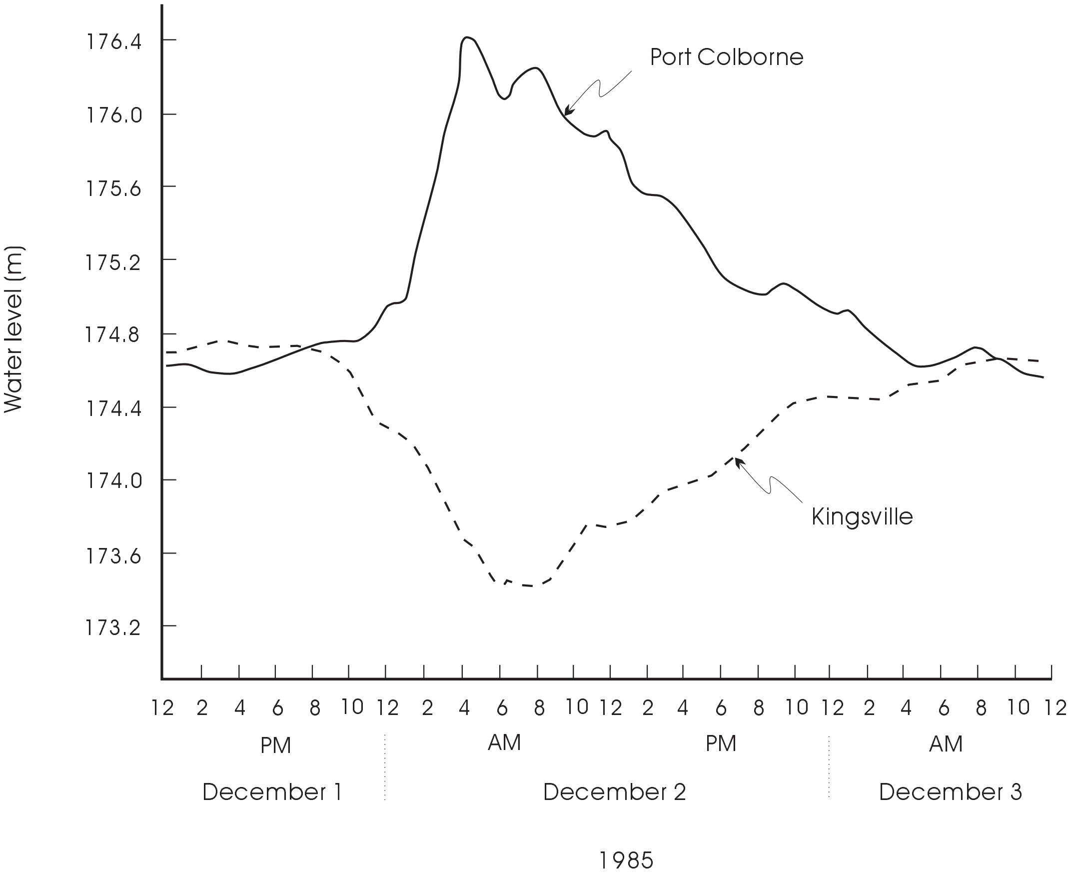
Channel modifications have been undertaken in the St. Clair - Detroit River system and have resulted in a lowering of Lakes Michigan - Huron by minor amounts. Channel and shoreline modifications have also been carried out in the Niagara River which have restricted the flow. This has resulted in a very minor increase in Lake Erie water levels.

Figure A1.2.12: Wind Setup

a) Wind Setup at the Shoreline



b) Wind Setup on Lake Erie



The controls, diversions and modifications have a net accumulated impact on the Great Lakes that is measured in centimetres and do not, therefore, constitute major factors in the natural system. The estimated accumulated impacts are as follows:

Lake	Impact on Water Levels
Superior	9 cm increase
Michigan-Huron	33 cm decrease
Erie	3 cm increase
Ontario	6 cm decrease

It is unlikely that many areas of the Great Lakes shoreline will ever experience truly stable water levels because of the magnitude of the natural fluctuations associated with seasonal variations in runoff and evaporation and the short-term fluctuations created by winds and barometric pressure changes. Further discussion of water levels is provided later in this Technical Guide (Part 3: Flooding Hazards).

In terms of the lake/land interaction, the water level elevation determines the portion of the nearshore zone over which breaking waves expend their energy. During periods of elevated lake levels, a portion of the wave energy may reach the toe of bluffs or sand dunes, and some washover of low-lying beach areas may occur. It is during these events that rapid erosion of the bluffs and dunes occurs. Some of the wave energy during these events is dissipated on the nearshore lake bottom, causing underwater erosion as well. Nearshore erosion tends to be controlled primarily by storm wave action and is weakly correlated with long-term lake level fluctuations. Toe erosion of bluffs and erosion of dunes is greatest during long-term high lake levels and is reduced during long-term low lake levels. However, during extended periods of relatively constant levels, whether high, average or low, erosion rates approach that of the long-term average.

As water levels change in response to seasonal and long-term changes in supply, sediments on the beach and nearshore profile adjust to maintain an equilibrium form and position. Often, however, there is a lag between the change in water level and the response of the profile to this change due to a lack of or limited number of storm events. Recognizing this, during a period of rising water levels, landward movement of sediment in the nearshore zone may lag behind the water level change, resulting in a temporary decrease in the degree of protection afforded by the beach. Similarly, during falling lake levels there may be a temporary increase in the beach width. When lake levels stabilize, the beach width adjusts to the equilibrium position within a period of months.

A1.2.4 Other Physical, Biological or Human-Related Processes

Aside from the shoreline processes described in Section A1.2.3, there are a number of other important physical processes acting in the coastal zone that are not shoreline processes per se, yet they can influence erosion and recession of the shoreline. These are briefly described and include the following physical, biological or human-related processes.

a) Groundwater

In bluff areas the presence and movement of groundwater can be a major factor in the erosion processes. Many bluffs consist of layers of different types of material of varying thicknesses and permeability. The ability of surface water to flow or infiltrate vertically downward through the bluff structure depends on the types of material from which it is composed. For example, water passes quickly and easily through a layer of sand, but if the sand is underlain by a layer of impervious clay, then the vertical movement of groundwater is halted and the groundwater then moves horizontally along the sand-clay boundary to the bluff face. The groundwater then exits through the face of the bluff at the sand-clay boundary and runs down the bluff face causing erosion of the sand layer, the bluff face, and over time, leads to the landward recession of the bluff.

The presence of groundwater in a bluff reduces its ability to resist collapse or bluff failure. This is due to the lubricating effect that a high water content has on the soil. A collapse or bluff failure of this type is most likely to occur when the soil is saturated with water. Soil saturation may be caused by natural influences such as in the spring snowmelt period or after an extended period of heavy rain, or by human-related structures or activities, such as a leaking swimming pool.

b) Surface Water

The flow of surface water down the face of a bluff can lead to erosion of a bluff face and ultimately to varying degrees of bluff failure or collapse. Frequently, concentration of surface water flows on a given shoreline bluff feature leads to the formation of gullies along the bluff face. As a gully grows, it may become the route for surface water drainage from an increasing tableland area, thereby increasing both the volume of water flow and the rates of gully growth. The creation of tableland water drainage networks, such as field tiles or drainage ditches, are typically the forms of surface water concentration that have led to the formation and growth of shoreline gullies.

c) Ice

The formation of ice during winter months affects shoreline processes in all the Great Lakes in two ways. The formation of shorefast ice, in combination with an "ice foot", protects the shoreline area, landward of the ice, from wave action even when the main body of the lake is ice free. As ice forms first along the shoreline, shorefast ice often persists for several days or weeks after ice on the main water body has melted, protecting the shoreline feature well after the ice has melted from the main body of the lake. However, local scouring can result from waves breaking directly against the ice foot, and sediments incorporated in the ice may be transported and deposited offshore.

The second main form of ice, that being ice formed within the greater water body, has the effect of reducing wave generation during the winter months and as such, reduces the potential erosion and the volume of sediment transport.

During the spring months, as the ice begins to breakup, ice jams, ice piling or ridging may result in flooding or erosion problems along the shoreline and particularly at the outlets of lakes into their connecting channels. Along a river or connecting channel ice breakup occurs as the channel snow and ice cover melts. As the melting process continues, water flows in the channel increase, water levels rise, fracturing the ice cover, and ultimately leading to the formation of ice floes.

During spring breakup, ice becomes detached from the shoreline (i.e., ice floe) and may be further broken up by the actions of winds and currents. Ice detached from the shoreline or lake ice that is piled up by wind action against the shoreline can often scour sections of the beach and nearshore as well as damage and destroy structures close to shoreline. It can also remove boulders from the shallow areas, reducing their protective effect, particularly along cohesive bluff shorelines.

Ice conditions on the Great Lakes and connecting channels can vary significantly from year to year and with location within the system. During maximum ice extent in an average year, the median ice concentration across the Great Lakes systems varies from 90% for Erie, 75% for Superior, 68% for Huron, to 24% for Lake Ontario. With respect to location within the system, the rapid decline in ice cover associated with spring breakup occurs during the first half of March on Lake Ontario, during the last half of March on Lake Erie, and during the first half of April on Lakes Superior and Huron. In some years ice can even persist into early May in Georgian Bay and parts of Lake Superior.

d) Weathering

Two typical forms of weathering along Great Lake shorelines are physical weathering, such as a repeated freezing and thawing action within the shoreline structure itself, and chemical weathering, involving a breakdown of the chemical structure or strength of a shoreline bluff or feature.

During the winter months, repeated freezing and thawing of soils within the bluff face reduces the strength of the soil and makes it more prone to erosion from surface and groundwater flows. This process is most prevalent on bluffs with a southerly exposure, where the sun's rays are concentrated on the bluff face and thawing may occur. Then alternately, when the air temperature falls several degrees below freezing, either during the night hours or during days with little or no sunshine, the moisture within the soil structure on the bluff face again freezes.

Similarly, a reduction in the strength of cohesive and over-consolidated bluff sediments can be caused by expansion and contraction due to wetting and drying of the bluff face or by the various processes of chemical weathering of the rock and bluff materials.

e) Human Activities

Beaches, dune complexes, and low lying shoreline bluffs and banks are often directly and indirectly affected by a wide range of human activities. These may range from trampling of vegetation in dunes, removal and mining of sediments from the beach and nearshore area, nourishment of beaches, and the effects of structures on the beach itself and on the supply of sediment from updrift source areas.

A1.2.5 Source, Transport and Deposition of Sediment Supplies

The number, magnitude and influence of sediment sources to beach environments within the *Great Lakes - St. Lawrence River System* are varied and may change over time. The primary sources include sediment derived from the erosion of cohesive bluffs and sedimentary bedrock, riverine deposition, glacial and glacio-fluvial deposition from post-glacial lakes, and lastly, from biological or human-related activities.

In the *Great Lakes - St. Lawrence River System,* a primary source of the sediment supply is derived from wave action eroding cohesive bluffs and relatively weak sedimentary bedrock. This material is eroded not only from the bluff or cliff itself but from the whole shoreline profile extending lakeward out to the limit of wave action on the lakebed (e.g., commonly 4-8 metres on exposed shorelines). These sediments may be retained locally, as is the case with headland-bay beaches areas (e.g., Thunder Beach near Midland, on Georgian Bay), or the sediments may be transported for distances upwards of tens of kilometres alongshore to form large beach depositional features (e.g., Pinery Provincial Park on Lake Huron; Long Point on Lake Erie).

A crucial factor in assessing the stability of sediment sources to maintaining beach environments is the relationship between grain size and value of the sediment supply to stabilizing a given beach environment. In general, fine sediment materials (i.e., silts, clays) are not stable in the beach environment and are usually removed in suspension to be deposited offshore in the lake basins or in enclosed bays. Only that fraction of sediment supplied that is sand size or greater is taken as contributing to the beach environment. On many of the cohesive shorelines of the Great Lakes less than 25% by volume of the material eroded from the bluff and nearshore is coarse enough to contribute to beach development.

A second major source of sediments is from rivers emptying into the *Great Lakes - St. Lawrence River System.* Although these sediment sources are generally less important when compared to bluff and nearshore erosion, there are a few large rivers emptying into the Great Lakes system which provide significant local supplies of sediment to neighbouring beach environments. In the lower Great Lakes, the Nottawasaga, Grand and Don Rivers transport modest amounts of sand and gravel to the shoreline, while greater amounts are transported by small gullies draining a number of stretches of cohesive shoreline, for example those along the Lake Huron shoreline between Point Clarke and Grand Bend. On Lake Superior, with cohesive bluffs providing only a limited amount of sediment, supplies provided by a number of rivers emptying into the lake provide locally valuable and quite abundant sediment supplies to shoreline environments.

A third source of sediment supply is the considerable volume of sediment in, and adjacent to, beaches on the *Great Lakes - St. Lawrence River System* shoreline which were derived initially from the reworking of glacial and glacio-fluvial sediments by post-glacial lakes. Enhancing this process are the sediment supplies resulting from the large changes in lake levels and accompanying shoreline regressions and transgressions. The result of these processes is that in some areas there are quite large beach deposits which are currently receiving very little new sediments. For example, in areas such as the Bruce Peninsula and along the north shoreline of Lake Superior, where isostatic uplift is resulting in shoreline regression, sediments are being stranded in the form of dunes and beach ridges above the reach of modern shoreline processes and as a result reducing the thickness and extent of the modern beach.

Additional sources of sediment supplies to the beach profile can include a number of natural processes such as carbonate material from shellfish and aeolian transport of sediment from sand dunes, although these types of sediment supplies are generally of minor significance in the Great Lakes. Sediment may also be supplied by human-related activities, either in the form of material dumped over eroding bluffs and cliffs in an attempt to halt or reduce recession, or where sediment is brought into or added to the beach profile to create or nourish the existing beaches. In these areas care must be taken to evaluate the effects of a cessation of artificial sediment supply on the stability of these beaches.

Information on the source of sediments for beach deposits, on the post-glacial lake level history, and on the current sediment budget is of extreme importance in assessing the stability and dynamic behaviour of beaches. Managers should ensure that this information is available and properly assessed as part of the studies carried out in the development of a shoreline management plan. In many areas these will be evaluated within the framework of littoral cells and sediment budget analysis.

a) Littoral Cells

In developing and assessing shoreline management options, managers need to ensure that selected management alternatives, particularly those involving issues of sediment supplies, erosion, sediment transport, beach maintenance and enhancement, and the installation of onshore-offshore structures which may impact on sediment supplies and transport, are assessed within the framework of littoral cells, including sources and sinks, and sediment budget analysis.

The term littoral drift cell is used to define a length of shoreline within which there is an uninterrupted net transport of sediment alongshore in one direction, with boundaries across which there is little or no exchange of sediment with adjacent cells. Characteristically littoral cells consist of an updrift source area where sediment is supplied to the littoral system, and a downdrift sink area where there is net deposition. The cell boundaries may be relatively sharply defined by a headland or an artificial barrier, such as a jetty at a harbour entrance, or they may be transitional in nature so that it may only be possible to define a zone separating two systems. For a more detailed discussion of sources and sinks refer to subsection (i).

In the lower Great Lakes, the source for most littoral cells is the eroding bluff and nearshore zone in glacial and glacio-fluvial sediments. For discussion purposes, an idealized littoral cell on a cohesive shoreline is illustrated in Figure A1.2.13. In this example, the updrift cell boundary occurs at a drift divide where sediment is transported to the right into one cell and to the left into another cell. The average location of the divide is a reflection of changes in the relative fetch lengths as one moves from one end of the lake to another, and of the wind climate. The precise location of the divide may vary as wind and wave conditions change and as such, the divide extends over a length of shoreline from which sediment may be transported in either direction.

Within the idealized littoral cell on a cohesive shoreline (see Figure A1.2.13) sediment is supplied to the littoral system directly by wave erosion of the bluff and underwater profile and by sediments delivered through gully erosion. In combination, these sources form a line source, as compared to the point source formed by a major river. Sediment is then transported alongshore at a rate that is limited by either the amount of sediment actually supplied to the shoreline or by the potential ability of the waves. Typically in many littoral cells located along the lower Great Lakes there are large stretches of the shoreline where the volume of sediment supply is much less than the capacity of the alongshore transport system. Where this occurs, these areas are referred to as "supply limited". Within the littoral cell, the sink area is typically located at the downdrift end of the cell and may exist as a baymouth barrier, spit or cuspate foreland (e.g., the Burlington Bar on Lake Ontario, Long Point on Lake Erie, and Pt. Pelee on Lake Erie), the head of a large bay (e.g., Wasaga Beach), or as an artificial barrier (e.g., harbour at Goderich, Lake Huron).

The material eroded directly by wave action or brought to the littoral zone by rivers and by slumping of bluffs is generally winnowed by wave action. As a result of this action, the fines, generally less than 0.06 millimetres, are dispersed offshore and deposited in the deep lake basins, while the coarser sediments are retained in the littoral zone to form the sediment prism of the beach and nearshore zone. The thickness and extent of the beach and nearshore sediments that make up the littoral sediment prism depend on the magnitude of sediment supplied from wave erosion and land sources and on whether the sediment is retained in place or removed alongshore to some other location by alongshore sediment transport.

To provide a more detailed assessment of the dynamics within the littoral cell, the following three factors warrant additional discussion:

- sources and sinks; and
- beach sediment budget.

A discussion of each, and their interrelationships, is provided in the following subsections.

i) Sources and Sinks

Deposition of eroded material is a continuous process along the shoreline. In studying shoreline processes it is necessary to identify zones of deposition or net accumulation in the nearshore area (e.g., beaches, offshore bars, and shoals), where they can affect the nearshore process or be a source of material for beach nourishment, and to identify areas which contribute sediment to the littoral zone. These are usually identified as "sinks" and "sources" respectively.

A "source" is a supply of littoral drift material to the shoreline. This sediment supply may be either a line source (i.e., erosion of the shoreline or bluffs), or a point source (i.e., material supplied to the shoreline by rivers and streams). Artificial nourishment, deposition of material by humans from inland sources or from dredging outside the littoral drift zone, are also considered sediment sources.

A "sink" is a loss of littoral drift material from the littoral transport zone. This loss may be a line sink (i.e., offshore loss to deep water), a point sink (i.e., loss into an offshore canyon), or deposition on a shoal. Losses of material to accretion and deposition areas (e.g., shoals, aggrading beaches, spits) are considered to be sinks. In addition, any removal of sediment supplies through dredging is considered to be a sink.

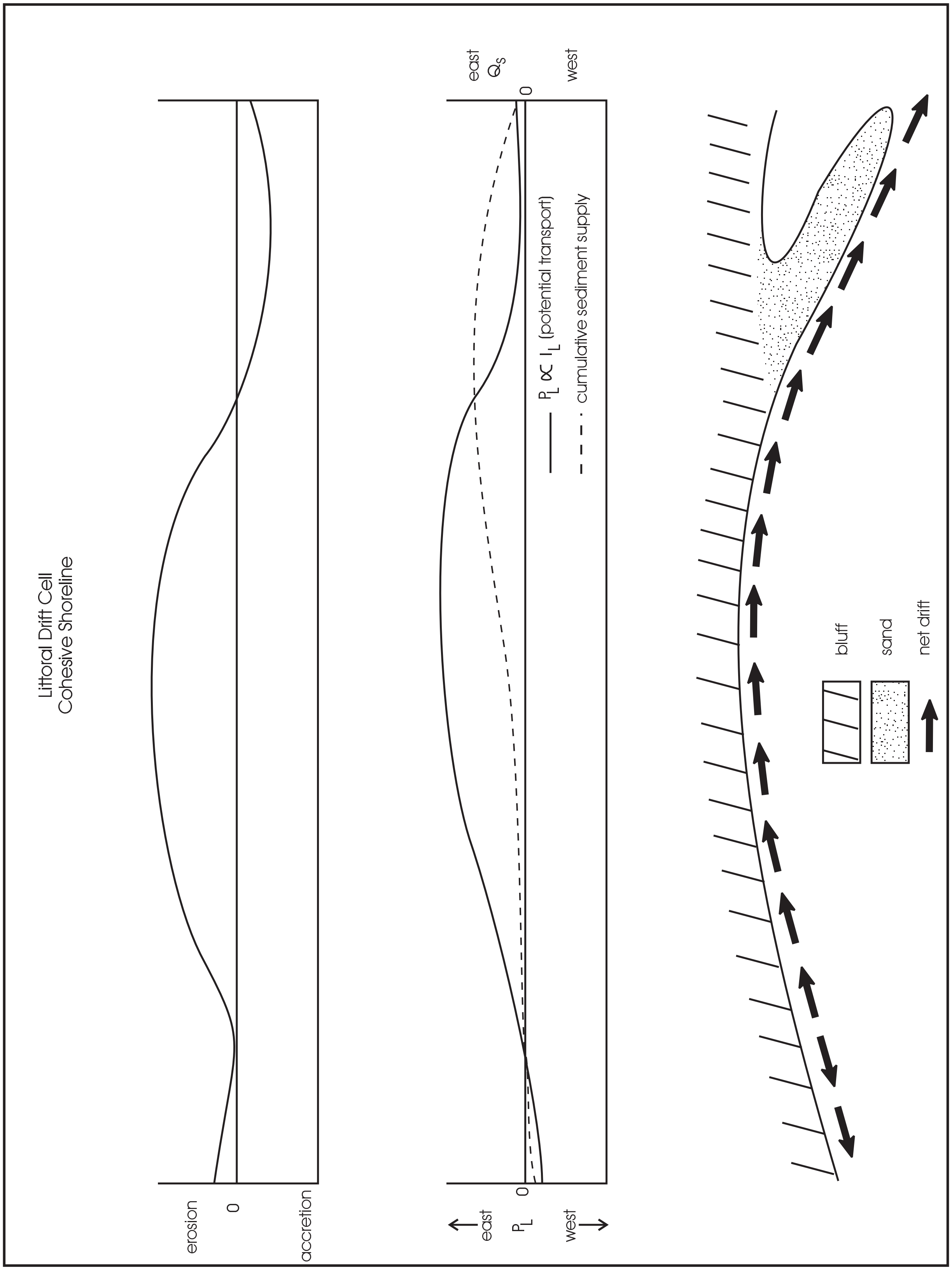
Evaluation of the shoreline, in terms of sinks and sources, is important to any critical analysis of alongshore transport, evaluation of long-term trends in natural geomorphological development of shoreline forms, and in the estimation of sediment budgets.

ii) Beach Sediment Budget

The concept of the beach sediment budget provides a framework for compiling information on the processes which result in the transport of sediment into and out of a section of shoreline and on the volumes of sediment involved. Calculation of the gross sediment budget involves the cumulative totalling of all sediment transfers into and out of the defined reach, measured in terms of sediment volume, through processes such as bluff recession, alongshore sediment transport, and transport/deposition into the dune complexes. This procedure provides a measure of the overall "level of activity" within the littoral cell.

In relative terms, the greater the gross sediment budget, the greater the dynamic range of the beach will be and conversely, the greater the potential negative impact on the beach should disturbance of the controlling processes by natural or human-related action occur.

Figure A1.2.13: Idealized Littoral Cell on a Cohesive Shoreline



The net sediment budget or sediment balance is obtained by subtracting all sediment outputs from the inputs to the defined littoral cell. The sediment budget is described as positive when inputs of sediment exceed outputs, as neutral when sediment inputs and outputs are approximately equal, and as negative when outputs of sediment exceed inputs. In practice, the sediment budget identifies sediment inputs from updrift sources and outputs at downdrift locations (i.e., may also include deposition into dunes or lagoons behind barrier systems). As such, a negative/neutral budget implies that the difference between sediment entering the shoreline segment (i.e., defined littoral cell) and leaving the segment is made up by erosion from within that segment.

In general, the net sediment budget can be viewed as an indicator of the long-term stability of the shoreline. If the sediment budget is positive then the beach will increase in size or prograde, if the sediment budget is neutral then the shoreline will remain stationary, and if the sediment budget is negative then shoreline erosion and recession will take place. Under conditions of negative sediment budgets, the rate of erosion and recession will be determined by the resistance of the material forming the shoreline to erosion and by the magnitude of the deficit.

b) Shoreline Changes

In analyzing the factors interacting within a littoral cell (i.e., sources, sinks, sediment budgets) examination of shoreline forms and features can provide valuable clues to the nature and character of shoreline processes, and identification of the erosional and depositional sections of the shoreline.

Assessing changes in shoreline form can generally be described using four basic terms: erosion, accretion, recession, and progradation. For discussion purposes, these terms are usually defined as follows:

Erosion	is a volumetric reduction of shoreline material by natural processes. It involves the removal and transport of soil, surficial deposits or rock from any part of the shoreform.
Accretion	is a volumetric accumulation of shoreline material by natural deposition.
Recession	is the landward retreat (i.e., measured in terms of a linear distance) of the shoreline due to erosion.
Progradation	is the accretional and lakeward advance of a depositional landform (i.e., measured in terms of a linear distance).

Within a defined littoral cell or comprehensive stretch of shoreline, the shoreline may be segmented into "shoreline reaches". These are basically defined as segments of shoreline having similar physical characteristics (i.e., soil composition, orientation, etc.). Shoreline reaches can be classified as progradational, or recessional, depending on whether accretion or erosion is taking place. On any shoreline, the erosional and depositional features may alternate spatially (i.e., size, dimension, location) and/or temporally (i.e., over time).

With respect to its horizontal position, a particular section of the shoreline may be experiencing stability, transgression (i.e., shoreline moving landward), or regression (i.e., shoreline moving offshore). Within the Great Lakes system, small regressions and transgressions, that is the relative displacement of existing shorelines, usually result from seasonal and long-term water level fluctuations.

Isostatic rebound also has an impact on relative shoreline displacement (i.e., horizontal position), particularly where there are differences in the rate of isostatic rebound between the lake outlets and shorelines. In general, within the *Great Lakes - St. Lawrence River System*, shorelines that lie north of a lake outlet are experiencing regressions, while those that lie south (i.e., downdrift) of the outlets are experiencing transgressions.

In comparison, vertical displacements within the *Great Lakes - St. Lawrence River System* are very small in the lower Lakes. The effects of the vertical displacements within the system are normally considered to be negligible when compared to shoreline changes due to erosion or accretion. In northern Lake Huron and Lake Superior, however, continued isostatic uplift is an important element along with the prevalence of bedrock in maintaining shoreline stability.

Setting aside the effects that the relative movement of land and water have on a shoreline, shorelines can be divided into three basic types: stable, accreting and eroding. Within these three basic shoreline types, stable shorelines can be further subdivided into two distinct types: static and dynamic.

Static stable shorelines generally occur where erosion is negligible due to very low wave energy (e.g., in protected bays and connecting channels) or on bedrock shorelines where the rock is extremely resistant to erosion.

In contrast, dynamic stable shorelines generally occur where there is a neutral net sediment budget and where a full sediment prism is developed and where the wave energy is being dissipated over the beach and nearshore profile. During periods of low wave energy, sediment is stored in the beach and foredune areas, and then, during storm events these sediments are eroded and transported offshore, forming a wide beach and surf zone.

In shorelines where a negative sediment budget exists, this means that there is insufficient sediment to absorb all the wave energy and an erosional shoreline develops with the rate of erosion determined by the extent/magnitude of the sediment deficiency. Conversely, where there is a positive sediment budget, such as the downdrift end of littoral cells, the excess sediment inputs from updrift sources will tend to lead to progradation of the shoreline.

A typical phenomena in the natural development of a shoreline feature is that the shoreline will naturally tend to "face" the waves so as to minimize alongshore transport and/or satisfy the continuity of the relationship between wave action/attack and littoral transport. In essence, there is a strong relationship between littoral transport, direction of wave action/attack and the resultant type of equilibrium shoreline form. Understanding this unique relationship, enables the shoreline manager, having first identified the type(s) of equilibrium shoreline forms within a defined stretch of shoreline, to then interpret or make an assessment on the littoral transport patterns and on the direction of predominant wave attack based on the type, location and/or size of particular shoreline forms. This assessment may be based on a review of either charts or aerial photographs of the beach/shoreline forms within the defined stretch of shoreline. Conversely, the current and potential future geometry of shoreline forms can be determined from an understanding of the relationship between littoral drift capacity and the direction of wave action/attack.

Headland-bays are a common shoreline feature between headlands or hardpoints on natural shorelines formed in unconsolidated deposits. Bay shapes have received various names: crenulate bays, headland-bay beaches, spiral beaches and zeta bays. Stable headland-bays have a straight segment downdrift, nearly tangential to the downdrift headland, followed by curved section of logarithmic spiral form which is then connected to an almost circular section behind the updrift headland (see Figure A1.2.14). The straighter downdrift section is parallel to the dominant wave crests. Over time, assuming fixed headlands, a headland-bay will approach an ultimate or static equilibrium shape. This occurs when the shoreline has adjusted so that the dominant waves arrive at right angles to the entire periphery with the result that there is no littoral drift within the bay. Evidence suggests that these bays maintain a relatively stable shape and recede mainly due to recession of the headlands.

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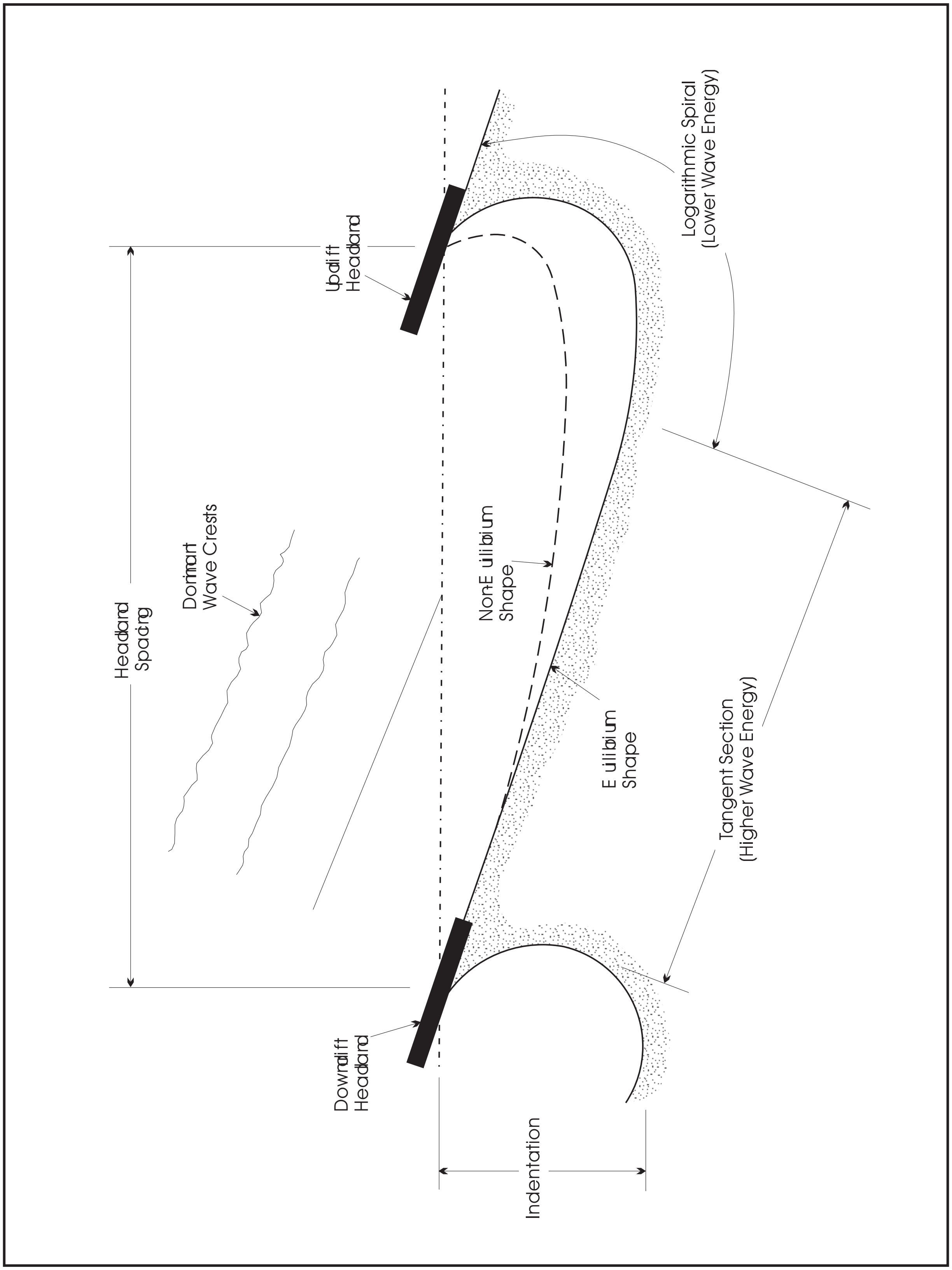
Figure A1.2.14: Definition Sketch of Headland-Bay



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LAKE/LAND INTERACTION